Development of Straw Insulation Board: Fabrication Methods, Structure, Thermal Performance

by

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ABSTRACT

Insulation board is being fabricated and tested for use in developing countries. It is made at a low density, in the area of 5 to 10 pounds per cubic foot (80 to 160 kilograms per cubic meter), and has good thermal properties for an air based insulation, meaning R3 to R4 per inch (Btu-in/hr-ft^2-°F)$^{-1}$, or a conductivity of .048 to .036 W/m-K. The initial effort is to produce a straw insulation board suitable for northern Pakistan, where we are studying the needs and construction of schools and houses. Some type of rigid insulation is needed, as opposed to loose fill, because the buildings have solid masonry walls without an air gap. These boards will be suitable for other developing countries as well

The initial survey of possible methods included 1) containing the straw in panels with wire and battens, 2) pulping the straw, and 3) binding with adhesive. In this latter category starch, PVA and sodium silicate were tried as adhesive using uncut and shredded straw, with various methods of application such as spraying, foaming, and dipping, at various adhesive loading rates. Small samples were formed at a range of densities to test structural and thermal properties. This survey suggested that all three of these approaches can succeed structurally and thermally, but that competing economically with existing insulation board is difficult. For boards with binder, the adhesive efficiency was poor.

In the final phase of the project, a batch of boards was made at ICI Polyurethane's North American research and development facility, using methane di-isocyanate as the binder. The boards, made at a range of densities and resin contents, and using straw with and without the fine particles, were tested thermally and structurally at MIT. Good mechanical properties were obtained at resin contents as low as 2% by weight. At densities of 8 and 10 pounds per cubic foot (pcf), these boards have R values of 3.7 and 3.45 per inch, respectively. The pressure required to compress the 10 pcf boards to 10% of their original thickness is approximately 15 pounds per square inch (psi), and the modulus of rupture in bending is in the range of 50 psi. Removing the fine particles from the straw improved board strength markedly.

These boards at a density of 10 pcf and 2 to 4 % resin content have an estimated materials cost of 2¢ per insulating unit (R-ft^2), substantially less than either the cost of the expanded polystyrene available in Pakistan, or the retail cost of any rigid board insulation sold in North America.

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I. Introduction

A. Purpose of work

There is a need for inexpensive insulation in many parts of the developing world. In cold climates the wood, charcoal, peat or dung used for heating fuel may be scarce, and insulation for the dwellings would conserve resources and better living conditions; in hot climates thermal comfort could be greatly improved by the use of insulation under the roofs of the houses. In some cases, for example the shantytowns of South Africa, people who can ill afford it are beginning to use electric heat. Economic and comfort conditions for these people would be ameliorated by the availability of cost-effective insulation board.

In the remote Hunza valley of Northern Pakistan, where Winter temperatures for some months average 30°F, firewood is burned to heat the traditional stone houses, as well as the newer concrete block homes. The newer construction methods, unfortunately, are even less energy efficient than the older ones. A very simple degree day analysis for these houses can show how much firewood use is curtailed by insulating the walls. For example, a pound of straw placed on the walls in a one foot square board would have an insulation value of about R5 (Btu-in/hr-ft^2-°F)$^{-1}$, and would prevent about three pounds of firewood from being burned every Winter. Insulating the walls and roofs of a significant fraction of the housing would result in dramatic regional firewood conservation. In a dry climate where wood is expensive, and better used as lumber, and forests are being unsustainably harvested, these savings are important (Sullivan 1995).

This thesis describes our effort to develop a rigid insulation board for use in developing countries such as Pakistan. We would like to make the board from locally available waste or near waste materials, using simple machinery and requiring little energy to manufacture.

In Pakistan, the boards would find application in schools as well as houses, both existing and under construction. They would be fastened to the inside of the concrete or earth block walls and roofs, and could receive a plaster finish coat. So the boards need sufficient integrity for transport, attachment, and plastering, but need not carry structural loads. Loose fill insulation, on the other hand, would have limited usefulness. It could be applied to a relatively small number of institutional buildings, health centers and a few upper-level schools, which have cavity walls.

At present little or no insulation is used in Pakistan, because of the high cost. The only rigid insulation material available is expanded polystyrene, which has been used in a very few schools. Our goal is to develop a less costly alternative, so that insulation could be widely used, thermal comfort in houses and schools could be improved, and forest depletion due to firewood demand could be reduced.

This rigid insulation will not have the thermal performance of foams filled with low conductivity gas, but must insulate well enough to justify the effort and material going into it. We should be able to approach the thermal value of foams that aren't filled with a low conductivity gas, meaning R3 to R4 per inch (.048 to .036 W/m-K). This is typical for the better air-based insulations such as fiberglass, cellulose, and expanded polystyrene. There is a possibility of going above R4 per inch (below .036 W/m-K) by careful control of the porous structure and the material radiative properties, although that work would have to be the subject of a further investigation.

We chose straw for the primary material, at least to begin with, as it has a long history of use in buildings, including structural and insulating boards, and is available at little cost in Paki-

stan. Another obvious option is wood, which might mean sawdust and shavings from sawmills, and could include the bark. There are many other agricultural or forest products worth considering in other countries, such as rice and peanut hulls, bamboo, coconut hulls, flax shives, cornstalks, sugar cane bagasse, jute, sisal, hemp, pine needles, etc. In industrialized countries, recycled paper and plastic are possibilities, as are certain inorganic plant wastes (such as fly ash from coal burning power plants). Kenaf, a fast-growing woody plant whose fibers have superior strength, is rapidly becoming an important paper fiber, and could also be used in boards. We are starting with straw, however, and the results will generalize at least to other lignocellulosic materials.

The first phase of the project was a search into fiber insulation boards, and straw boards in particular, as well as general background research on board making and pulping methods, adhesives, and insulation heat transfer. There is a wealth of literature about wood, straw, and other insulation boards, including historical products and patents as well as journal articles. This is reported in the remainder of this chapter. Our initial experiments with fabrication methods are the subject of chapter II. We identified three general approaches, which might be described as 1)little or no processing, holding the straw stalks together in panel form by some containment, and 2) maximal processing, which could mean pulping the straw to form a strong homogeneous board. Between these, we can 3) use some combination of slight processing, such as shredding or soaking or heating, and adhesive binding. In the third chapter we focus on one promising adhesive, MDI (isocyanate), and describe the making of boards at the ICI research facility and subsequent testing and analysis at MIT. The fourth chapter presents conclusions and outlines further development directions.

In the remainder of chapter I many promising methods are presented, and some of them became starting points for our laboratory work. Many of them, however, are not applicable to our effort in Pakistan because they were developed in regions with a vastly different resource base, in a different cultural context, or with a different end use in mind. In general these reservations are noted below. Wood fiberboard, for example, was developed in timber rich North America and Europe, and cannot be sensibly made in arid climates.

Likewise, many of the products discussed below have been structural boards at high densities (30-80 pounds per cubic foot (pcf), or 480-1280 kg/m3), and even the boards and panels used for insulation have had higher densities (10-30 pcf or 160-480 kg/m3) and lower R values than we are looking for. In addition to diminishing thermal qualities, the higher density may require too much straw to meet cost criteria.

We include nevertheless an extensive discussion of wood fiberboard, and many other concepts, just as general background necessary for making insulation board. A familiarity with fiberboard manufacturing, and an understanding of adhesive mechanisms, should be helpful in experiments with any new form of rigid insulation.

Some of the historical methods discussed might be useful to us, but more evaluation is needed. For example, a flexible insulation sheet was made from cattle hair mixed with other materials in the 1940's. Cattle hair could provide reinforcement for our straw boards, but we need to research issues such as cost, sanitation, transportation, processing, etc. In the same vein, a Canadian inventor in the 1950's worked out in great detail a simple shredding and chemical soak process for straw insulation board. Details of the process are not readily available; more library, patent and industrial research is required to find them. We simply did not have time to pursue all auspicious avenues of investigation.

B. Existing and Past Insulations

Insulations used today

Of the materials currently used for insulating buildings in this country, fiberglass in batt form and loose fill cellulose are the cheapest. The rigid materials have lower conductivities and cost considerably more per insulating unit. Table 1 gives an approximate idea of prices at the retail level in 1996.

	density lb/ft3	aged R per inch thickness (Btu-in/hr-ft^2-F)$^{-1}$	¢ per R-foot squared
wood fiber insulation board	17	2.8	
fiberglass batt	1.5	3.2	1.4
cellulose attic	2.2	3.6	1.0
cellulose wall	3.5	3.5	1.6
expanded polystyrene	1-2	4	4
rigid fiberglass	5	4	10
extruded polystyrene	1.8	5	6.5
polyurethane foam	1.8	5.6-6.5	5.2
phenolic foam		7	6

Table 1. Density, Thermal Resistance and Cost of Current Insulation

In general cost per unit of resistance rises as conductivity goes down, although other qualities play a major role. For example extruded polystyrene works well below grade and is used on the exterior of foundation walls, and so commands a price equal to or greater than polyurethane, which has higher R value but can't tolerate the moisture. Rigid fiberglass can withstand high temperatures, and absorbs sound well, and thus has a high price for its niche uses such as ductboard and hot water heater insulation.

In Pakistan, prices for one inch thick expanded polystyrene are in the range of 6 to 10 rupees per square foot (Sullivan 1995). This is a retail price for a board available in one of the larger cities in the South of the country; there could be additional cost associated with transport to remote regions. At an exchange rate of 33 rupees per dollar, that is 4.5-7.5¢/R-ft^2. A board for Pakistan based on organic material, with inferior moisture and bio resistance, should beat that cost by a significant margin, in order to gain market acceptance. In fact moisture and biological issues may not be be a problem in Northern Pakistan's arid climate, although they would be crucial in other parts of the world. If substantially cheaper insulation were available in Pakistan, it could have a major influence on building practices, and great benefit for the regional economy and environment.

Insulation boards made in the past

Bricks made from clay with straw mixed in are an ancient building material used all over the world. The straw is used for structural reasons, but also improves thermal qualities. Excava-

tions at the palace of Knossos on Crete revealed bathhouse walls made of clay with straw; apparently the Minoan people in 2000 BC were using the straw for its insulative value (Hermannson 1993).

Straw panels were used to insulate European buildings earlier in this century. Under the name Solomit, they were large (about 5 ft. by 10 ft. and 5 inches thick (1.5 m. by 3 m. by 120 mm.), with a density of 20 pcf (320 kg/m^3) and an R per inch of 2 (.07 W/m-K). They were held together with a wire mesh and stuccoed on the outside. They were treated against rot, but our source does not identify the chemical (Hermannson 1993).

As a somewhat more modern improvement on this, compressed straw panels made by the Stramit method were developed in Sweden in the 1930's. Still made today, they are used for interior partitions, archery targets, and to some extent for exterior walls. Uncut straw is pressed to 19-23 pcf at 390°F. The panels hold together well with no added glue, presumably because the lignin in the straw softens with the heat as the stalks are compressed and entangled. On cooling the lignin hardens and the pieces are locked together. They have a modest R1.8 per inch thermal resistance (Wilson 1995). They are generally sold with paper facings on each side, which are stripped off in the event of plastering. An engineer at a recently opened North American Stramit facility reported that they occasionally and unintentionally made lower density panels, as when starting a production line, but that these do not hold together well enough to handle. He felt 23 pcf was the lowest possible density for the process (Stramit USA 1995).

Generally the higher the density of a straw product, the lower is its insulating value, as explained in section F of this chapter. Our goal in this project is to create a board with better thermal performance than either Solomit or Stramit, by working at lower densities.

Houses were built with straw bales in this country in the prairie states around the turn of the century (for lack of other materials). Some of them are still sound. In the past decade there has been renewed interest in this technique, and hundreds of houses have been built. The whole bales are stacked in offset rows, like bricks, and reinforced with rebar. They are stuccoed on both sides, and stand up extremely well to the weather. The stucco is reinforced with woven wire mesh pinned into the bales. Proponents claim the straw resists rot well as long as it stays dry. At high moisture content, above 70%, fungi will grow, so the houses are designed to minimize exposure of the walls to bulk water, by using wide roof overhangs, sloping the ground away from the walls, and installing an impermeable barrier between the foundation and the straw wall. The straw has little food value, and insects such as termites apparently do not infest it. Rodents may live in the straw however, and straw bale house owners emphasize the need for careful, complete plastering inside and out (Jaccaci and Bodzin 1996, Wilson 1995).

At a density of around 8 pounds per cubic foot (128 kg/m^3), the bales do not sustain fire, because there is not sufficient oxygen available. The straw will char but not support combustion. Anecdotal evidence suggests that the straw bales will not burn even when wooden framing of the house is completely consumed, and an ASTM standard test showed 18" straw bale walls resisting fire for 34 minutes unplastered, and more than two hours plastered. This is better than average wood frame walls (Jaccaci and Bodzin 1996, Wilson 1995).

There are two published thermal conductivity measurements for straw bales. The baling machine aligns the straw stalks as it presses them together, so there is a difference in thermal value depending on whether the heat is flowing parallel or perpendicular to the stalks. The results suggest, roughly, that resistance is about R2.5 per inch "with the grain", and R3 per inch "across the grain" (Wilson 1995).

We have not contemplated introducing a whole new building style such as straw bales to Pakistan. Our focus is rather on a sheet product that could be incorporated into existing practice. However this report suggests that straw in its whole stalk form can achieve R3 per inch, at the low end of our target range. We therefore made trials of this type, in the experimental work described later.

A number of insulation boards made earlier in the century were phased out as the plastic foams became available. The insulation materials shown in table 2 are listed in the Handbook of Chemistry and Physics from 1953, classified as "soft flexible sheet," "semi-flexible sheet," and "stiff fibrous sheet." Also listed are two loose fill materials that are still made, but have been for the most part replaced. These have also been made into board form (Wilkes 1950, Nisson and Dutt 1985).

Note that although the Celotex company continues to make bagasse board, they are now better known for their polyisocyanurate board.

Comparing Table 1 with Table 2 it can be seen that the plastic foams have very low densities compared with the natural material boards. At the same time, the foams have fairly good structural properties; they are used over wall studs, as roof decking, on foundation walls, in sandwich panels, etc. This is due to the tremendous cohesive power of the crosslinked polymers. Although these foams use little material per unit of production, their unit insulation cost is substantially higher than that of cellulose or fiberglass, or, we can assume, other organic based boards listed in table 2. This is because they are made from petroleum products in an energy and technology intensive process.

Boards made from natural materials at such a low density would fall apart (barring a major technological advance). However for our project there are no especially stringent requirements for high R per inch values, or for structural performance: the most important criteria are cost and availability. Higher density organic boards with modest thermal and structural properties, such as those listed in table 2, may be a reasonable solution for places like Pakistan.

Although we have developed at least one workable method for making straw insulation board, as described in chapter III, there are many alternatives worthy of study. Technology for making several of the boards in table 2 might be applicable to our efforts with straw. Balsam wool, in particular, was a common insulation that can still be found in attics in New England. The technology for shredding and treating the wood fibers and making a cohesive batt might be applied to straw. Likewise hair and jute fibers are natural candidates for reinforcing filaments in a rigid or flexible board, as used in the above "Thermofelt," and in one of the products mentioned below. The pursuit of this information could be the subject of further work.

Many of the other boards are clearly not relevant to us. Eel grass (seaweed) is a candidate for coastal areas, cork is only produced in certain regions, asbestos is too dangerous. Vermiculite and perlite could be used in those countries where they are found, although they have a high energy embodied in the heat expansion process. The pulped boards listed as "stiff fibrous sheets," are denser than we would like for our effort, however their fabrication is of interest and is described below.

Material	description	density lb/ft^3	R per inch (Btuin/hrft^{2}F)$^{-1}$
soft flexible sheets			
Balsam wool or Kapoc	chemically treated wood fibers	2.2	3.7
Hair felt	felted cattle's hair	11-13	3.8
"Hairinsul"	combination of hair and jute (75/25 or 50/50)	6	
"Linofelt"	flax fibers with paper facers	5	3.6
"Cabot's Quilt"	eel grass with Kraft paper facers	3.4-4.6	3.1
"Thermofelt"	asbestos with jute or hair	8-10	3.6
semi-flexible sheets			
Flax fiber		13	3.2
Flax and Rye fiber		13.6	3.1
Corkboard	still used for bulletin boards, flooring	7-16	3.8-3.2
"Rockcork"	rock wool block with binder	14.5	3
"Lith"	board with rock wool, flax, and straw pulp	14.3	2.5
stiff fibrous sheets			
"Celotex"	sugar cane fiber (bagasse)	13-15	2.9
"Masonite"	hardboard from waste wood (sawdust, etc.)	high	low
"Insulite"	pulped wood insulation board, still made today	16-17	2.9
"Maizewood"	pulped board from cornstalks and other materials		2.6-3
Cornstalk pith board			3.3-4.2
loose fill			
vermiculite	micalike hydrated laminar mineral, expanded by heating, contains Al-Fe-Mg silicates	4-8	2.3-2.1
perlite	naturally occurring siliceous volcanic glass, expanded by rapid heating, mostly aluminum silicate	2-11	4-2.5

Table 2. Insulating materials used in the 1920's to 1960's.

Wood fiber Insulating Board

Wood fiber boards such as "Insulite" in Table 2 were one of the dominant insulation boards in this country in the middle third of this century, and there are still six manufacturers producing hundreds of millions of board feet per year. These boards are used for roof insulation, wall sheathing, sound deadening, dunnage (packing for such items as car windshields), and other niche uses (such as tatami mats). The industry has lost most of its market share to foamed insulation board, gypsum wall board, fiberglass ceiling tiles, and the like, and is in decline. Wood fiberboard does not resist fire as well as fiberglass tiles, accounting for its discontinued use in dropped ceilings. It is however less combustible than foamed plastics, which are required by building code to be covered by .5" gypsum board when applied to interior spaces (Wagner 1995, Suchsland and Woodson 1987).

These boards are made by pulping wood mechanically, rather than chemically. The manufacturers chip logs into 1/8" (3 mm.) thick pieces, then defiberize them. One defiberizing method is the masonite gun, which steams the chips at moderate pressure, then explodes them by opening the port to the vessel suddenly. In another method the chips go to a disk refiner, in which they pass between two rotating grooved steel disks with a given clearance, on the order of a few hundredths of an inch (about 1 mm). The result in both cases is pulp in which the wood fibers or cells are nearly completely separated, but have not been ground up as finely as in paper pulp. The lignin and hemicelluloses are not removed, as they are in most paper pulping. Many plants add a small amount of recycled newspaper to the pulp.

The pulp is watered down to a consistency of a few percent, and sized with asphalt (about 10% to weight of dry board) or wax (about 1 or 2%). The sizes are precipitated on the fibers by lowering the pH with aluminum sulfate; they make the board water repellent and have some binding properties. Starch (about 1%) may be added as an additional binder. The wet mat goes to a Fourdrinier machine with big rollers and long continuous screens, similar to those used in paper manufacture. Water is pressed out of the mat, and drains off through the screen. Remaining water is evaporated in a dryer. The boards may have to be heated enough in the drier to make the asphalt flow (Wagner 1995, Suchsland and Woodson 1987).

Additional binders notwithstanding, it is thought that the primary mechanism of cohesion in fiberboard is hydrogen bonding. As the water evaporates, surface tension pulls fibers into intimate contact, within the range of attractive forces of surface hydroxyl groups, which can act either from wood fiber to fiber, or from adhesive to fiber. In addition, lignin in the wood acts as a thermoplastic, softening under the effects of heat and water, then binding fibers together when cooled and dried. For this effect it is necessary to heat the board to the softening point of lignin, which is around 383°F when the lignin is dry. The softening point is lower when the lignin contains moisture, for example it drops to 240°F at 13% moisture content (Suchsland and Woodson 1987).

This is water, energy, and equipment intensive. It yields a board with excellent mechanical and modest thermal properties. As these boards are made for a variety of end uses, from semi-structural wall and roof sheathing, to completely nonstructural insulating and decorative panels, they are produced in a range of densities, from 16 to 30 pcf. Conventional plants can and have made these boards at densities as low as 10 pcf, although none are doing so at present. For the less structural boards, density is generally 17 pcf (1.0 kg/m3) and R/inch is 2.8 (.05 W/m-K). Modulus of rupture is in the 200 psi range, and tensile strength parallel to the surface is about 150 psi (Suchsland and Woodson 1987, Huebert Fiberboard 1995). We ruled the complete fiberboard process out altogether for our work in developing countries where fuel and water are scarce. Some of these concepts, however, can be copied in a simpler, less resource intensive format. For example, instead of passing wood or straw chips through a pressurized disk refiner, they could be boiled in water at atmospheric pressure. Simpler yet, they could be hammer milled dry; this was one of the first things we tried in our lab efforts.

Similar boards, such as "Maizewood" in Table 2 were made from a variety of agricultural materials. The Maizewood plant at Dubuque, Iowa, operated from the 30's through the 50's, and made a pulped board from a combination of flax shives, wood, straw, cornstalks and waste paper. The plant used a semichemical pulping process, in which the raw materials were cooked in a digester with sulfite liquor for about an hour at elevated temperature and pressure, then passed

through a disk refiner. The pulp was sized and formed in a manner similar to the wood fiber boards above, and had similar properties (Porter 1950).

A simpler method for making straw insulation board is reported in a pulp trade journal from 1952 (MacIver 1952). The article gives plans for a production plant in Canada. In this case the straw sits for eight hours into a concrete "soaking tank." It is then shredded into 3-4 inch pieces and slowly dragged through a "chemical tank" for 24 hours. The wet fibers are agitated, formed into a uniform mat, pressed, and dried. The final product had two-thirds the density of a wood insulation board, i.e. 11 pcf, with good structural and fire resistance properties. No details of the chemicals used for breaking down the fibers, or for binding, are given, and no other references to this "Bodite" process have been found, so that it is unclear if such a plant was ever built. It suggests however that a simplified chemical process, not as involved as full pulping, might be used, and that relatively low density straw boards have been made in the past.

C. Board Making Methods

Wet and Dry Process

The pulped wood insulation board described above is one example of a wet process board. Structural wood boards are generally made by either a wet or a dry method. The basic technology for the wet process was developed in the paper industry. In this case the medium for conveying the fibers is water, and the wood pulp is diluted into a "stock" which is pumped from tank to tank, where it is sized, washed, beaten, and otherwise processed, before passing to a Fourdrinier machine and dryer as described above. The soaking and subsequent drying activate the natural bonding properties of the cellulose and the lignin, and there is little need for additional adhesive. The final product may be superior to dry process boards in strength and appearance.

However the plant must have access to massive amounts of water, as much as 100 times the weight of board produced, and must then either release the polluted water to the environs, or have an expensive recovery system. Extraordinary quantities of such wastes are produced each year; for example in 1960 it was estimated that 8 billion gallons of spent sulfite liquor were generated in the US, where the sulfite pulping process is just one among several. There is also a substantial energy demand for the fossil fuel or electric dryers: the economics of production do not allow for a slow ambient-air drying. Wet boards usually can have only one smooth side, called "S1S" for smooth one side, because the mat must be pressed against a screen, to allow water drainage, and the bottom side of the board carries the imprint of the screen. In addition, there may be a thickness limitation imposed by the need to squeeze out, and then evaporate, the water. Medium density fiberboard (MDF) produced by the wet process is made to one-half inch thickness maximum, and insulation board to one inch maximum (Suchsland and Woodson 1987, Macdonald and Franklin 1969).

Wet process boards include insulation board at 10 to 30 pcf; MDF, which is similar but made at a higher density, in the 40 to 50 pcf range, and used largely for siding of buildings; and hardboard or Masonite, which is made at even higher densities, in the 55 to 70 pcf range, or about twice the density of softwood. Hardboard is used for interior paneling, exterior siding, and in furniture and automotive products, etc. Clipboards, for example, are generally made of hardboard.

Hardboard was invented by William Mason in the 1920's to make use of the vast quantities of sawmill by-products such as sawdust and log trimmings. Pulp made from sawdust is com-

posed of very short fibers, which make for weak boards. Hardboard cannot carry structural loads, but develops strength by the extreme densification. It is not a thermal insulator. Insulation board and MDF, on the other hand, are generally made from larger wood chips derived from whole logs: they need the longer fibers for strength. Sawmill by-products are therefore not good candidates for insulation board.

In the lab work discussed later, we used a modified wet process where an aqueous solution was used to convey and distribute the adhesives, but the overall water requirement was very modest in comparison with pulping techniques. We felt that any true wet process would consume too much water for an arid climate. This meant however that we did not get the benefit of the innate hydrogen and lignin bonding that is the basis of paper and wet process boards.

In the dry process, originally developed for particle board, the wood particles, referred to as the furnish, are carried by air in large ducts. Resins such as urea-formaldehyde, phenol-formaldehyde, or isocyanate provide virtually all the adhesion. The airborne fibers are sprayed with resin, deposited onto a plate, and pressed in a hotpress which compacts the mat and cures the resin. Water problems are minimal, but there may be air pollution problems, as the resins and their solvents are hazardous, and a ventilation system is required to draw off the fumes. There is still a substantial energy requirement as heat is needed for the chemical cure. Also the pulping is much the same for the wet and dry process, and the pulped fibers may have to be dried before they can be introduced to the dry process equipment.

Dry boards can be made smooth on both sides however-- S2S-- and can be thicker than wet process sheets. MDF and hardboard are made by both wet and dry processes, but insulation board has been made only by the wet process. It may be harder to achieve the lower density with the dry method. Other dry boards include particle board, in which the wood chip size is on the order of a millimeter, and density is in the 40-50 pcf range, and structural sheathing such as flake board, oriented strand board, and plywood (Suchsland and Woodson 1987).

A dry process is a natural choice for an arid climate, and we devoted the latter phase of our project to a dry process isocyanate board. We therefore faced the challenge of developing adequate cohesion and strength entirely from the resin, at densities lower than any existing dry boards.

Pulping

The above boards, wet or dry, can be divided into fiberboards, in which the particle size is of the order of the wood cells, and boards which use much larger pieces. The fiberboards all require pulping of the raw material, and this is a complex, energy intensive part of the manufacturing process.

Pulping can be either mechanical, chemical, or a combination of the two. Mechanical pulping involves breaking apart the wood by grinding, heat, and steam, possibly at elevated pressures. Fibers are separated but the lignin is not removed. Chemical pulping tends to remove lignin, as required for quality writing paper. Choice of pulping method depends on the properties needed in the end product.

Current fiberboard operations in this country rely on mechanical pulp as the lignin is desirable for its bonding ability. The first insulation board plant in the US, starting during World War I in Minnesota, made "groundwood" pulp with one of the original pulping devices, which is just a rotating grind stone against which whole logs are pressed, in a water spray. Today the pulp is

made with either a masonite gun, or a disk refiner. Disk refiners are classified as either atmospheric or pressurized; in the pressurized refiner the wood chips pass between the spinning plates in the presence of pressurized steam. In the atmospheric method, the chips may be heated or steamed before going through the refiner (Panshin and Harrar 1962). It is worth noting, as part of our search for low energy fiberizing methods, that although modern operations apply heat, mechanical pulping can be accomplished at room temperature.

These pulping methods each produce pulp with different characteristics. The method determines where in the their anatomy the wood cells are broken apart. Pressurized refining, for example, produces more lignin rich cell surfaces than the other techniques, and so is desirable if lignin bonding is being used. The lignin reduces hydrogen bonding however (Schaller 1996). These considerations must be balanced against the effluent problem: if chemicals are used, or if large amounts of sugars or lignin are released from the pulp, the effluent will be toxic and need treatment.

Chemical pulping is not used for fiberboard in this country, however chemical or chemimechanical techniques are an option for making boards. In searching for inexpensive, low energy pulping methods, we looked at a room temperature process using sodium hydroxide. This is a subset of a more conventional class of alkaline pulping methods that involve "digesting" the wood chips with sodium hydroxide and other chemicals under added heat and pressure. These methods are old: the Arabs in 750 AD pulped linen rags by boiling in an alkaline solution made by soaking wood ash in water. The process reappeared in Europe in the nineteenth century, first with straw, then with wood, where the source of the base was sodium hydroxide.

In cold-soda pulping wood chips are steeped for about two hours in a 2 to 4% solution of caustic soda in water at room temperature, then fiberized in a disk refiner. The wood swells rapidly in the solution, and the high-lignin outer layers of the cells are thrown off in the refiner. The liquor is fortified with more sodium hydroxide and used over and over. The "yield" is around 90%, which means that 10% of the mass of the wood chips is lost in the pulping process (Macdonald and Franklin 1969).

People have been soaking straw in caustic soda since the 1920's to make it more digestible for cows and sheep. As with wood, the cells swell so much that the stiff outer lignin sheath is cast off, making the cellulose more accessible to enzymes and microorganisms. One article mentions that the straw can be made into blocks without binder because "NaOH acts as a binding agent in the presence of lignin" (Soltes 1983).

Simple caustic soda treatments are also used in India to process various plant fibers into pulp. In an even simpler procedure, Indian researchers made insulation board just by "cooking wheat straw in water for 15 minutes and using 1% wax emulsion as sizing agent" (Singh 1993).

Straw can be pulped with less grinding action, at lower temperatures, and with less alkali than wood, because it occurs naturally in small diameter stalks which contain 11-15% lignin, where wood has 20-25%. The lignin is a crosslinked polymer which gives wood much of its strength and stiffness. This means that the high energy and chemical requirements of the above methods would be reduced. Either mechanical or chemical pulping could be a possibility for our project, within the constraints of energy, water, and chemical consumption. We chose to focus on the simplest room temperature processes; grinding and alkali digesting. There is no need to remove the lignin for insulation board, so mechanical means may be preferable to chemical, however the ambient temperature alkali process might be very cheap, especially if the source of alkali could be lime or wood ash.

The Chinese, whose paper is made primarily from straw, are in all likelihood making straw insulation board currently. They probably use mechanical pulping, which is favored in third world countries where chemicals are hard to obtain. Hammer milling is one of the simplest of mechanical methods, and would give a crude pulp, with rough bundles of fibers, not as fine and homogeneous as the disk refined pulp. Boards made this way would have reduced but perhaps still acceptable strength (Schaller 1996). Although we worked with a hammer mill in our survey of possible fabrication techniques, we did not try to make a true wet process pulped board of any kind, because of the high water requirement. This would nevertheless be a fruitful path for future work.

Pulped wheat straw board

As mentioned above in section B in regard to the Maizewood plant, straw, corn stalks, and flax shives can all be pulped and made into insulation board. Sugar cane bagasse is also used by Celotex in its Louisiana plant. Small adjustments are made to the wood pulping process to account for differences in the form and quantities of cellulose, hemicellulose, and lignin.

Wheat straw was substituted for wood at several insulation board plants during World War II due to shortages. A major federally funded study of pulped wheat straw insulation board was conducted in the late 1940's to support this activity. They evaluated the overall merit of wheat straw for this use by looking at the effect of fiber length and type on the density and strength (tensile, flexural, impact) of the boards, and comparing with the wood product.

The investigators used a standard or non-hydrated pulp made by mechanical means, mixed with lesser amounts of hydrated chemical pulp, which apparently serves as a binder. For the mechanical pulp, the straw passed through a chopper with knives and hammer-mill, which produced .5 to 1.5" pieces. These were cooked in water at moderate temperature and pressure for about an hour and passed through a disk refiner. This pulp was separated by fiber length using screens with round holes (less than 1/8", more than 3/4", 1/2 to 3/4", etc.). The hydrated pulp was made by cooking uncut straw with lime and sodium hydroxide for five hours at 290°F and 40 psi, then beating and washing.

They then mixed three components in varying proportions; 1) short filler fibers (less than 1/8"), 2) long fibers (1/8 to 3/4+"), and 3) hydrated fibers. Small lab-scale boards were pressed, oven-dried, and tested. Lathrop and Naffziger report, "it is possible by suitable pulping and refining of straws and stalks to produce long, springy, resilient fibers which cannot be produced in any manner from wood." They made boards in the 9-22 pcf range, and, for example, one of the better points for a low density board was 15% hydrated pulp, 15% short fiber filler, and 70% long fibers.

The main trend of their results is to show that, at a given density, strength increases as the fraction of long fibers increases, and as the fraction of hydrated pulp increases. This is especially true for impact strength. Impact strength indicates how well the boards will hold up in normal handling; for example the "dog-earing" of corners is a sign of low impact strength. At the same time the longer fibers make fabrication of lower density boards possible, and they conclude that straw could make stronger, lower density boards than wood.

The mechanism has to do with the reinforcing effect of long fibers, combined with the fine chemically broken down fibers, analogous to glass fibers used in plastic sheets. The authors write, "long fiber bundles may be considered as beams or girders. Some material is required to spot

weld or tie these structural members together in the board so that the maximum amount of small air spaces within the board will be produced. Hydrated pulp serves in this capacity." Although they prepared two separate pulps, they note that a certain amount of hydrated pulp is naturally present in pulps made by grinding into small bits, such as groundwood. And in boards with a certain percentage of used newspaper, as is common in the wood insulation board industry, the paper supplies the hydrated pulp.

Although their lightest boards were 9 pcf, they thought that boards could be made at lower densities if the fraction of filler fibers was very low, and if the remaining fibers had lengths greater than 3/4". Structural properties were, to be sure, lower at lower densities. They did not test the boards thermally (Lathrop and Naffziger 1948, 1949a and 1949b).

Although the above study used complicated methods and equipment, it is relevant to our effort in indicating operating ranges for fiber length, density, and strength, and suggesting mechanisms that could perhaps be copied with simpler processes. We tried in our lab work to use longer pieces for strength, mixed with smaller pieces to create the fine porous structure needed for insulation. We also borrowed the concept of using a stronger, more expensive pulping method on a small portion of the fibers, which were then to serve as a cement for the less treated particles.

A great variety materials besides straw and wood have been made into building boards. A "Literature Review on Use of Nonwood Plant Fibers for Building Materials and Panels" published by the Forest Products Laboratory in 1994 has 1200 listings for some 50 plant materials. Thirty percent of the items pertain to bagasse and rice, and the other most represented plants are bamboo, coconut, flax, and straw. There are 120 listings for insulation board (Youngquist et al. 1994).

D. Innovations in Insulation Board

A new insulation product developed in Germany is a resilient block made from recycled newspaper. Made in one to four inch thicknesses, it is halfway between a board and a batt, and could be used either way. The manufacturer of "Homatherm" claims the 6.2 pcf board has a thermal resistance of R3.6 per inch. In addition to the borates normally used in cellulose for fire-retardance, the product contains fine jute fibers, as well as Tall oil, lignin sulfonate, and aluminum sulfate (Homann Dammstoffwerk 1996). The latter three are by-products of sulfate or sulfite paper pulping. Tall oil consists of fatty acids from resinous softwoods, that can be skimmed off the "black liquor" remaining after the wood is cooked. It is sometimes used as an adhesive in fiberboards. The ligneous portion of spent sulfite liquor has limited uses in leather tanning, dyes, inks, and adhesives (Panshin 1962).

We do not know the cost of this product, but it has excellent properties and represents an environmentally sound option for any region with pulp mills and waste paper. Northern Pakistan has neither. We used jute reinforcement for our experiments. We might also consider adding a small amount of waste paper to the straw boards as a filler and binder.

Researchers at Lund University in Sweden have studied what they call "wood wool slabs," which are wood shavings formed into concrete boards. This product has been around for decades and is made by a company in Georgia as cement excelsior board. In the US it is used for its fire-proofing and acoustic qualities. In developing countries these boards may be the basis for low-

cost shelter as they are strong enough to make exterior walls and roofs, and still have thermal value.

The Swedes developed a version of this board made from straw. It uses two to four times as much cement as straw by weight, and so is costly and heavy. It can be made at densities as low as 14 pcf, where it has R2.1 per inch, although it is usually made at much higher densities. They have worked out plans for a village scale shop requiring only a cement mixer, barrels, concrete tubs, wooden molds, and a manual press. They found it best to soak the straw in salt water for two days prior to use. The calcium chloride is an accelerator for the cement, reducing curing time of the slabs, but they also note that the straw has a very thin cutaneous layer of wax, which tends to prevent adhesion of the cement, and the soaking somehow enhances adhesion. They estimate a 1993 materials cost of 26¢/ft^2 of 4" thick slab, or about 3.3¢/R-ft^2, assuming the straw is free (Hermannson 1993).

Cement is too dense and expensive for our purposes, so we have not considered this approach, which only makes sense for a combined structural/thermal panel. We would like to determine, however, if the saline soak erodes the straw coating with beneficial effects.

A researcher in the Philippines, using materials available in large quantity there, made insulation boards from milled bark, powdered volcanic ash, and PVA. The PVA was foamed to improve distribution and create a cellular structure. Five percent polyvinyl alcohol was added to the PVA to stabilize the foam while dry ingredients were added. The mixture was poured into an aluminum mold and dried in an oven. The oven is necessary to dry the PVA before the foam collapses. Because the bulk density (density of the settled material, including the air spaces) of the bark was high, at 30 pcf, and the ash even higher at 80 pcf, the boards had high densities even with the foaming, around 28-38 pcf. At these densities, and with glue to solid ratios of .5/1 or .4/1, this product is not economical for our purposes. The boards had good modulus of rupture (200-300 psi) and internal bond strength (100 psi). Modulus of rupture is the maximum strength of boards in bending, and is described in chapter II, section 4. Internal bond strength is a measure of tensile capacity. The ratio of 5 to 1 bark to ash was found to be best, where the small amount of ash had a beneficial effect on the foaming (no reason given). The boards were not pressed in any way, as the pressing breaks the foam structure (Mari 1991).

Although we do not wish to emulate this product, we did try mixing wood ash in with the straw. Wood ash is much less dense than volcanic ash and has a high thermal resistance (R4.5 per inch). Our hope was that the small particles would fill the pores in the straw board, enhancing insulative value. We also foamed the PVA that we used, although we did not dry the boards in an oven.

E. Adhesives

General

As a considerable part of our effort was devoted to making boards from straw held together by some kind of glue, we needed to identify those adhesives suitable for our purpose, and understand their limitations and mode of action.

Generally speaking good adhesives are made from highly polar molecules that have good adhesion, or grip from the adhesive to the adherend. They also need good cohesion, which is the bond of the adhesive molecules among themselves, and for this long chain, high molecular weight

substances work best, such as cross-linked polymers. Proteins, starches and celluloses are naturally occurring examples, and vinyl polymers, polyesters, epoxies, polyurethanes, and formaldehydes are synthetic examples.

Adhesives may also be categorized as either thermoplastic or thermosetting. The thermoplastic bond, once it is cured, may be softened and broken by heat, and perhaps by a solvent, either water or other. These include the natural glues, and some of the synthetic, or partly synthetic ones, such as the cellulosics, vinyls, and acrylics. The thermosets cure with an irreversible polymerization reaction, effected most often by heat, but also by catalysts at room temperature. These glues have much greater resistance to heat and water than the thermoplastics. An additional category is the elastomerics, or "elastic polymers." These generally refer to some kind of rubber, and include adhesives made from natural or reclaimed rubber, butadiene, neoprene, silicone, and the like.

For an insulation board installed on the interior of buildings, that is not exposed to ambient weather or extremes of temperature, thermoplastic resins would be adequate, although thermosets would give greater overall strength and durability. Thermoplastics tend to have lower cost, and greater ease of use, and were therefore our initial choice for lab work. Later we tried a thermoset.

The adhesive must wet the surface to form a good bond. The viscosity of the adhesive should be low to wet the surfaces well and penetrate the pores, but high to resist shear forces. As the high molecular weight substances often have high viscosity, it is frequently necessary to dissolve or emulsify them to obtain good wetting properties. Likewise, a high surface tension inhibits wetting; hence the general use of wetting agents or surfactants in the raw adhesive, as well as solvents and emulsifiers. Sometimes with wood or other porous surfaces, the glue may flow into the pores so much that the joint becomes "starved," so in these cases viscosity and surface tension must not be lowered too much. The goal is partial but not excessive penetration of the adhesive into the adherend.

When the contact angle between the adhesive droplets and the substrate is greater than 60°, there will be little penetration by capillarity. In these cases pressure or clamping is required; this is why glued wood joints must be clamped. The viscosity and surface tension of the wood glue have been intentionally kept high enough to prevent the joint from starving.

Generally adhesion is better with rough, clean, dry surfaces. Any dust or grease or water should be removed. The viscosity of the glue determines the method of application, whether it is by spraying, brushing, or spreading with a knife (Parker and Taylor 1966, Skeist 1962).

These considerations are important for the highly porous straw we worked with. The glue that we apply must have its viscosity and surface tension reduced enough to allow it to spread over the straw surfaces and enter the rough pores, but it must not permeate the straw so thoroughly that nothing is left on the surface to make a bond. To solve this problem, it is easiest to formulate a fairly stiff glue mix, then apply pressure to the boards during setting; however this runs counter to our goal of low density. This was perhaps our greatest obstacle in the first phase of the work. We also need to determine the effect on adhesion of the wax coating on the outer surfaces of the stalks.

Protein Glues

Although largely replaced by synthetic adhesives, which tend to have better performance characteristics, there are still sizable natural glue industries. These glues are used in large quantities in textiles, paper and cardboard, furniture making and other wood products, leather goods, etc. These glues represent a potentially low-cost source of adhesive.

One major category of natural glues is based on protein. Examples include the collagen in the connective tissue, bones and hides of animals, and albumen from blood. Factories for these glues are usually located near slaughterhouses. Another protein glue is casein from milk; this is only feasible in regions with a large dairy resource. Ordinary white glue for household use in this country was originally casein based, before being replaced by PVA, which explains the cow logo on Elmer's and Borden's glue bottles. Another large source is soy protein from soybeans.

Protein glues are typically available in cakes or gels, or as powders, which can be mixed with water. They have good initial tack, and set by loss of water. They form strong bonds, but may be susceptible to water exposure, bio-deterioration, and heat. Animal glues have been used in surprisingly demanding applications. For example airplane plywood in World War I was made with specially treated blood glue, which was the most water resistant adhesive at the time. It was later replaced by phenol-formaldehyde (Skeist 1962, Shields 1970).

Animal or soy glues would be fine for insulation board, although we do not know of the availability of any in our focus region.

Starches

The other major class of natural adhesive is starch-based. The large starch molecules are polymers which can act to hold things together in the same manner as the protein molecules. In this country wheat, corn and potatoes generally provide the raw material. The natural starch is modified by enzymes, acid, heat, or oxidizing agents, to reduce the viscosity of the aqueous solution, shorten drying time, and increase tack and solids content. Starch adhesive comes as a powder which is mixed with water, and sets by loss of the water. It is used to hold textile fibers together, size paper, bind books, hang wallpaper, and make boxes, cartons, tapes, etc. These glues have poor resistance to moisture and bio-attack; however they are among the least expensive (Skeist 1962, Shields 1970).

Starch is used in many wood fiber products, for example it is added to paper pulp to reduce "beating" time. The added binder means that less effort need be expended in releasing the natural wood fiber bonding properties. Similarly, starch is added to pulped wood insulation board to increase stiffness. In both these cases the amount of starch added may be one or two percent by weight of the final dry product: it is thought that any larger amount of starch will carry too great a risk of biological problems (Suchsland and Woodson 1987). Starch is not therefore a good candidate for the primary binder in insulation board.

Inorganic Adhesives

People have used inorganic adhesives and cements for centuries: they include common materials such as Portland cement and gypsum plaster. More relevant to the current topic are air-dried inorganic adhesives, which set by the loss of water, rather than by the reaction of two com-

ponents. They tend to have low cost, and excellent fire and biological resistance. Sodium silicate is perhaps the simplest and most common of this class. It is also known as water glass, as it has a similar structure, and bonds fiercely to glass. It is widely used for gluing paper products, such as layers of corrugated cardboard, the flaps of envelopes, paper towel rolls, etc. These products set quickly as the water is absorbed into the paper.

It is usually supplied as a viscous water solution, and has relatively little tack, so it is best to apply pressure until it is sufficiently dry. The glued material is often heated to hasten the drying. Made by melting purified sand with soda ash or sodium sulfate, then dissolving in water, sodium silicate is one of the cheapest binders available. We were quoted a price of 40¢ per pound (drum quantity) by a local adhesive supplier, who suggested it might be available for 20¢ per pound in large quantities such as a tote or truckload.

Sodium silicate is often mixed with other materials to obtain desired properties. For example wetting agents may be added to increase the rate at which paper is wetted, or clay as a filler that increases viscosity and so reduces unwanted penetration into the substrate. It can be mixed with other glues. For example mixing sodium silicate with animal glues gives a mixture with higher initial tack and greater plasticity than sodium silicate alone, and better biocidal properties than the animal glue alone. Borax has been added to sodium silicate to increase viscosity at a given drying temperature, and thus speed production lines.

Numerous insulation materials have been made with sodium silicate as the adhesive, more in decades past than at present. These include high temperature pipe and boiler coverings made of asbestos, mica, vermiculite, and kieselguhr (diatomaceous earth). Also paper, cotton, and wool felt have been sprayed with sodium silicate against a solid backing material as insulation or padding (Skeist 1962, Shields 1970).

The facts that it is inexpensive, and unlikely to burn or be consumed by mold or fungus, make sodium silicate an excellent option for this project. The drawback is that it does not have great gripping power, so that larger quantities, and/or pressure during setting are required.

Ashpalt, Wax, Rosin

Asphalt, wax and rosin natural materials widely used in paper and wood board products to enhance moisture resistance. These substances also have a modest adhesive effect, and could be an important part of a combination of binders and waterproofers in a straw board. Sizing controls the penetration of ink on paper, and thus is essential for writing qualities. In fiberboard it controls water penetration, which is important for boards that may be exposed to bulk water or water vapor. The size coats the fiber surface and lowers its surface energy. Wetting is determined by the relationship between the surface energy of the liquid and the solid: in this case the solid surface energy is reduced enough to make it hard for water to wet the fibers. In a wet process this is accomplished by adding alum to the stock, lowering the pH, and making the size precipitate on the fibers. In a dry process the size can be sprayed into the blender (Suchsland and Woodson 1987).

Asphalt is essentially bitumen, which occurs naturally, and can be refined from petroleum. The asphalt used for sizing fiberboard has lower oil and higher resin content than the asphalt used on roads. It can be ground to a fine powder and mixed in dry, or emulsified and added to a wet furnish. The emulsions are unstable. In either case, the board must be heated up enough to make the asphalt "flow but not blow." The asphalt must be heated to its melting point so that it flows onto the fibers, but must not be heated so much that it ignites. The asphalt is liquefied in boards

that go through a dryer to evaporate water, or a hot press to cure resin, so no additional heat is required. If we intended to air dry boards, however, there would be an additional "energy penalty" to melt the asphalt (Wagner 1996).

Asphalt has been used in cardboard, and in all kinds of wood fiberboard, sheathing and siding products, and provides excellent weather and water uptake resistance. It is the primary size in fiberboard siding which serves as the exterior weather skin (Perot 1953).

Wax is added to wood insulation boards and to structural boards such as OSB. It can be sprayed into the blender in a dry process, or mixed into the hot stock as an emulsion in the wet process. Although the amount is small, less than 2%, the cost is not negligible: in the case of OSB for example, the cost may be one third that of the resin. Natural wax comes from bee hives, Carnauba palm trees, and sheep wool (lanolin); however 90% of the wax in use today is derived from petroleum. Most crayons and candles, for example, are made from petroleum wax (Encyclopedia of Science and Technology 1989).

Rosin is derived from the gum or wood of pine trees, or from the paper pulping by-product Tall oil. It is used in the same way as wax (Skeist 1962).

We have not addressed the issue of water resistance in the initial straw board development. This problem is less pressing for boards intended for use in a dry area such as Pakistan, but should be studied for other regions.

Synthetic Adhesives

Of the multitude of synthetic adhesives a few are widely used in the structural building board industry, namely urea and phenol formaldehyde, and isocyanate. Others such as acrylic latex and polyvinyl acetate (PVA) are used for spray insulation. Many of the others are unsuitable or too expensive for building product applications.

The thermoplastic resin PVA is now the primary glue for household and wood bonding use, and is massively produced in many locations. It has high initial tack and sets rapidly by loss of water. It has fair resistance to moisture and solvents compared to natural glues, but much less than its thermosetting cousins. Although PVA is subject to creep under sustained loads, and will soften when exposed to heat, it is extremely non-toxic and easy to work with, cleans up with water, and does not require heat to cure (although heat may improve the result in some situations). It is not suitable for exterior or other demanding uses, and cannot compare with the older heat-cured resins on a cost per performance basis.

The raw materials are calcium carbide, made from limestone and coal, and butane from natural gas or oil. It is generally sold as an emulsion in water or as a redispersible powder. The powder is often part of a dry mix in building products such as joint compounds, mortars, caulks and mastics. It also has wide use in paints, coatings, textile finishes, printing ink and chewing gum. PVA is used for spraying insulations such as cellulose in wood frame wall cavities. The emulsion, which normally contains 55% solids, is diluted with water and sprayed together with the dry fiber.

United States cost is about 60¢ per pound wholesale in barrel quantities. For our project PVA is a medium cost, medium performance option, which we used extensively in our trials. Its main advantages are great availability and ease of use. The key issues are the same ones we face with sodium silicate: how to spread the glue over the large area of straw particles without starving the surfaces, and achieve bonding without high pressure.

The standby thermosetting resins of the wood board industry are phenol and urea formaldehyde (UF and PF), and now methane diisocyanate (MDI). Phenol formaldehyde was one of the first synthetic resins to be manufactured, in the first decade of this century, and it has had the greatest volume of production. It has low cost, high strength, dimensional stability, and great durability. A PF glue line is not only waterproof but boilproof. One of its drawbacks is a long cure time, so that, for example in a strand board plant, the boards must stay in the hot press many minutes, and this limits the overall rate of production. UF is similar to PF, but costs less and performs less. It is considered to have a moderate moisture resistance. Where PF plywood or oriented strand board (OSB) is rated for exterior use, UF particle board or fiberboard are only for interior applications.

An additional concern that has surfaced in recent years is volatile organic emissions. Apparently the urea based resin outgases more than phenol resin, so that UF board products are often prohibited in energy efficient houses with low air leakage. This prohibition includes not only the exterior sheathing, but also the boards in cabinets, furniture, and any interior woodwork. PF boards are allowed in such houses.

These resins are used both in fiberboards, such as hardboard and MDF, and in plywood, strandboard, particleboard, etc. In one method of PF application, the resin is sprayed, in solution, into a blender with wood chips. This may be a colloidal water solution, with sodium hydroxide added to make it basic, and it can be cured at temperatures around 250 to 300°F. The resin must be maintained at this temperature for a specified time to complete the cure. With boards, the hot press time depends on the thickness of the board, as the center plane is slower to heat up. Press times are on the order of two to ten minutes. In another method, dry particles of the resin are mixed with the wood particles, sintered (heated to near the melting point), pressed and cured. This latter process requires less energy as there is no water to be evaporated. Phenolic resin is also used as a binder for fiberglass insulation batts: resin in solution is sprayed onto the glass mats, after which they pass through a heater for the cure.

UF on the other hand can cure at lower temperatures, or at room temperature with a catalyst. It is also used both as a liquid solution, and as a powder. Convenient powder mixes are available that contain the UF resin, the catalyst, and fillers, and need only be mixed with water and cured at room temperature.

The MDI which we used for our straw boards is a competitor of UF and PF in the structural wood board industries. It is a petrochemical derived from benzene with several intermediate steps. At about $1 per pound, it costs about twice as much, but only half as much is required, and is reported to give superior properties. Where UF and PF are used in OSB at rates of about 4 to 8% by weight, MDI can be used at rates as low as 1 or 2%. The lack of a method for achieving a uniform distribution of resin at this tiny loading rate, in mass production, barred MDI from the industry until the spinning disk blender was developed. In these blenders the resin in liquid form is fed onto the outer surface of the rapidly rotating steel disk, which is conical in section. The resin flows down the disk and is thrown off as a fine mist. Problems with clogged spray nozzles are avoided. Conventional spray equipment is adequate for small scale work however.

The mechanisms that permit successful boards to be made from such marginal amounts of binder are not fully understood. MDI wets wood surfaces extremely well, forming, it is thought, a mono-molecular layer. It has a mixture of molecular weights, so that the smaller particles may be moving into the pores and acting as anchors while the larger ones remain on the surface forming

bonds and spot welds. It penetrates more deeply than UF and PF and may give greater moisture resistance for that reason.

MDI is usually cured by heat at about 375°F, and requires less time at that temperature than PF. Press times for strandboard may be less that two minutes. The MDI is, however, very reactive with water, and will cure at room temperature over a time period of days. The manufacturer ICI has a catalyzed version of MDI that cures at room temperature in twenty minutes. This version may not deliver the same performance as the heat cured resin, and it costs about 50% more.

All three of the above thermosetting resins pose health hazards. Inhalation of MDI mist, for example, may cause irritation of the respiratory tract and cold-like symptoms, although it is not thought to be a neurotoxin or carcinogen. Sensitization resulting from exposure may last years. PF and UF are also hazardous. Any small board making operation would have to provide for safety of the workers (Skeist 1962, Shields 1970, Encyclopedia, Newman 1996).

These resins are natural candidates for insulation sheets as they have been used for wood boards for decades. In addition to the cohesive structure, they provide moisture and rot protection, and better overall durability than the previously discussed adhesives. The tradeoff is that a higher level of technology is needed, and risks to personnel are much greater. They are expensive on weight basis, but may be cheap on a performance basis. If heat is required for the cure, that adds to cost considerably.

Although the UF ambient temperature catalyzed system would be a good low cost option for small scale rural production, the indoor air quality concerns make it unacceptable. The catalyzed MDI system, however, is a natural choice. For the heat cured PF and MDI resins, an estimate of the energy requirement is needed to determine feasibility. We used heat cured MDI for initial experimentation. PF would probably also work well.

F. Fibrous Insulation Heat Transfer

For porous media such as insulations the concept of apparent thermal conductivity is used to measure performance. Although heat transfer takes place within the material by conduction and radiation, and in some cases convection, the medium is modeled as a continuous solid with heat flow obeying Fourier's law for thermal conduction. This overall heat flux is measured with a device such as our conductivity tester described below. This is fine for calculating the effect of the material as a component of larger systems, for example when it is installed in the wall of a building. To make the insulation, however-- to decide what material to use, how dense, how fine the pores, how to orient the fibers, what surface properties the fibers should have, etc.-- we need to go inside the insulation and model the various components of heat transfer.

Generally the different heat transfer mechanisms can be thought of as operating in parallel, so that

$$k_{app} = k_s + k_g + k_r + k_{conv} \qquad (1)$$

where k_{app} = apparent thermal conductivity of the insulation,
k_s = contribution of conduction through the solid portion to k_{app},
k_g = contribution of conduction through the gas in the pores,
k_{conv} = contribution of convection.

Note that k_s is not the conductivity of the solid material (such as the glass in fiberglass insulation), but the fraction of overall conductivity that can be attributed to conduction through the solid. This is of course a function of the solid material conductivity, but it also depends on the geometry and void fraction of the porous medium. Likewise k_g is not the conductivity of the air itself. The components k_g and k_{conv} may be combined into one term.

The void fraction is the volume portion of the material occupied by gas. For our boards the gas is air, although some insulations use low conductivity, high molecular weight gases to enhance performance. Void fraction δ is found as follows (Glicksman 1994).

$$\delta = \frac{\rho_{solid} - \rho_{air} - \rho_{insul}}{\rho_{solid} - \rho_{air}} \approx \frac{\rho_{solid} - \rho_{insul}}{\rho_{solid}} = 1 - \frac{\rho_{insul}}{\rho_{solid}} \qquad (2)$$

Here ρ_{air} is the density of air, ρ_{insul} is the bulk density of the insulation, and ρ_{solid} is the density of the solid materials in their nonporous state. In the case of our straw boards this is the density of the straw and adhesive. This latter quantity is unknown, and difficult to ascertain, because even a "solid" piece of straw stalk has large pores and may contain air. The only reliable way to determine the solid straw density may be with a pycnometer. This vessel of known volume, equipped with temperature and pressure measuring devices, can be used to determine the volumetric gas fraction of a porous medium, employing the ideal gas law.

Until such a measurement has been made, we can estimate the density of the straw base material by referring to its lignocellulosic cousin wood. There is considerable variation among woods, however; softwoods are generally in the 30 pcf range, while hardwoods are closer to 50 pcf. In addition, wood is itself a cellular material, and the cells may contain air. The density of the cell walls has been calculated as about 90 pcf (Gibson 1988). The best we can do at present then is to take solid straw density as somewhere between 30 and 90 pcf.

For the boards made with MDI described in chapter III, with the straw density at these two extremes, and neglecting the few percent of resin, the void fractions for various densities are as follows.

insulation density, pcf	6	8	10	12	15
void fraction ρ_{straw}=30 pcf	.8	.73	.67	.6	.5
void fraction ρ_{straw}=90 pcf	.93	.91	.89	.87	.83

For comparison, in fiberglass batts δ is usually 99%, in polyurethane foam 97%, and in cellulose insulation 94%.

Convection should not be present in an insulating material. One of the purposes of the cellular structure is to trap the gas in small pockets in which convection cannot take place. Natural convection is governed by the Rayleigh number (Ra), and although there is some fluid motion when Ra is greater than zero, there is no significant convective transfer until Ra equals 1000 (Mills 1995). The standard Rayleigh number is defined as follows, where the characteristic dimension and the temperature difference apply to one pore of the material.

$$Ra = \frac{g\beta\,\Delta T_{pore} L_{pore}^{3}}{\upsilon^2}\mathrm{Pr} \qquad (3)$$

where g = gravitational constant, 9.8 m/s^2,

β = volumetric coefficient of thermal expansion, K^1,

ΔT_{pore} = temperature difference across the pore, °C,

L_{pore} = average dimension of the pore, m,

ν = kinematic viscosity, m^2/s,

Pr = Prandtl number for the gas in the pore.

For a 25 mm (one inch) thick insulation board with a temperature difference of 28°C across it (50°F), Ra will not reach 1000 until pore size is 10 mm (.4"). At average pore sizes of 3 and 6 mm (1/8" and 1/4"), Ra is 10 and 140 respectively. All the straw boards we made had average pore sizes less than .25", by inspection, and generally quite a bit less, so that even though there is considerable nonuniformity, there should be no appreciable convection in these boards.

As for conductive heat transfer, a model developed by a researcher working with mineral fiber insulation gives two limiting cases for conduction through the solid and the gas, k_{cond} (Pelanne 1977). In one case the gas and solid are thought of as in parallel, and

$$k_{cond} = k_{air}\,\delta + k_{straw}(1-\delta)\,. \qquad (4)$$

Here k_{air} is the conductivity of air, and k_{straw} is the conductivity of the solid straw. In the second case the solid and the gas are in series and

$$k_{cond} = \left(\frac{\delta}{k_{air}} + \frac{1-\delta}{k_{straw}}\right)^{-1} \qquad (5)$$

The researcher cited above states that "lightweight fibrous and particulate insulations more nearly approximate the case of series conductivity." In the case of fiberglass, where δ is very high, and the conductivity of the glass is thirty times greater than that of the air, the solid term in the above equation can be neglected

A more extensive model has been established for polyurethane foams. These foams have a regular closed cell structure with thin cell walls and concentrations of polymer in the struts, or intersections of the walls. The model gives solid conduction in terms of the polymer conductivity, the void fraction, and the portion of material in the struts as opposed to the cell walls (Glicksman 1994). The part of this model that describes the cell walls may not apply to fibrous insulations with their irregular, open cell structure; however the struts considered alone may behave similarly to loose fibers or particles. The model provides a conduction term for isotropic struts as follows;

$$k_{cond} = k_{air}\cdot\delta + \tfrac{1}{3}\,k_{straw}(1-\delta) \qquad (6)$$

where the factor of 1/3 arises from the fact that in a regular array of cubical cells 1/3 of the struts are oriented parallel to the direction of heat flow, while the remaining struts are perpendicular, and so do not contribute to conduction through the medium.

In the case of straw boards, the solid conduction term can not be neglected, as the solid makes up a comparatively large share of the volume.

The remaining important term is radiation. In fiberglass, radiation is only important at densities below 2 pcf. If the particles in insulation are opaque and black to infrared radiation, then k_r can be found from a linearized form of the equation for radiative transfer between black bodies:

$$k_r = 4\sigma T_m^3 d \qquad (7)$$

where Tm = mean absolute temperature, °K,

d = distance between black surfaces, here average pore size, m,

σ = Stefan-Boltzmann constant.

Our conductivity tests were done at a mean temperature of about 90°F. In this approximation, then, k_r would be .04 Btu-in/hr-ft^2-°F for an average spacing between particles that "see" each other of 1 mm, and .08 Btu-in/hr-ft^2-°F for an average spacing of 2 mm. For our 10 pcf boards which had overall insulative values of R3.5 per inch, or k_{app} of .286 Btu-in/hr-ft^2-°F, radiation could be 14-28% of the total heat transfer.

To make an accurate determination of the average spacing between particles, it would be necessary to model the morphology of the straw boards. Typical straw pieces appear to be flat and rectangular. They are generally aligned parallel to the surface of the board by the pressing, but have no preferred direction in those planes. This is shown in photos 9 and 10, and a crude model is depicted in figure 1.

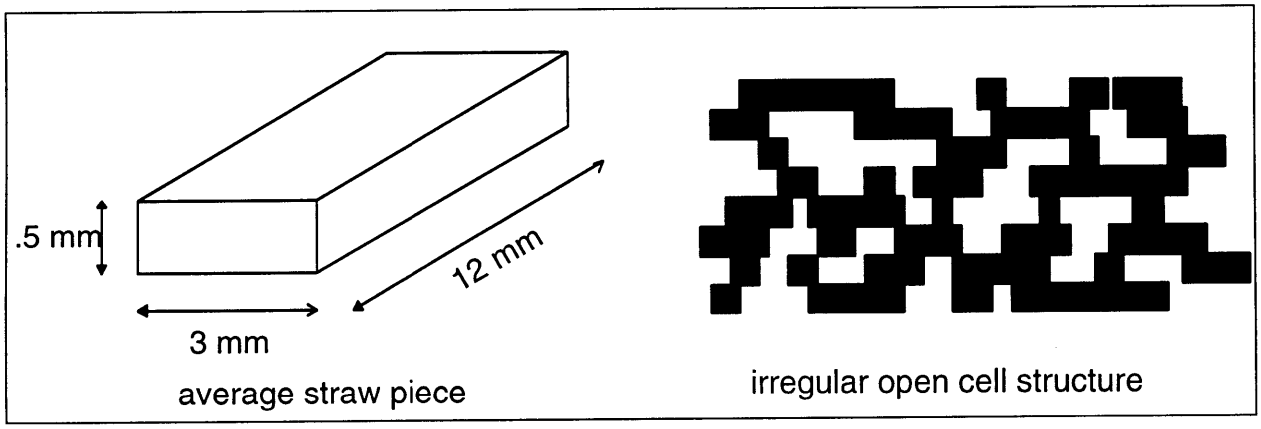

Figure 1. Model of Straw Board Structure

If the particles are not opaque and black, then the radiative transfer is given by the Rosseland equation for optically thick porous media, which requires a knowledge of the extinction coefficient (Modest 1993). Although this can be found by measuring the light transmitted by a laser through insulation wafers of various thickness, or estimated from the geometry of the medium, if known, it is beyond the scope of the current effort.

Simple models for heat transfer in the boards then could come from either equation (5) or (6) above, with the addition of the radiation conductivity.

$$k_{app} = \left(\frac{\delta}{k_{air}} + \frac{1-\delta}{k_{straw}} \right)^{-1} + k_r \qquad (8)$$

$$k_{app} = k_{air} \cdot \delta + \tfrac{1}{3} k_{straw}(1-\delta) + k_r \qquad (9)$$

Either of these may provide a rough idea of behavior, where we have to approximate the unknown quantities. The thermal conductivity of softwood is 1.7 Btu-in/hr-ft^2-°F parallel to the grain, and .7 Btu-in/hr-ft^2-°F perpendicular to the grain. We could then estimate k_{straw} as 1 in the same units for the case where ρ_{straw} is that of softwood, and the void fraction is .67 for the 10 pcf MDI straw boards, as shown above. We might then take the radiation component as .04 Btu-in/hr-ft^2-°F, for this case of low void fraction, and a relatively short 1 mm radiative spacing. An alternative scenario is that ρ_{straw} is much higher, closer to 90 pcf, δ is .89, and k_{straw} is somewhat higher than 1 Btu-in/hr-ft^2-°F. We could estimate k_{straw} as 2 Btu-in/hr-ft^2-°F in this case. The radiation component would then also be higher, perhaps .08 Btu-in/hr-ft^2-°F, for this case of greater void fraction.

The two possible models would then give thefollowing numbers for these two scenarios.

	δ=.67, k_{straw}=1, k_r=.04	**δ=.9, k_{straw}=2, k_r=.08**
	k_{app} in Btu-in/hr-ft^2-°F (R per inch)	
equation (8)	.293 (3.4)	.283 (3.5)
equation (9)	.248 (4.0)	.312 (3.2)

Equation (8) seems to model the material well, as our measured apparent thermal conductivity for the 10 pcf boards was R3.45 per inch. This is, however, highly speculative until we have a better idea of the actual values of δ, ρ_{straw}, k_{straw}, and k_r. The solid conductivity can be measured with the transient hot wire method, while the straw is compressed in a small cylinder by a loading machine.

The most important considerations for the early stages of straw board work are that pore size must be less than .4", and that solid conduction should be minimized as much as possible by increasing the void fraction, which means reducing overall density.

II. Apparatus and Test Methods

A. Thermal test apparatus

We used a simple steady state thermal conductivity tester made by Greg Sullivan, an MIT Building Technology Masters student working on the project in 1995. See figure 2. It consists of a metal screen heated by an electric current, sandwiched by insulation board samples. The sample boards must be 15" X 25" (38 cm X 64 cm), and may be as thick as 1.5" (38 mm). Thermocouples made by welding the leads of chromega-constantan thermocouple wire are placed on the heated screen, and on the outer side of each insulation sample, along the bisecting lines. The screen is made of Nichrome wire. Solid aluminum plates, one quarter inch thick (6 mm), are located on the outer side of each sample board, to provide a nearly isothermal surface. One of the insulation samples is a reference material of known conductivity (Sullivan 1995, McElroy 1985).

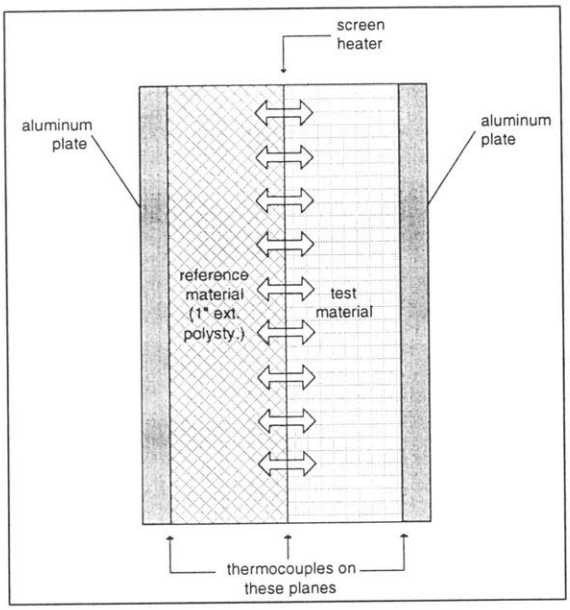

Figure 2. Conductivity Tester

The heat dissipated in the screen was originally found from voltage and current measurements. The portion of that heat flowing through the reference material can be calculated knowing the thermal resistance and the temperature difference across it. Then, knowing the heat flow through the test material and the temperature drop across it, its thermal resistance and conductivity are found. The equations for this are:

$$Q_{total} = Q_{ref} + Q_{test} = IV$$

$$Q_{ref} = \frac{A\Delta T_{ref}}{R_{ref}}$$

$$Q_{test} = \frac{A\Delta T_{test}}{R_{test}} \qquad (10,11,12,13)$$

$$k_{test} = \frac{R_{test}}{L}$$

where Q_{total} = total heat dissipated in the designated area of the screen, Watts

I = current in the circuit, Amps

V = voltage drop across the portion of the screen used for measurement, Volts

A = area of heated screen between the voltage taps, square feet

ΔT = temperature difference across the boards, °F

R = thermal resistance of the boards, $(Btu/hr\text{-}ft^2\text{-}°F)^{-1}$

k = thermal conductivity, $Btu\text{-}in/hr\text{-}ft^2\text{-}°F$

L = thickness of test sample, inches

and the subscripts ref and test refer to the reference and test insulation boards, respectively.

Combining these equations,

$$k_{test} = k = \frac{\left(\frac{IV/.2931}{A} - \frac{\Delta T_{ref}}{R_{ref}} \right) L}{\Delta T_{test}} \qquad (14)$$

where the factor .2931 has been added to convert Watts to Btu/hr.

Uncertainty Calculation

This device is not intended for precise measurement. The precision depends on the accuracy of measuring the variables in the above equation, and on the extent to which certain assumptions are true. The most important of these assumptions are 1) one dimensional heat flow, and 2) negligible contact resistance between the sample boards and the screen and the aluminum plates. No effort is made here to guard the screen heater to prevent lateral heat flow. It is assumed that packing fiberglass insulation around the perimeter of the samples will minimize such flow, so that heat flux will be substantially one-dimensional. We used about one inch of fiberglass (R3) around the edge (Sullivan 1995).

We assigned an uncertainty to all of the above variables, and made an estimate of the overall uncertainty in k, using the standard formula from, for example, Kline and McClintock (Kline and McClintock 1953):

$$\Delta k = \sqrt{\left(\Delta I \frac{\partial k}{\partial I} \right)^2 + \left(\Delta V \frac{\partial k}{\partial V} \right)^2 + \left(\Delta L \frac{\partial k}{\partial L} \right)^2 + \ldots} \qquad (15)$$

The variables in an average conductivity measurement, as originally set up, and the uncertainties associated with them, are shown in the table 3.

parameter x	typical value	units	original uncertainty Δ x	dk/dx	Δx(dk/dx)
current	14.4	amps	2	0.028	0.0560
voltage	0.4	volts	0.002	1.024	0.0020
thickness	1	inches	0.1	0.218	0.0218
area	2.4	ft^2	0.01	-0.171	-0.0017
ΔTref	20	°F	1.0	-0.0096	-0.0096
ΔTtest	20	°F	1.0	-0.011	-0.0110
Rref	5.2	$(Btu/hrft^{2\circ}F)^{-1}$	0.1	0.037	0.0074

Table 3. Uncertainties in Conductivity Measurement

In this case the typical values are taken from a run with a milled straw piece made with PVA, which gave a k of .33 Btu-in/hr-ft^2-°F. These are sufficiently close to the values we will encounter with the other sample insulations to give an accurate idea of the uncertainty for all the conductivity measurements made on the straw boards.

The uncertainty estimate for each parameter was based on the apparatus or source of the reading. The uncertainty for the current is high because we were originally using an inductance type ammeter, which had a small panel meter which could not be read accurately. The voltage was read with a digital voltmeter which gave a fairly steady reading in millivolts. The length of screen between the voltage taps, and the width of the screen could be closely determined with a tape measure.

According to Sullivan, there is an error of .9°F associated with the thermocouples, and 1.8°F with the Omega transducer that displays the temperature. Our consistent experience, however, was that the thermocouples tracked each other to within a few tenths of a degree when immersed in water baths. When in ice, and boiling water baths, we obtained readings within one or two degrees F of 32°F and 212°F. We assigned an uncertainty of 1°F to each individual thermocouple reading.

The ΔT's however are derived from the difference between the averages of the 13 thermocouples on each plane.

$$\Delta T_{test} = \frac{\sum_{1}^{13} T_{scr} - \sum_{1}^{13} T_{plate}}{13} \tag{16}$$

Using the Kline-McClintock formula,

$$\Delta(\Delta T_{test}) = \sqrt{\left(\Delta T_{scr1}\frac{\partial \Delta T_{test}}{\partial T_{scr1}}\right)^2 + \left(\Delta T_{scr2}\frac{\partial \Delta T_{test}}{\partial T_{scr2}}\right)^2 + \ldots} \tag{17}$$

where T_{scr1}, T_{scr2}, etc., are the individual thermocouple readings. If these have an uncertainty of 1°F then the uncertainty in the temperature difference across the reference and test samples is .4°F, so the effect of the multiple readings is to reduce the error.

The thickness of the sample boards can easily be measured to within about .1 inch. One way to do this is to place the sample board on a flat table, press a larger, very flat wood board down on the sample, and take readings around the perimeter with a metal ruler. This would tend to give a somewhat high reading, as the flat surfaces on each side of the board sit on the "peaks," and ignore the "valleys."

The reference insulation material used by Greg Sullivan was a piece of one inch thick extruded polystyrene obtained directly from the manufacturer, who tested it and provided the value R5.2 (Btu-in/hr-ft^2-°F)$^{-1}$ ±2%. This was for ΔT of 50°F and a mean temperature of 75°. This would imply an uncertainty of±R.1.

With the original uncertainty figures shown in the above table, the cited equation gives an accuracy in the k value of ±18%. This might be adequate for the purpose of making rough com-

parisons between new boards, but we wanted also some sense of the absolute conductivity. Examining the right hand column of table 5, it is clear that the uncertainty in electric current is the largest contributor, and that the thickness variability is next in importance. We therefore exerted some effort to improve the reliability of the current and thickness numbers.

Changes to Improve Accuracy

Electric current is often measured by putting an accurately known resistance, or shunt resistor, in the circuit, and finding the voltage drop across it. In our circuit the screen has a resistance of about .025 ohms, and we wish to generate anywhere from 5 to 20 Watts, so the current must be 15 to 25 amps. Any ordinary resistor will heat up considerably with such a large current, which will alter its resistance. Also a resistance large in comparison with the screen would draw a huge amount of power. We therefore attempted to install a precisely known resistance of less than .02 Ω, which would not heat much under 15 to 25 amps.

We found the resistance of a 20 ft. long piece of solid copper wire at room temperature to be .0213 Ω ±.0003 Ω. However this wire heated somewhat under 15 amps, and we were unable to closely measure the resistance when it was hot.

These kinds of shunt resistors are generally sized so that they do not heat appreciably under the test conditions: in some cases large solid copper bars are used. In our case that would mean using a longer, thicker wire-- thicker to eliminate the heating problem (less resistance per unit length), and longer so that there would still be a resistance large enough to measure.

This shunt wire method could give fair accuracy in power measurement. We decided to use the heating screen itself, however, because it is made of Nichrome wire, which has a temperature resistance coefficient (TRC) of very nearly zero. This means its resistance will not change significantly when hot, so the power draw of the screen can be found from V^2/R, where the electrical resistance of the screen is measured at room temperature.

Nichrome is a Nickel alloy which contains about 15% Chromium and 20% Iron, and is often used for heating elements, in toasters for example. Its actual TRC is .00017 Ω/Ω°C. As the screen is at most 20-30°F above room temperature, its resistance will only change by about .3% from the ambient value.

The electric resistance measurement was made by connecting the screen in series with the three nominal 27.5 Ω calibrating resistors whose resistance had been measured with digital meters that give readings to the thousandth of an ohm (their resistances varied by up to 5% from the nominal value). The resistance of the screen was found from

$$R_{scr} = \frac{V_{scr}}{3}\left(\frac{R_a}{V_a} + \frac{R_b}{V_b} + \frac{R_c}{V_c}\right) \qquad (17)$$

where R is resistance in ohms, V is voltage in volts, and the subscript scr refers to the screen, and a, b, and c are the three calibrating resistors. Three resistors are used instead of just one to provide the added accuracy of averaging three readings. Since the currents determined by each of the three calibrating resistors generally agreed with each other to within less than one percent, we had high confidence in the ohm values of the calibrating resistors. Calibration setup is shown in figure 3.

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We took two measurements, and obtained values of R_{scr} as .02736 and .02754 Ω, respectively. We chose .0274 as the number to use in calculation, and assigned an uncertainty of .0003 Ω.

As for the thickness measurement, we arranged a dial guage over a 2" X 2" block of aluminum, such that the boards could be moved under the guage, and a local thickness found. We put a piece of 1 cm^2 sheet aluminum on the boards under the dial guage, to negate the effects of extremely local peaks and valleys. Six readings per board were taken in a grid 3" in from the edges, and averaged. Each reading was easily accurate to within five mils (.005 inch). The boards generally ranged in thickness from .9 to 1.0", with a positive correlation between density and thickness. The difference between the largest and the smallest of the six measurements was often 50 to 70 mils, and the standard deviations for the six measurements were for the most part in the range of 20 to 30 mils. The average of the standard deviations in thickness for the 40 ICI boards was .024", and we used ±.03" as the uncertainty.

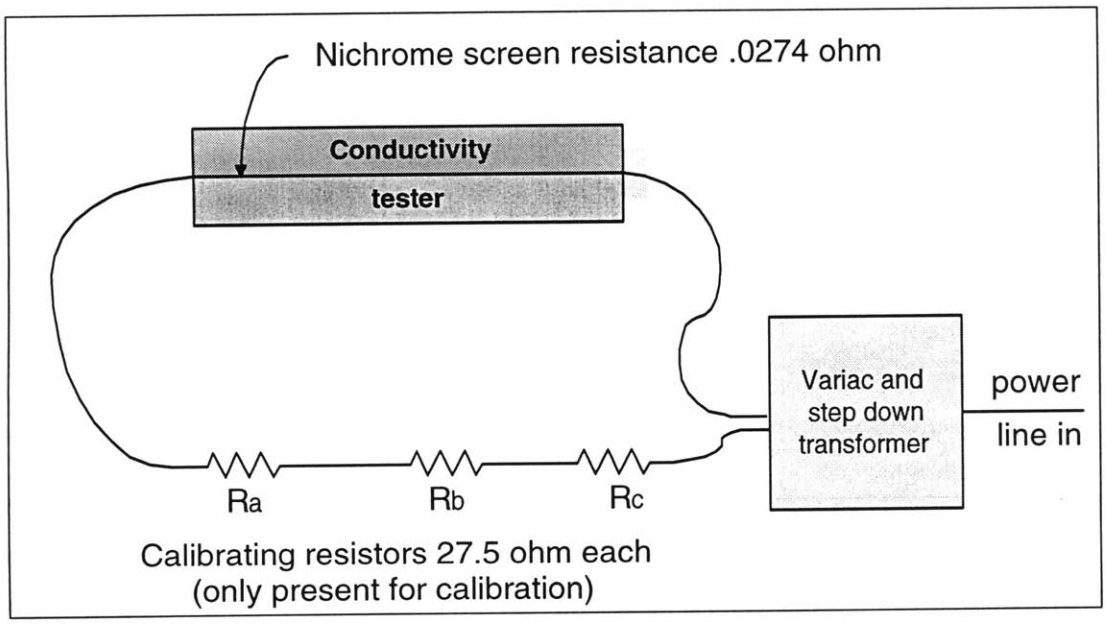

Figure 3. Calibration of Screen Resistance on Conductivity Tester

With regard to the accuracy of the R value of the reference material, we found that the piece in the tester had swelled unevenly with the repeated testing and exposure to moisture from still wet boards. We replaced it with another piece of extruded polystyrene made by UC Industries that came from the calibrated sheet Sullivan obtained in 1995. We attempted a simple check on its conductivity by running a second sheet of UCI extruded polystyrene in the test board spot. With the assumption that the reference and test pieces have an equal R value, the above equations become

$$R_{e\,qual} = \frac{A(\Delta T_{ref} + \Delta T_{test})}{Q_{total}}. \qquad (18)$$

When determining R value by a two sided test, one variable must be eliminated by assuming either that the two pieces have identical conductivity, or that heat flow is equal through both the upper and the lower pieces. Since the upper and lower convective transfer coefficients may be different, as discussed below, it is better to assume the two pieces have equal R value. A two sided test therefore is only useful when the two samples are known to be very much alike.

For the first run we got an R value for the pieces of polystyrene of 5.31 at a mean temperature of 87.1°F and a ΔT of 23°F. We then switched the two pieces, top to bottom, and got R 5.20 under roughly the same conditions. This was in excellent agreement with Sullivan's value. We therefore used a reference R value of 5.2 for all the succeeding tests. The uncertainty for our calculation was kept at R.1.

With these improvements in power and thickness measurement, the formula defines a k uncertainty of ±5%. Details of this calculation are shown in table 4.

This is, again, subject to the assumptions of one-dimensional heat flow, and negligible contact resistance. It is apparent from table 5 that we could improve accuracy still further by measuring the resistance of the heating screen more closely. A limit on more precise readings would also come from the variability of electric grid voltage. A further consideration is that these values are for temperature differences of 16 to 20°F, at mean temperatures of about 88°F. Most handbook values are for different ranges, e.g. ΔT of 50°F at a mean of 75°F, for building shell applications, and conductivity will vary somewhat as these parameters are altered.

As an additional check, we put a piece of 1" thick Dow extruded polystyrene in the tester with our chosen reference piece. We obtained values of R4.78 and R4.85 in two runs on the same piece, using R5.2 as the reference value. This material has a nominal R value of 5.0, and according to a National Institute of Standards engineer who works in the thermal testing department, Dow Styrofoam is measured consistently at just under R5.0 (Zarr 1996).

We also ran a 1" thick piece of .8 pcf expanded polystyrene, and recorded R3.87. This was at a mean temperature of 87°F and a temperature difference of 19°F. For expanded polystyrene at this density and mean temperature, the ASHRAE Handbook suggests an R value of about 3.7 per inch. The ΔT for the ASHRAE data is not given

These results show an accuracy within 5% of known values, in agreement with our calculation. This is certainly acceptable for comparing products in development work, where the priorities are to identify trends and establish rough values. It also gives us an accurate idea of where our boards stand in relation to existing insulation.

parameter x	typical value	units	new uncertainty Δ x	dk/dx	Δx(dk/dx)
screen R	.0274	ohms	.0003	-18.2760	0.0548
voltage	0.4	volts	.0020	2.4547	0.0049
thickness	1	inches	.0300	.3000	0.0090
area	2.4	ft^2	.0100	-.2113	-0.0021
ΔTref	20	°F	.3900	-0.0110	-0.0043
ΔTtest	20	°F	.3900	-.0171	-0.0067
Rref	5.2	$(Btu/hrft^2°F)^{-1}$	.1000	0.0388	0.0039

Table 4. Revised Uncertainties for Conductivity Tester

Convection and 2-D Heat Flow

When the tester is mounted such that the sample boards are horizontal, there should be a somewhat different heat transfer coefficient h (W/m^2K) from the aluminum plate to the air, for the top and the bottom plate. The top plate is a "heated plate facing up," and the bottom plate is a "heated plate facing down," and the natural convection flow patterns are different in these two cases, and thus the h's are different. While this difference does not affect the calculation of k directly, it does affect the portion of heat flowing in each direction, and it determines the best assumption to make in a two sided test. We would prefer that the two heat flows not be grossly unequal, as the accuracy of the very small Q would suffer.

Heat flow in the conductivity tester can be represented as two parallel paths from the screen to the ambient air, with an applied flux at the screen. This is shown in figure 4. The known variables are the three temperatures measured with thermocouples, T_{screen}, T_{ref}, and T_{test}, the total heat Q_{total}, and the reference resistance R_{ref}.

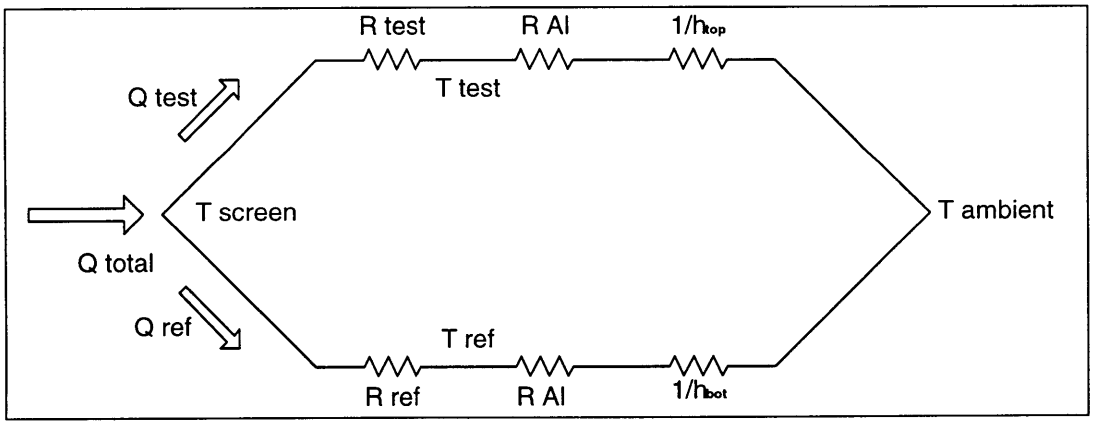

Figure 4. Conductivity Tester Heat Flow Paths

The thermal resistance along any one path can be written as

$$R_{onepath} = R_{ins} + R_{Al} + R_{conv} = \left.\frac{L}{k}\right|_{ins} + \left.\frac{L}{k}\right|_{Al} + \frac{1}{h} \qquad (19)$$

In SI units, k_{test}~.042 W/mK, k_{ref}~.029 W/mK, k_{Al}~168 W/mK. The heat transfer coefficient from the aluminum plates to the air can be estimated from the data. For each run, we can find the heat flowing through the reference and test materials, and we know the temperature of the plates and of the ambient air. The h's can be found from $h = q/\Delta T$, where ΔT is now the temperature difference between the aluminum plate and the air. Looking at data from four runs, we see h's in the vicinity of .62 to .85 btu/hr-ft^2-°F, with the top and the bottom nearly equal, and no clear pattern as to which is larger. This is about 4 W/m^{2}K. So

$$R\sim.6 + .00005 + .25 \quad m^2K/W. \qquad (20)$$

The resistance of the aluminum is negligible and the convective resistance is less than that of the insulation boards, but large enough to be important in the determination of heat flow.

The convective transfer coefficients are affected by the air flow in the room, and may change significantly when the blower in the overhead fan-coil unit comes on. This could explain the scatter in the h's found from the run data. It would be preferable to have the tester in an enclosed space with still air at a constant temperature. It is also important not to have a source of radiation, such as overhead skylight, bearing on one of the aluminum plates.

Two-dimensional effects could be estimated by looking at a 2-D slice of the boards extending from the centerline to the edge in the short direction. Boundary conditions would be $dt/dx = 0$ at the centerline by symmetry, and T(x) known at the top and bottom edges numerically. Sullivan has some T(x) data in his thesis that show the edge temperature of the heated screen as some 6°F less than the center temperature, at steady state. It is fairly level in the center area, and falls off sharply near the edge. The outer edge boundary condition would be contact with air (possibly with edge insulation present also), and the convective transfer coefficient and the temperature would have to be known there. With air temperature taken as zero, the problem could be solved by the superposition of two solutions, each with one nonhomogeneous boundary condition.

B. Structural Test Method and Equipment

Compression tests were performed on three 4.25" square samples cut with a bandsaw from those boards selected for structural tests. The Baldwin loading machine that we used was capable of 60,000 pounds force maximum, but on its lowest range full scale was 6,000 pounds, with 50 pound increments marked on the large dial face. Position of the crosshead that applies the load could be read on a small dial guage marked in .001".

The part of the test that introduced the greatest uncertainty was the establishment of a base point. The compression measurement should in theory start from the point at which the loading plate makes contact with the sample, however this is hard to determine by eye, and in practice the contact position was taken as the point where 20-30 pounds of force was applied, representing about 1 psi. Force readings were then taken at every .05" compression up to .3". This data, along with the measured thickness of the board, were typed into a spreadsheet. As the boards were not exactly 1 inch thick, the force required for 10% and 20% compression was found by interpolating between data points, assuming a linear force-displacement relationship. This was converted to psi by dividing by the area of the sample.

Bending measurements were made on a small Instron machine fitted with a 100 pound load cell. Four sample pieces were cut with dimensions 2.75" X 7.5". We placed the pieces on narrow supports with a span of 6", and applied the load in the center as shown in figure 5. The load bar moved downward at a steady rate of 2 mm per minute and the Instron tracked the bending force, and produced a plot of force versus displacement. The maximum force recorded is the rupture force, and the bending strength or modulus of rupture is found from:

$$\sigma = \frac{3F_r a}{wt^2} \qquad (21)$$

where σ = modulus of rupture, psi,
F_r = rupture force, pounds,
a = one half the span, inches,
w = width of the test sample, inches,
t = sample thickness, inches.

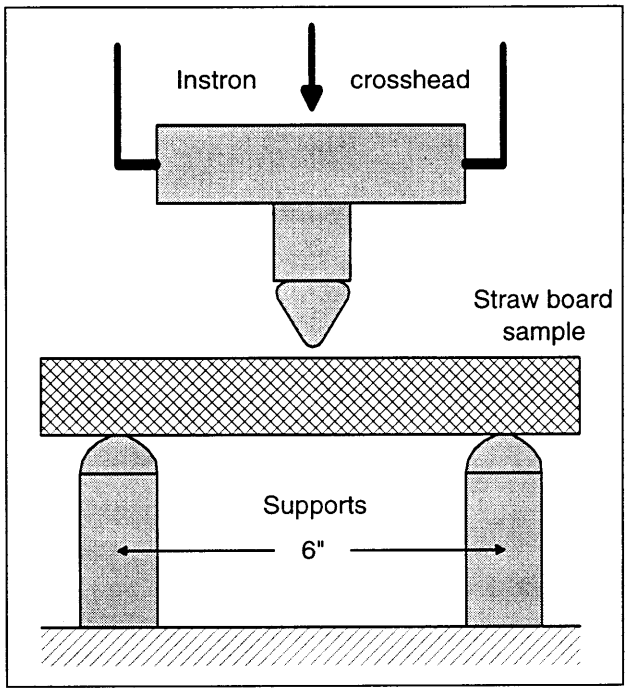

Figure 5. Bending Test

C. Milling, Molding, Mixing

The proposed raw material for the insulation boards was wheat straw available in Pakistan. We have a sample of typical output from one of their threshing machines, collected by our on-site team member; shown in photo 1 at the end of this chapter, it consists of .5" to 1.5" long pieces, and most of the whole stalks have been sheared, leaving flat fragments. For our experiments we obtained bales of oat straw from a local farmstand. This straw has similar appearance and characteristics to the Pakistani wheat straw.

Although we wished to work with straw shreds similar to those likely to be found in Pakistan, we also looked at larger and smaller particle size. The largest possible size is the uncut straw in the American bales. In this case the stalk segments are long (3-12") and whole in cross section. This is shown in photo 2.

We shredded the straw in two ways: 1) with a rented leaf shredder, which has a cylindrical hopper with rotating blades at the bottom, and produces chopped bits .25" to 2" in length, as well as a considerable quantity of fines (dust or small bits less than .25" in length), and 2) with an unusual hammer mill designed to grind flour in third world countries. This mill has blunt blades (steel bars) rotating in a vertical plane in a three inch deep space. Straw is fed into the center of the space and pulverized. Instead of passing through a perimeter screen as in a conventional hammer mill, the chopped bits are carried out an opening in the front face of the mill by a slight pressure gradient in that direction created by crude fan blades mounted in back of the grinding blades. This opening is located in one of the upper quadrants of the face, and the size of particle drawn off can be controlled by the distance of the opening from the center of the face. Larger, heavier particles are concentrated near the perimeter. The product is gathered in a fine weave, air permeable bag, such as a pillow case, tied onto a tube at the exit. See figure 6.

As the mill was intended to make flour, it tended to produce small pieces, with a high fraction of fines (even when the exit port was located as far as possible from the center). So the leaf shredder did a better job of reproducing Pakistani thresher output, but the mill was useful for investigating fine grinds, which could be used for mechanical pulping. Photos 3 and 4, respectively, show the shredded and milled straw.

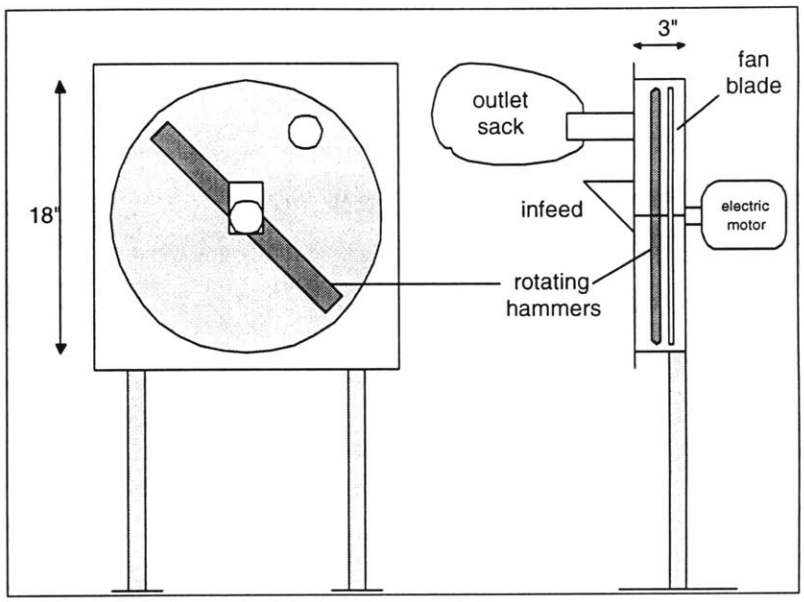

Figure 6. Hammer Mill

After shredding or milling, we in some cased separated out fines with screens. One-fourth inch hardware cloth allowed too many larger pieces to pass through, but screen with 1/8" mesh size worked well. Photo 5 shows the screened shredder output, and photo 6 shows the fines. In photos 7 and 8 the unscreened and screened wheat straw used at the ICI laboratory is pictured. This straw was milled in a conventional hammer mill. The unscreened ICI material is very similar to the Pakistani threshed straw.

Molds were made of .75" thick pine boards screwed together to make a square with inside dimension of 8", and a depth of 2.5". The bottom screen was .25" hardware cloth securely fastened at the perimeter with screws. A larger 15" X 25" mold produced boards for thermal testing, and in this case the bottom screen had to be reinforced with wooden cross members so that the boards would remain flat when pressed. It was helpful to apply a release agent to the wood, such as an oil soap, to make it easier to remove the sample from the mold when dry. It would also be beneficial to apply a release agent to the screen. We had as well 2" X 2" molds made from .25" acrylic for small scale work.

Mixing and foaming of the adhesives were accomplished with a kitchen type electric beater. Spraying was done either with a spritzer bottle, a 2 gallon hand-pumped tank sprayer, or a diaphragm pump powered by a one horsepower motor, capable of 250 psi at 6 gallons per minute, with hydraulic line and spray nozzles as used for sprayed-on insulation.

III. Initial Survey of Materials and Methods

A. Thermal Value of Straw

We tested loose straw, that had not been formed into boards, to establish the thermal value of the material. A quantity of straw sufficient for a target density of 5 pcf was poured onto the conductivity tester screen, contained at the edges by thin 1" strips of polystyrene. The straw was slightly compressed as the upper aluminum plate was tightened down with nuts. Shredded oat straw was screened with .17" screen, so that we had three products to test; unscreened,

screened (larger pieces), and the fines (smaller pieces) that were separated out in the screening. The fines have a natural, settled density of about 6 pcf, so we measured them at that density.

The measured R values and densities, along with the mean temperature and temperature difference across the test sample, are shown in table 5.

Straw	density pcf	R/inch (btu-in/Rft^{2}F)$^{-1}$	mean temp. °F	temp. diff. °F
unscreened	5.4	3.83	84.6	19.9
screened	5.4	3.52	87.1	19.3
fines	5.9	3.48	85.1	18.5

Table 5. Thermal Resistance of Loose Straw

This suggests that the fines improve insulating qualities somewhat when present with the larger pieces, as we expect. The radiation component of heat transfer is reduced by increased "barriers," while solid conduction is not appreciably affected. We cannot ascertain how the fines alone perform in comparison with the larger pieces until we have tests at exactly the same density.

The value of R3.8 per inch for shredded unscreened straw indicates that straw boards can have excellent thermal performance at 5 pcf density, equivalent to expanded polystyrene.

B. Containment

We made a few samples of "wire and batten" boards. Strips of hardboard on each side of the straw panel were 1 inch wide (2.5 cm) and had a center to center spacing of 5 inches (15 cm). They were fastened to each other through the panel with wires in such a way as to clamp the straw. Uncut straw was oriented perpendicular to the battens. Sample size was two or three times longer than the average straw piece length. See figure7.

Doing this with no binder didn't work at all. The sample came apart with a cleavage between and parallel to the battens, and would not support its own weight. We tried again using a small amount of binder, .12 to 1 by weight PVA emulsion to straw. This worked reasonably well.

The Aga Khan housing board in Gilgit, Pakistan, provided a 1996 wood lath cost of 130 rupees per square foot, or about $4.00. For the scheme we tried, where one inch strips of wood are spaced 5" apart on each side of the board, so that wood requirement is 40% of the board area, the cost of such wood lath would be prohibitive. Even if the board was 6" thick, the wood would cost about 7.5¢/R-ft^2, and some adhesive is needed in addition to that. In wood scarce Northern Pakistan, the spacing between strips would have to be much greater. In parts of the world where wood is more plentiful, such a concept would be easier to implement.

Whole straw stalks are required for this method, which may impose a limit on thermal performance.

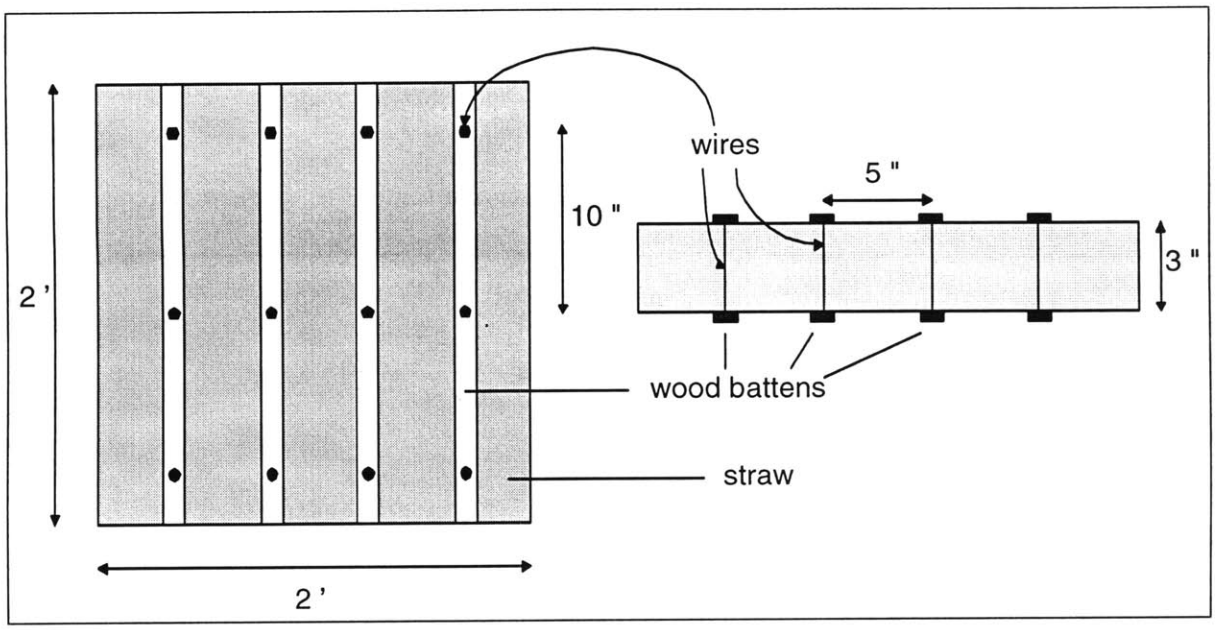

Figure 7. Wire and Batten Board

C. Cold Soda Pulping

Following our research on simple pulping methods, we tried a cold soda technique with the straw. We soaked two small (one-half ounce) samples of shredded straw (1/2" to 2" or 12 to 50 mm. length pieces) in a 4% aqueous solution of sodium hydroxide (NaOH-- caustic soda), for two and eighteen hours, respectively. The straw was dumped out onto a screen, pressed with a putty knife to squeeze out the caustic solution, and left to dry under a fan. When dry, the samples were quite cohesive, and had lost some mass, both effects being greater with longer soak time. We repeated this with a 20% NaOH solution, and got even greater cohesion and mass loss, again at two soak times. The longer soak time breaks the straw down more and gives a result similar to the stronger NaOH solution.

Steeping in 4% solution for two hours resulted in a straw block that did not quite hold together well enough for our purpose, and in a 20% solution for 18 hours resulted in a board that was very dense and rock hard. But the two middle options, 4% for 18 hours or 20% for 2 hours, produced a chunk of material of the right density-- in the 5-10 pcf range-- and quite cohesive. The 20% solution is more hazardous to work with, as splashes on skin or especially eyes could be injurious. Ten percent is considered a safety threshold.

This was not a complete cold soda pulping because the caustic steep was not followed by disk refining, which does the bulk of the defiberizing. There is no added adhesive here. We assume the cohesion of the samples comes from released and softened lignin, as well as hydrogen bonds between fibers that have been liberated in the caustic treatment.

We made a trial on a larger scale in an effort to quantify the amount of sodium hydroxide needed for a cohesive board. Fifty grams of NaOH were mixed with 450 grams of water to make 500 grams of 10% solution. Eighteen grams of chopped straw were added to the solution and allowed to sit overnight. The idea was to release the lignin (or whatever causes adhesion) from a small amount of straw, then mix the liquor with a larger amount of straw. The following day the

mixture was poured over 500 grams of dry, untreated, shredded straw, and enough water was added (about two kilograms) to allow the NaOH mix to be distributed over the comparatively large bulk of straw. This made a damp mash which was pressed into a mold, making a sample about 12" X 15" and 2" thick. Because it was so wet, a considerable amount of dark brown liquor drained out the screen on the bottom, so that the amount of NaOH actually consumed in the board was unknown.

The calculation for this was made by assuming 5 pcf boards with R3 per inch, and a bulk cost of $3.00 per pound for NaOH. In this case the following mass ratios of NaOH to dry straw are the maximum permissible for the given cost levels.

NaOH cost ¢/R-ft^2	1¢	2¢	3¢	4¢
mass percent NaOH/straw	2.5	5	7	9

The process is hard to simulate in a batch trial. In practice there would be a continuous process, where the liquor was reused and refortified. However this was the rationale for using 500 grams of straw with 50 grams of NaOH-- 9% by mass, which would give the 4¢/R-ft^2 binder cost, at the upper limit of economic possibility. (When labor and overhead costs are considered, this may be beyond economic possibility.

Even this large amount of NaOH was hard to distribute over the straw. The board that resulted took a long time to dry, more than two weeks, and when it did it had marginal structural properties, and could scarcely be handled without crumbling.

In the case of cold soda pulping of wood, industry studies show that between 2 and 10% of dry wood weight in NaOH is consumed in the process. The larger consumption rates are associated with greater breakdown of the wood structure, and more dissolving of lignin (MacDonald and Franklin 1969). If we could work at the low end of that range, around 2%, the process would be much more attractive economically.

The premise of this trial, that a small amount of straw can be pulped in the caustic solution, which can provide adhesion for a much larger amount of straw, is doubtful in light of our result. Rather than the caustic solution releasing a "lignin glue" which can act on untreated straw, it looks as if each piece of straw must receive caustic treatment, over a time period of hours, for the method to work.

A more general drawback of this method is that alkaline pulping, in the paper industry, is followed by extensive washing to remove the sodium hydroxide. To the extent that the NaOH is not removed, the paper yellows and becomes brittle with age, as newspaper does. The caustic soda continues to react with ambient moisture and breaks down the fibers. In our trials, the straw was not washed at all, so some NaOH remains in the board. These samples, kept for over six months, showed a thick white crust forming on the surfaces exposed to air.

Another factor is that recovery of chemicals is necessary in any chemical pulping both to cut cost and to reduce environmental problems. Although the liquor can be fortified and reused many times, it accumulates dissolved or broken down straw or wood components so there is a limit to reuse. Eventually it must be processed, and commercial pulp mill recovery operations are energy intensive, as the spent liquor is boiled to produce steam and reduce the chemicals.

In view of the above considerations, further work would need to examine the feasibility of soaking in very dilute solutions of sodium hydroxide. A longer soak time, finer grind of straw, or

use of heat might allow the needed cohesion to be developed with modest use of the chemical. The long term effect of the NaOH in the boards should be determined, and if necessary the feasibility of washing the straw could be tested. To make a pulped, wet process board, it might be more fruitful to investigate a purely mechanical pulping process.

A different use of sodium hydroxide is to wash pressure treated lumber to improve the adhesion of glues. The washing may remove surface deposits and change the surface tension of the wood. Since the straw with its thin coating of wax may have adhesion problems, this raises the possibility that a sodium hydroxide wash could be used in combination with an adhesive (Vicks 1996). Likewise textiles such as wool are treated with NaOH to remove wax and improve dyeing, in a process called Mercerization.

D. Adhesive Binding

Our initial efforts were with three readily available, non-hazardous, water soluble glues; PVA, sodium silicate, and wheat paste. We ran side by side tests to see which of these three representative binders worked best. At the same time we tried different straw grinds; uncut, shredded, milled, with and without screening. The method of applying the adhesive was likewise varied from spraying to foaming and dipping.

Some of the 8" square boards made in this initial phase of the work are shown in tables 6, 7, and 8. The tables shows the key parameters: glue type, amount, and application method; straw grind; final density; a qualitative assessment of structure; and a cost per insulating unit. Although the 8" boards were too small for our thermal tester, they were large enough to allow mechanical properties to be rated as excellent, good, fair, poor, or bad. "Excellent" means the boards could be made at full size and shipped to a job site for installation (at least as regards structure; fire and biological attack are separate issues). "Good" also means it has enough cohesion to work for our use, namely to be handled and transported, attached to walls, and plastered, although it is not as strong as the "excellent" boards. "Bad" means it cannot be picked up without crumbling. "Fair" and "poor" are in between. The dry glue load is an estimate of the glue solids remaining after the water vehicle has evaporated, made by finding the actual density of the dry board, and subtracting the known weight of dry straw that is in it. Frequently the glue solution would drain out of the board, or be lost in the mixing process, so the dried board would not contain the full amount of intended binder.

The cost figure includes only materials. We used a Pakistani straw price of 3.8 rupees per kilo or 5.3¢ per pound (Sullivan 1995). (North American straw prices are 1-4¢ per pound.) A Rhode Island adhesives dealer quoted us prices of 60¢ per pound for PVA and 40¢ per pound for sodium silicate, in barrel quantities. These prices will vary regionally, over time, and depending on the volume purchased, so the cost data is approximate. The insulating unit is a square foot of material thick enough to give R1, where R is in $(Btu/hr\text{-}ft^2\text{-}°F)^{-1}$. For tables 6 and 7 conductivity was estimated, using measurements we made on similar boards as a basis. For the later tables we used measured R values. Our benchmark for cost was $6¢/R\text{-}ft^2$ for expanded polystyrene in Pakistan. We wanted our materials cost to be well below that, under 4¢, and preferably under 2¢ per unit, so that delivered product cost would be a marked improvement over the polystyrene.

In general the method for all these boards was to weigh out 4 ounces of dry straw, and the chosen amount of glue, combine them by one of the techniques listed below, deposit the mixture into one of the molds, and leave it to dry under a fan. As we were striving for the lowest possible

density, the boards were not pressed in the molds (with a few exceptions), other than a light pressure at the start to make the material fill the mold.

MIT ID number	ratio wet glue to dry straw	glue preparation (oz. glue/ water)	straw preparation	actual density lb/ft^3	structure qualitative	estimated materials cost cents/R-ft^2	glue load by mass when dry %
96323	.12/1 PVA (wire and batten)	sprayed	dry	6.4	fair	3.9	
96220	1/1 PVA	sprayed (4/4)	dry	5.6	good	9.4	23
96219	1/1 sod. sil.	sprayed (2/4)	dry	5.3	fair	6.3	25
96222	.5/1 PVA	sprayed (2/4)	soaked in water	5.2	fair	4.7	6
96221	.5/1 sod. sil.	sprayed (2/4)	soaked in water		bad		
96227	.5/1 PVA	foamed (2/8)	dry	4.2	fair	4.4	12
96226	.5/1 sod. sil.	sprayed (2/8)	dry	4.4	poor	3.2	16

Table 6. MIT Boards, Whole Stalks

MIT ID number	ratio wet glue to dry straw	glue preparation (oz. glue/ water)	straw preparation	actual density lb/ft^3	structure qualitative	estimated materials cost cents/R-ft^2	glue load by mass when dry %
96229-A	.5/1 PVA	foamed (2/8)	dry	6.5	fair	5.5	18
96229-B	1/1 PVA	foamed (4/16)	dry	8.9	good	11	35
96301-A	.38/1 PVA	foamed surf. (1.5/16)	dry	5.5	fair	4	11
96301-B	.38/1 PVA	foamed surf. (1.5/8)	soaked in water	2.7	bad	2.6	
96311-A	.5/1 PVA	foamed surf. (2/4)	soaked in ethanol	7.6	good	high	16
96312	.25/1 PVA	foamed surf. (1/4)	soaked in ethanol	6.1	fair	high	5
96314-C	.25/1 PVA 10% ethanol	foamed (1/12/1.2)	dry	5	poor	6	

Table 7. MIT Boards, Shredded Straw

Whole Stalks

Uncut straw was very hard to work with. The whole stalks did not pack together well, or fit into the corners of the mold. They absorbed the liquid-born adhesive by capillary action into the hollow cores, where it does not contribute to cohesion from stalk to stalk. As it is the outer side of the stalk that is coated with wax, the binding surfaces in a whole stalk board are nearly 100% wax covered, whereas the sheared fragments of the milled straw board only have half the surfaces wax coated. The final samples were inhomogeneous and had large voids, .25" or greater in average dimension, which will cause poor thermal performance. They lacked strength unless the amount of binder was exorbitant. The only sample that held together well enough to make an insulation board was number 96220, shown in table 6, in which the ratio of PVA emulsion to dry straw, by weight, was one to one, and the fraction of PVA solids in the dried product was around 25%. The estimated unit insulation cost of 9.4¢ for this board is much too high. The density however was in our target range of 5-6 pcf.

In addition to the above factors, the boards made from whole straw stalks have a very rough appearance, lacking a uniform, machine processed look associated with modern building materials. We therefore moved to shredded and milled straw, which gave a more controllable, uniform product. Further efforts with whole straw should focus on aligning the stalks, pressing to a somewhat greater density, and perhaps combining with fine particles.

Shredded Straw

The main issues in applying the adhesive to the straw are control of the amount and the distribution: too much glue is too expensive; too little, or glue that is not spread evenly over all the straw surfaces, will not give sufficient cohesion. In our first attempts we diluted the glues in water, and sprayed the mix on the dry straw while agitating manually, to make a damp mash, which was then forced into a mold. Our problem was that the stirring action did not expose a great enough fraction of straw surfaces to the glue. In our efforts to distribute the adhesive we diluted it more and more. As shown in table 6, we added from one part to four parts water to the PVA emulsion or sodium silicate solution. With the higher amounts of water, however, the mixture was too inviscid and drained out of the straw mat, carrying away the adhesive. The glue that *was* deposited on the straw surfaces was too thinly dispersed to make strong bonds.

In order to distribute the adhesive evenly over the straw, we found we had to use four parts by weight of adhesive-water mixture for one part of dry straw. If the straw had been soaked in water, this ratio was two parts mixture to one part wet straw. So we introduced a great deal of water to the boards which then had to be removed by drying.

This is why commercial dry process operations use large tumblers, or loft the fibers on an air stream. The manufacturers can provide a much greater stirring and mixing action, to scatter small amounts of an adhesive, which has appreciable viscosity, over the large surface area of fibers. In the case of wet process boards, so much water is added to the fibers that they only make up 1 to 4% of the stock. An adhesive or size can then be thinly and uniformly distributed over the fibers by a precipitation method. So it is apparent that in conventional mass production a great deal of energy is expended, and technological sophistication required, for good distribution. The boards, dry or wet, are then pressed at high pressures, forcing the glue coated particles into inti-

mate contact with each other until the adhesive sets. Absent good distribution and high pressure, our boards did not cohere well.

In our initial survey we did not use a tumbler or hot press, in accordance with our mission to make low density boards with simple equipment and low manufacturing energy. However it would certainly be worthwhile to investigate the actual energy requirement of such machinery in future work.

Of the PVA boards made by spraying (not foaming) glue over shredded straw, satisfactory mechanical properties could not be obtained unless the mass ratio of PVA emulsion to dry straw was .5 to 1 or greater. See tables 7 and 8. Cost at this ratio was high, in the 4-10¢ per insulating unit range. In the case of sodium silicate, this "wet ratio" needed to be closer to 1/1 to give sufficient strength, so that, even though sodium silicate costs less than PVA, the insulation cost was still in the 5-10¢ range. When labor, overhead, and some kind of biocide are added in, these boards would certainly cost more than expanded polystyrene that is already available in Pakistan for about 6¢.

MIT ID number	ratio wet glue to dry straw	glue preparation (oz. glue/ water)	straw preparation	other materials	structure qualitative	estimated materials cost cents/R-ft^2
96614-A	.25/1 PVA	sprayed (1/16)	dry		bad	
96614-B	.25/1 PVA	sprayed (1/16)	dry	15 g jute	fair resilient	5
96617-A	.12/1 PVA .5/1 sod. sil.	sprayed (2.5/16)	dry	4.5 g boric acid	poor	
96617-B	.5/1 wheat .5/1 sod. sil.	sprayed (4/16)	dry	4.5 g boric acid	bad	
96617-C	.5/1 sod. sil.	sprayed (2/16)	dry	4.5 g boric acid	bad	
96617-D	.5/1 wheat	sprayed (2/16)	dry	4.5 g boric acid	bad	
96621-A	.12/1 PVA .25/1 wheat	sprayed (2.5/16)	dry		good	
96621-B	.25/1 PVA .25/1 wheat	dry mix/spray (2/16)	dry		bad	
96621-C	.06/1 PVA .25/1 sod. sil.	sprayed (1.25/16)	dry		fair	
96624-A	.25/1 wheat .25/1 sod. sil.	sprayed (2/16)	dry	15 g jute	fair	
96631	.12/1 PVA .25/1 wheat	sprayed (2.5/16)	dry	15 g jute	good	

Table 8. MIT Boards, Shredded Straw with Jute, Boric Acid, and Glue Combinations

All these boards were made without pressing, and had final densities of 5-8 pcf. For the same quantity of glue, strength is enhanced by working in 8-15 pcf, as we demonstrate with the MDI boards described below. Boards made in the Fall of 1996 were pressed with many concrete blocks stacked on a 15" X 25" piece, and had good structural integrity, sufficient for the purpose. Glue amounts were high however.

For a board at 10 pcf straw density, for example, we can estimate the cost of insulation as 5-7¢/R-ft^2 for either PVA or sodium silicate, *if* wet glue ratios were maintained at .25/1 and .5/1 for PVA and sodium silicate respectively. If the higher density allowed these glue ratios to be cut in half then unit costs would be in the 4¢ range, still high. This suggests that wet glue ratios would really need to be in the .1/1 or .2/1 range to enter the economically competitive range. Nothing in our work to date indicates that this is possible.

In the case of a starch-based adhesive, boards were made by mixing wheat flour with water, and stirring this thin paste into the straw. Where the weight ratio of flour to straw was 1 to 2, the boards were remarkably strong. At a flour cost of about 10¢/lb in Pakistan, this makes insulation at a cost of 2¢ per unit (6 pcf density). However we presume that the product is too attractive to micro-organisms, insects and rodents. Samples in our lab showed signs of mold growth while drying. Since the cost of starch cohesion is low, further work could investigate the use of much less starch with another binder and biocide. The starch boards also raise the possibility that adhesive in paste form is more effective for making low density boards. Any adhesive can be made into a paste by the addition of fillers.

Foaming

In an effort to make less expensive boards, we turned to foaming the adhesives. This is documented as a way to enhance adhesive distribution and reduce penetration into the substrate. By using air as the conveying medium, in part, drying requirements are lessened (Ziegler 1959). In our case we also thought foaming would keep density low.

We were unable to foam sodium silicate, but the PVA emulsion, when diluted in water, foams readily with an electric mixer. A few drops of surfactant increase the volume of foam produced. We used ordinary dish soap, as well as Tegopren 5840 (tm), an organo-modified siloxane surfactant recommended by the manufacturer, Goldschmidt Chemical Corp., for use with PVA. It took less time to obtain good distribution by folding the foam into the straw than by spraying. The foaming also produced a lower final density board, and it is possible to "float" the straw pieces on the foam, and make a very low density (2-3 pcf) board, as was accomplished in sample 96301-B, shown in table 7. This sample had poor structural qualities however.

The foaming made it easier to apply the glue, in the case of PVA, but, as shown in Table 7, it did not give better structural properties for a given amount of adhesive. Test samples 96229-A, 96229-B, 96301-A, and 96301-B did not hold together well unless the PVA wet ratio was 1/1. The basic bonding mechanism was not improved, and cost was still too high.

Other researchers using PVA dried the boards in an oven to speed the cure time, as mentioned above. A scientist at the Forest Products Laboratory told us that a PVA bond must form under pressure. As the glue sets by loss of water, the board should remain clamped until sufficiently dry (Vicks 1996). Further work on our project should examine the effects of oven drying. The key problem, however, is how to apply pressure during curing but still maintain a low density.

Dipping

We also tried dipping the straw into an aqueous PVA solution. Table 9 shows a three by three matrix of tests made with 5%, 9%, and 33% solutions. In the first run we used dry straw, in the second run straw that had soaked in water overnight, and in the third run dry straw with a sili-

con wetting agent in the PVA solution. The samples were weighed wet, just after being placed in the molds, as well as after drying.

The 33% solution conveyed too much adhesive to the straw, producing a hard block with an adhesive solids content of about 40% by mass, much too high. The 5% and 9% solutions conveyed too little, or what was conveyed didn't act efficiently, and the resulting samples fell apart in our hands.

Soaking the straw in water before dipping in the PVA solution did not improve strength. This suggests that the dry straw aids setting of the glue, because water is drawn out of the solution into the dry interior of the straw pieces. This is the mechanism used in gluing paper and cardboard products.

Nor did the surfactant make the samples stronger per amount of glue. In some cases it had an adverse effect. The data in table 9 show that dry straw will absorb about 3 or 4 times its weight in water in a 30 second immersion, and slightly more with an additional 30 second soak time. The straw will absorb about 30% more water in 30 seconds if a surfactant is present, presumably due to increased capillary action. On the other hand, the straw retains more liquid as concentration of PVA rises; perhaps because the more viscous liquid does not drain away when placed on a screen. In all cases a large mass of water is taken up, so the dipping method would entail a long drying time, in ambient air, or high costs in a dryer.

The test needs to be repeated to determine if this method can distribute the "right amount" of adhesive, and make an economical board. This would be a continuous process where the dipping mixture was used repeatedly.

Run number	sample number	PVA solution percent	wet weight ounces	PVA solution taken up ounces	dry weight ounces	dry glue load %
1	96328-A	5	1.8	1.3	0.4	
1	96328-B	9	2.4	1.9	0.5	
1	96328-C	33	2.9	2.4	0.9	44
2	96405-A	5			0.4	
2	96405-B	9	2.5	2	0.6	17
2	96405-C	33	2.7	2.2	0.8	38
3	96408-A	5	2.8	2.3	0.5	
3	96408-B	9	3	2.5	0.6	17
3	96408-C	33	3.3	2.8	0.9	44

run 1: straw dipped in PVA solution
run 2: straw dipped in water first, then in PVA solution
run 3: straw dipped in PVA solution treated with silicon surfactant

Table 9. Straw Samples Dipped in PVA Solution

Alcohol Treatment

One interesting result is a remarkable increase in structural integrity, for a given amount of glue, achieved by soaking the straw in 100% ethanol. Compare samples 96229-A, 96301-A, 96311-A, and 96312 shown in table 7. Adding 10% ethanol to the PVA-water mix, with no prior soaking, did not have a beneficial effect.

There are at least two important effects here. Ethanol has a surface tension of about 23 dynes/cm compared to water at 73. Water and alcohol are completely miscible and the mixture has a surface tension between 23 and 73. Wetting is crucial in adhesives, as the vehicle has to wet the substrate to deposit the glue, and decreasing surface tension should allow greater wetting of the straw.

Also there is some interaction between the alcohol and the PVA, that we observed by dropping some PVA into pure ethanol. The alcohol appears to pull water rapidly out of the PVA emulsion, leaving the gummy solid behind. The water-ethanol mix then evaporates much faster than plain water, as shown by rapid drying of our samples.

So the PVA solution spreads well over the ethanol soaked surfaces, then dries rapidly. We looked at pieces of the board under a microscope, and it appeared that the alcohol boards had fine drops of glue well dispersed on the straw, making many little spot welds, whereas in the boards without alcohol the PVA seemed to be in bigger globs which were falling away from the straw surfaces into void areas, where they are useless. Rapid drying is therefore beneficial because it "freezes" the glue on the surfaces where it is needed, before it has time to drip or ooze away into the large void volume.

We did not quantify the amount of ethanol necessary for this effect, but it is significant. If the straw absorbs its own weight in ethanol, and the ethanol costs 50¢/lb (somewhat less than the laboratory price), then for a 6 pcf board like 96312 with a resistance of R3.5 per inch, the cost of the ethanol alone would be 7¢ per insulating unit. This does not therefore look like a viable production method, unless the effect can be achieved with small quantities of ethanol.

Reinforcement

We looked at a number of boards under a microscope at 10 and 40 power. It is hard to see the straw well with a light microscope because at a high enough magnification to observe the glue droplets, the focal depth is too narrow to scan over the straw surfaces. Scanning electron micrographs could give a much better picture. In general, however, examination of the above boards suggests that there is a great deal of adhesive which is not functioning to bind straw pieces. Most of it is gathered on surfaces that do not touch another piece.

In a further effort to achieve strength with less glue, we mixed jute strings in with the straw. Jute is by a low cost, widely available natural fiber used for rope, sacking and twine. We created 2 mm diameter strings pulling apart burlap bags, but finer jute threads are available and would probably be more efficient. In sample 96614-B, shown in table 8, 15 grams of jute string were mixed with 112 grams of straw (13%), and the mixture was sprayed with a .25/1 wet ratio PVA solution. Structural properties were much better than a board with the same glue content and method made without the jute. The resulting material was resilient and could bend and stretch somewhat without cracking or breaking. Prices in Pakistan are reported to be 20 rupees for a 3' X 4' section of loose weave jute. We found that a section of burlap sack weighs about .062 lb/ft^2. If the Pakistani jute is similar, it would cost about 80¢/lb. Unit costs for 96614-B would then be in the vicinity of 5¢/R-ft^2.

In this case the cost of the PVA in a .25/1 ratio still pushes the cost of the insulation higher than we would like, regardless of the cost of the jute, so the amount of adhesive would have to be decreased. The long filaments may provide strength at low densities that we have been

unable to achieve in other ways. In further work, we should try lesser amounts, and other kinds, of glue, and finer jute threads, to make a cost-effective board.

We do not know if a biocide is needed in the boards. In a dry climate such as Northern Pakistan, there may be no danger of mold or fungal or insect attack. If there is to be a possibility of using the boards in wetter climates, however, such as Eastern North America, there may be a need to treat the straw. For this reason we made trials with boric acid, perhaps the most common biocide used in wood board and insulation products. These efforts are shown in table 8, where boards 96617-A, 96617-B, 96617-C, and 96617-D are all significantly weaker than their counterparts made with the same amount of adhesive but without boric acid. The boric acid apparently interferes with the action of the adhesive.

Small Scale Tests

In an effort to understand the action of the adhesives on the straw we undertook some small scale tests. Drops of glue were applied to single pieces of straw stalk to observe wetting. Figure x shows the behavior of the undiluted PVA emulsion, of the emulsion mixed with an equal part of water, and of the diluted emulsion with one drop of Tegopren surfactant added. Clearly dilution in water causes the glue mixture to wet the straw better and spread over a wider area; this is the behavior we want to coat all the straw surfaces with the minimum of glue. With the surfactant, the wetted area is increased considerably again, which is desirable up to a point, but it looks as if the adhesive has now penetrated so well that the surface is starved, and insufficient adhesive remains make a bond. When the test was repeated with sodium silicate, the same effects were observed. The glues were applied to both the inner and outer sides of the straw stalk pieces. The outer side has a thin wax coating, where the inner side does not, and in a qualitative way it could be seen that wetting and penetration were somewhat less on the waxed surface, although the difference was not large.

We attempted to test adhesive strength by gluing two sections of straw stalk, each a few inches long, together with a drop of binder placed on an area about 4 mm X 6 mm. When dry, the two glued straw pieces were each held with a powerful alligator clip, one of which was fixed, and the other attached to a small basket. Weights were placed in the basket until the glue bond, or the straw stalks themselves, broke. This was repeated with the PVA and sodium silicate, and with unwashed pieces, as well as those that had been washed in ethanol. A sample of the data is shown in table 10.

	force required to break joint, ounces	
	sodium silicate	**PVA**
unwashed	13	9 b
	0 a	21
	0 a	
alcohol wash	3	2 b
	4	26
	8	10
		45

a fails immediately b straw piece breaks; glue joint holds

Table 10. Small Scale Straw Adhesion Tests

This test was too limited to produce useful data. At a minimum, we would need a large number of data points to extract meaningful information, because of the highly irregular nature of the material. It was difficult to find pieces of stalk flat, straight, and regular enough to test. The sections of stalk tend to have curvature and splits and breaks. A drop of glue from an eye dropper was applied to an area of stalk intended to be .125" X .5 ", but it was hard to control the size of the contact area between the two pieces. There are large local variations in surface roughness and cleanliness. Testing should perhaps begin with flat planed wood chips, whose surface characteristics might be very similar to straw.

Perhaps most important, in the absence of clamping pressure, bond formation was erratic. The pieces can easily shift relative to each other before the glue sets. Although we did not measure it, there appeared to be a great improvement in the strength of the bond when a small weight was placed on the straw stalks while the glue set.

When the pieces failed, the hardened glue tended to shear off the straw as one piece. The high viscosity, undiluted, glue, whether PVA or sodium silicate, did not penetrate the straw pores well at all.

It would also be necessary to have a more accurate device, such as a very low force load cell, or a spring of known force constant which can be gradually stretched by turning a wheel. With such a device, and a large number measurements, adhesion could be systematically studied.

In this initial survey of techniques we gained an understanding of mechanisms, but the boards with sufficient strength were not cost-effective. In the second part of this investigation, we were able to make boards with greatly reduced amounts of an adhesive that sets by chemical reaction.

IV. MDI Straw Boards

A. Fabrication

We made 42 20" X 28" (50 X 70 cm) straw boards at ICI Polyurethanes Inc., West Deptford, NJ research plant. The furnish (raw fiber) for the boards was hammer-milled wheat straw from the western US. For most of the tests we used the complete straw furnish, with no fines screened out. For two blender loads we used furnish that had been screened in a commercial, rotating sifter with a 4 mm screen. We used the coarser pieces, rejecting the approximately equal volume of fines. The resin was methane di-isocyanate (MDI) supplied by ICI.

Their blender has a drum about 4 feet in diameter and 18" thick, sitting on rollers with its diameter in a vertical plane. The motorized rollers turn the drum at about ten rotations per minute. The drum has a door on the perimeter to load and unload the furnish. Hydraulic lines feed in through a sleeve at the center of the back face to spray heads positioned just off center in the interior of the blender. The spray heads remain fixed as the drum turns. The perimeter of the drum has vanes-- 3" wide cross members-- to carry the furnish up, then dump it into the path of the spray nozzles. The front face is made of clear acrylic to permit visual observation. See figure 8.

The resin is kept in a stainless steel pot, sitting on an electronic scale, under a fume hood. Compressed air pushes the resin through the lines to the spray nozzles, which are selected to deliver a fine, misting spray. The ICI operators had found a flat spray pattern more effective than a round pattern at delivering the resin evenly to the furnish. The nozzles are similar to those used in commercial spray painting operations. The mass of resin delivered is controlled by watching the scale, and turning off the spray at the appropriate time. For a 2% resin content, e.g., the mass of furnish in the blender, in this case 15 pounds, is multiplied by 2%. The volume rate of spray is adjustable via the pressure in the air lines feeding the spray pot. The spray rate is diminished as the resin loading drops, so that the total spraying time remains roughly constant. For these 15 pound runs, the ICI operators thought that ten or fifteen minutes spray time was necessary to give a uniform distribution of the resin over the comparatively large mass of straw. This was probably conservative, and we did not try shorter times as the goals for the runs were to establish feasibility and properties of the boards, rather than to optimize process parameters.

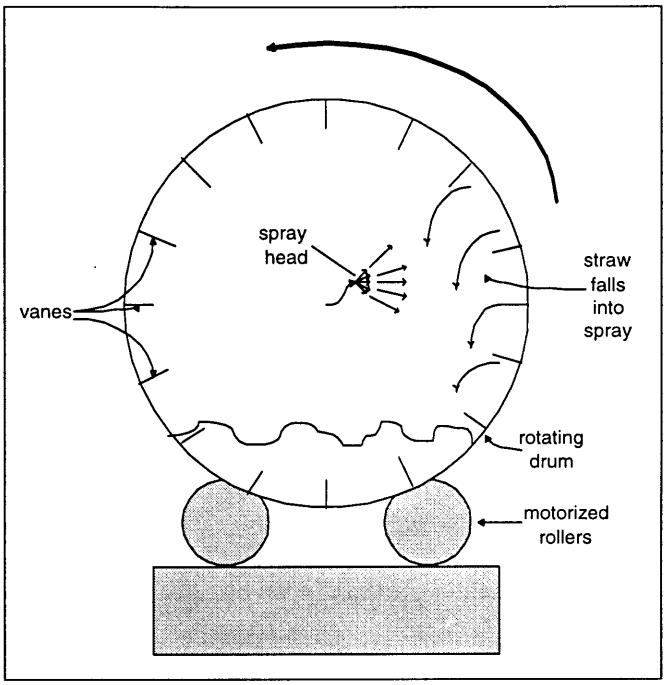

Figure 8. Blender

Uniform distribution of the resin is crucial to achieve a good product with these very low mass fractions. The spinning disk head is the preferred method of distribution for commercial operation, because it can produce a finer mist than the spray nozzles, and has fewer problems with clogging. With this equipment, resin is fed onto the outside surface of a conical steel section, which is rotating at high speed. Tiny droplets are thrown off in all directions. For the small scale tests, however, the aerosol spray heads were adequate and did not have any congestion problems.

A duct from the central exhaust and filter system keeps the interior of the blender at a slight negative pressure; not so much as to suck out the fine particles, but enough to prevent any spray from escaping the blender into the room. After the spraying is completed, the mixture of resin and straw is left to sit for two minutes, to allow any remaining fumes to be sucked out. The furnish was then removed from the blender with a hoe-like tool, and weighed out into amounts for each board sample, in plastic bucket liners. The people doing this wore protective gloves, but no respiratory mask was required. After cleaning with an air hose, the blender is ready for a new load.

The furnish with the uncured resin was spread into the mold by hand, by scattering a handful at a time in such a way as to distribute the particles evenly. The straw is clumpy at this point and hard to rake smooth, so it is best to sprinkle it into the mold in even layers; otherwise the boards have local variations in density. This is very slow; it took two of us about eight minutes to lay out one board. In commercial operations the "mat" is laid out by machine. The mold

was a simple rectangular form made of hardboard: both it and the steel press platens were sprayed with a soap release agent before each board was made.

After the straw pieces were carefully spread and smoothed, the form was lifted off, and the steel plate with the mat on it slid into the press. The upper press plate came down until stopped by the shims, producing a board one inch thick. The upper and lower press plates were maintained at 375°F by circulating oil. Press time was eight minutes for these boards, considerably longer than the time for the thinner, more conductive MDI boards they are accustomed to making. Again, this was conservative. The thermosetting resin cures fully with the heat, and after the press plate was lifted, the finished board could be pulled out like a pizza out of an oven.

We made boards at a range of resin contents, starting at 11%, and working our way down to 1%. Two furnishes were used; unscreened and screened milled straw, both from North Dakota wheat straw hammer milled at the ICI facility. The average length of the readily visible straw pieces was .25" for the unscreened, and somewhat greater for the screened. The unscreened material contained many fine bits (see photos 7 and 8). Density was varied from 4 to 15 pounds per cubic foot.

In general we made three boards of a given type (density, resin percent, and furnish type), so that we could find a variance, to give some statistical meaning to the results. The most consistent data set is for 10 pcf boards; in addition we were able to make good boards at 8 pcf, but the board at 4 pcf fell apart as it came out of the oven, and boards at 6 pcf were very fragile. We also made boards at 12 and 15 pcf. There are about ten sets of three, one set of two, and several single boards, as shown in table 11.

At least part of the reason that the low density boards did not hold together well is that the furnish with the uncured resin has a settled density of around 5 pcf, so when enough material is placed in the mold to produce a 6 pcf board, there is very little compression in the press, and the top platen has poor contact with the mat. The screened furnish had a lower settled density, as the fines were eliminated, and did make a somewhat better 6 pcf board.

A related problem occurred with the 4" thick board that we made at 10 pcf and 2% resin. In this case the interior of the board was crumbly, even after 20 minutes press time. Presumably the board insulated well enough that the platen heat did not penetrate well to the inner region.

The boards were trimmed on a table saw to 15" X 25", the size of our conductivity tester, and shipped to MIT for testing. Photos 9 and 10 show the surface and the edges of two boards, one at the high end of our density range, and one at the low end.

B. MDI Test Results

We measured the thickness and performed a thermal test on all boards as described above. Temperature readings from the top plate, bottom plate, and screen heater, were entered into a spreadsheet which calculated thermal resistivity and cost per insulating unit. Examples of these data sheets are shown in the appendix. Materials costs were based on the Pakistani straw price of 5.3¢ per pound, and the international MDI price of $1.00 per pound for the heat cured resin. The cost figures in the tables reflect only materials: the costs of labor, equipment, etc., are not included.

ICI #	nominal density pcf	MDI %	straw type	actual density pcf	R/inch hr-ft2-F/ Btu-in	10% compress psi	20% compress psi	modulus rupture psi	cost cents/ R-ft2	qualitative structural assessment
52-B	15	2	screen	14.29	2.92	45.9	99.8	276.2	4.35 (2.93)	excellent
45-Q	15	1	unscr	13.97	2.83				2.57	excellent
45-G	12	4	unscr	11.72	3.20				2.77	excellent
45-H	12	4	unscr	11.55	3.21	23.2	50.1	149.1	2.72	excellent
45-M	12	4	unscr	11.72	3.15				2.82	excellent
52-A	12	2	screen	11.25	3.24	23.7	46.7	326.9	3.09 (2.08)	excellent
42-A	10	11	unscr	9.89	3.43				3.78	good
42-B	10	11	unscr	9.97	3.48				3.75	good
42-C	10	11	unscr	10.08	3.40				3.88	good
42-D	10	11	unscr	9.75	3.50	10.4	21.1	54.5	3.65	good
42-G	10	8	unscr	10.14	3.51				3.10	good
42-H	10	8	unscr	9.70	3.36	14.4	28.8	48.1	3.09	good
42-I	10	8	unscr	9.92	3.39				3.14	good
42-L	10	6	unscr	9.70	3.30				2.69	good
42-M	10	6	unscr	9.96	3.48	25.8	40.7		2.62	good
42-N	10	6	unscr	9.70	3.38				2.63	good
45-A	10	4	unscr	9.75	3.41	17.4	33.6	62.5	2.17	good
45-B	10	4	unscr	9.47	3.45				2.08	good
45-C	10	4	unscr	9.50	3.49				2.06	good
45-I	10	2	unscr	9.80	3.48	14.4	33.6	38.6	1.69	good
45-J	10	2	unscr	9.37	3.46				1.63	good
45-K	10	2	unscr	9.47	3.50				1.62	good
45-R	10	2	screen	9.50	3.32				2.55 (1.72)	good
45-S	10	2	screen	9.57	3.29	17.0	38.0	71	2.59 (1.75)	good
45-T	10	2	screen	9.50	3.40				2.48 (1.67)	good
45-N	10	1	unscr	9.42	3.43				1.43	fair
45-O	10	1	unscr	9.33	3.49				1.39	fair
45-P	10	1	unscr	9.59	3.42	10.4	26.7	19.4	1.46	fair
42-J	8	8	unscr	7.61	3.59	6.9	14.2	16.3	2.27	fair +
42-K	8	8	unscr	8.24	3.82				2.32	fair +
42-O	8	6	unscr	8.32	3.80				2.00	fair +
45-D	8	4	unscr	7.75	3.69	6.3	13.6	8.2	1.59	fair
45-E	8	4	unscr	8.04	3.68				1.66	fair
45-F	8	4	unscr	7.45	3.64				1.55	fair
45-L	8	2	unscr	7.89	3.68	4.2	10.9	10.1	1.29	fair
45-U	8	2	screen	7.75	3.63	8.1	18.2	18.2	1.90 (1.28)	good -
45-V	8	2	screen	7.59	3.54				1.91 (1.29)	fair +
45-W	8	2	screen	7.55	3.62				1.85 (1.25)	fair +
52-C	7	2	screen	5.65	3.81				1.32 (.89)	poor
42-F	6	11	unscr	5.78	3.65				2.08	poor
45-X	6	2	screen	5.97	3.71				1.43 (.96)	poor
42-E	4	11	unscr							bad

Table 11. Basic Data for Individual ICI Boards

We then selected one board from each group of three for structural tests. Although the larger data base gained from testing all the boards structurally would be preferable for accuracy of results, we chose to retain two boards from each group for repeated thermal tests, if required.

We then selected one board from each group of three for structural tests. Although the larger data base gained from testing all the boards structurally would be preferable for accuracy of results, we chose to retain two boards from each group for repeated thermal tests, if required.

Three compression and four bending tests were made on pieces cut from each board selected for structural tests. Two of the structural data sheets are shown in the appendix. Data from these sheets are gathered in table 12 which shows the mean values and standard deviations, as a percentage of the mean, for each sample board. The 20% compression values are very nearly twice as much as the 10% values: this shows that the straw boards are still in their elastic range, where compression is proportional to force, and the board should spring back when force is released. This is also shown by the straight line region on the plots on the structural data sheets, which indicate that the elastic range of the boards extends to about 30% compression. In fact the boards returned to about 90% of their pre-test thickness, but this was after being crushed somewhat more than 30%.

We also tested samples from five commonly used insulation boards for comparison as shown in table 12. For two of the compression tests we only had enough material for one test, so there is no standard deviation shown. We were unable to perform bending tests on fiberglass and wood fiber boards for the same reason. Thermal values for all five of these comparison boards were taken from the ASHRAE Handbook of Fundamentals.

Results for the straw board compression tests were fairly consistent, with average standard deviations of 16% and 13% of the mean values. The deviations can be explained by local variations in density resulting from the manual lay out of the mat, and by the fact that it was difficult to take the readings with high precision (it was hard to read the force and position guages at exactly the same moment). The bending tests show larger standard deviations, with a 35% average. Examination of the bent samples showed, in some cases, a plane of cleavage or area of poor adhesion, which caused rapid failure in bending. Using wider samples, or a greater number of samples, in the bending tests would minimize the effect of these local weak spots, and produce more consistent results. However the data should indicate general trends.

Structural and thermal results are collected in Table 11, which shows the basic data for all the individual boards. The ICI number is the identification number recorded in the lab notebooks at the ICI laboratory. The nominal density, resin percent, and furnish type are the variables in the fabrication. The nominal density was the intended straw density, and was used to determine the quantity of furnish for each board. The actual density was somewhat different due to losses, variations in thickness, etc., and was determined at MIT by measuring dimensions and weighing. In the cost per insulating unit column, for those boards made with screened furnish, the first number is cost assuming the 40% fines have no value, and can only be discarded; the second number in parentheses assumes the fines could be sold for the same price as the original straw.

The last column in table 11 shows a qualitative assessment of the overall strength of the boards, using the same categories as were used for the earlier boards made at MIT. Generally speaking the strength follows density; the 12 and 15 pcf boards are strong enough for trial installation, and the 10 pcf boards are nearly so, although further tests and refinements are needed. The 8 pcf boards in general need some structural improvement to be usable, and the 6 pcf boards would need major reinforcement.

ICI #	nominal density pcf	resin %	straw type	mean 10% comp psi	standard deviation %	mean 20% comp psi	standard deviation %	mean modulus rupture psi	standard deviation %
52-B	15	2	screen	45.9	12%	99.8	4%	276.2	6%
45-H	12	4	unscr	23.2	20%	50.1	14%	149.1	24%
52-A	12	2	screen	23.7	11%	46.7	10%	326.9	128%
42-D	10	11	unscr	10.4	8%	21.1	7%	54.5	20%
42-H	10	8	unscr	14.4	36%	28.8	29%	48.1	77%
42-M	10	6	unscr	25.8		40.7			
45-A	10	4	unscr	17.4	5%	33.6	2%	62.5	34%
45-I	10	2	unscr	14.4	16%	33.6	11%	38.6	21%
45-S	10	2	screen	17.0	4%	38.0	5%	71.0	12%
45-P	10	1	unscr	10.4	35%	26.7	30%	19.4	47%
42-J	8	8	unscr	6.9	16%	14.2	11%	16.3	11%
45-D	8	4	unscr	6.3	19%	13.6	21%	8.2	29%
45-L	´8	2	unscr	4.2	13%	10.9	13%	10.1	15%
45-U	8	2	screen	8.1	16%	18.2	15%	18.2	30%
			average standard deviation		16%		13%		35%
other boards			density pcf						
wood insulation board			16.6	13.1		41.2			
rigid fiberglass			5	1.6		2.7			
polyisocyanurate			2	16.6	15%	26.3	1%	50.3	19%
extruded polystyrene			2	36.9	2%	40.2	1%	68.6	6%
expanded polystyrene			1	4.6	31%	10.8	6%	20.9	4%

Table 12. ICI Board Structural Data

Table 13 shows all the different kinds of boards made, where data for the sets of three boards have been condensed into one group entry. In this case the means of actual density, thermal resistivity, and cost are means of the values for the three boards in the group. The mean structural values are means for the three or four pieces cut from one of the boards in the group. Also shown are test results for boards where there was only one board in the category. For example, we only made one board at 8 pcf, 2% resin, and with unscreened furnish (45-L). We tested this board thermally, and the single data point is shown in table 13, but this number does not have the same reliability as the group R values, where three points have been averaged. However in the interest of gaining a quick sense of trends in the data, all points in table 13 have been treated with equal weight. Further research could focus on areas of interest with more thorough testing.

Group #	nominal density pcf	MDI %	furnish type	mean actual density pcf	mean R/inch (Btu-in/ hrft^{2}F)$^{-1}$	st.dev. R/inch %	mean 10% comp psi	mean 20% comp psi	mean modulus rupture psi	mean cost cents/ R-ft^2
52-B	15	2	screen	14.29	2.92		45.9	99.8	276.2	4.35 (2.93)
45-Q	15	1	unscr	13.97	2.83					2.57
45-Hgroup	12	4	unscr	11.66	3.19	1.11%	23.2	50.1	149.1	2.77
52-A	12	2	screen	11.25	3.24		23.7	46.7	326.9	3.09 (2.08)
42-Dgroup	10	11	unscr	9.92	3.45	1.30%	10.4	21.1	54.5	3.77
42-Hgroup	10	8	unscr	9.92	3.42	2.24%	14.4	28.8	48.1	3.11
42-Mgroup	10	6	unscr	9.79	3.39	2.73%				2.65
45-Agroup	10	4	unscr	9.57	3.45	1.27%	17.4	33.6	62.5	2.10
45-Igroup	10	2	unscr	9.55	3.48	0.62%	14.4	33.6	38.6	1.65
45-Sgroup	10	2	screen	9.53	3.34	1.87%	17.0	38.0	71.0	2.54 (1.71)
45-Pgroup	10	1	unscr	9.45	3.45	1.03%	10.4	26.7	19.4	1.43
42-Jgroup	8	8	unscr	7.92	3.71		6.9	14.2	16.3	2.29
42-O	8	6	unscr	8.32	3.80					2.00
45-Dgroup	8	4	unscr	7.74	3.67	0.78%	6.3	13.6	8.2	1.60
45-L	8	2	unscr	7.89	3.68		4.2	10.9	10.1	1.29
45-Ugroup	8	2	screen	7.63	3.60	1.47%	8.1	18.2	18.2	1.89 (1.27)
52-C	7	2	screen	5.65	3.81					1.32 (0.89)
42-F	6	11	unscr	5.78	3.65					2.08
45-X	6	2	screen	5.97	3.71					1.43 (0.96)
42-E	4	11	unscr							

Table 13. ICI Board Group Data

The standard deviation in R value measurement for the three boards in each group was extremely low, averaging 1.4% of the mean. This suggests both that the boards are thermally consistent, and that the accuracy of our test apparatus in comparing two samples (rather than finding an absolute value) is better than the 5% calculated above.

Table 13 is the basis of all the plots that follow.

The general method in data analysis was to plot one of the measured quantities (thermal resistance, compressive strength, modulus of rupture) against one of the variables (density, resin content, furnish type). We used actual measured density for all plots, which was slightly lower than the nominal density. In some graphs values for other insulation boards are shown with the straw values.

Figure 9 shows the R value, which in this case is R per inch or thermal resistivity in (Btu-in/hr-ft^2-°F)$^{-1}$, as a function of resin content, for various densities. Resin in the 1-11% range, which has coated the straw surfaces, clearly does not influence thermal properties. The resin does not create significant additional paths for heat conduction. We can therefore increase resin content to strengthen the boards, within cost constraints.

Figure 10 compares the insulating performance of the screened and the unscreened straw furnishes, for the various density ranges. Removing the fine particles has only had a small thermal effect, and the direction of the effect is unclear. For 6, 12 and 15 pcf boards, the screened straw insulates slightly better than the unscreened. For 8 and 10 pcf samples, the reverse is true. However in this case the 8 and 10 pcf results are the averages of several data points, and are therefore more reliable than the higher and lower density numbers, which come from very few points. This result should be compared with the tests we ran on loose fill straw of various grinds, described in chapter II. In that case, at 5-6 pcf, the unscreened material was significantly more resistive than the screened. The bulk of the evidence therefore is that there is a modest increase in insulative value for material containing the fines, on the order of several percent. As this is a key design parameter, further tests are called for. Perhaps the fines reduce radiative transfer but increase solid conduction, so that the net effect is small, certainly much smaller than the effect of density as shown below.

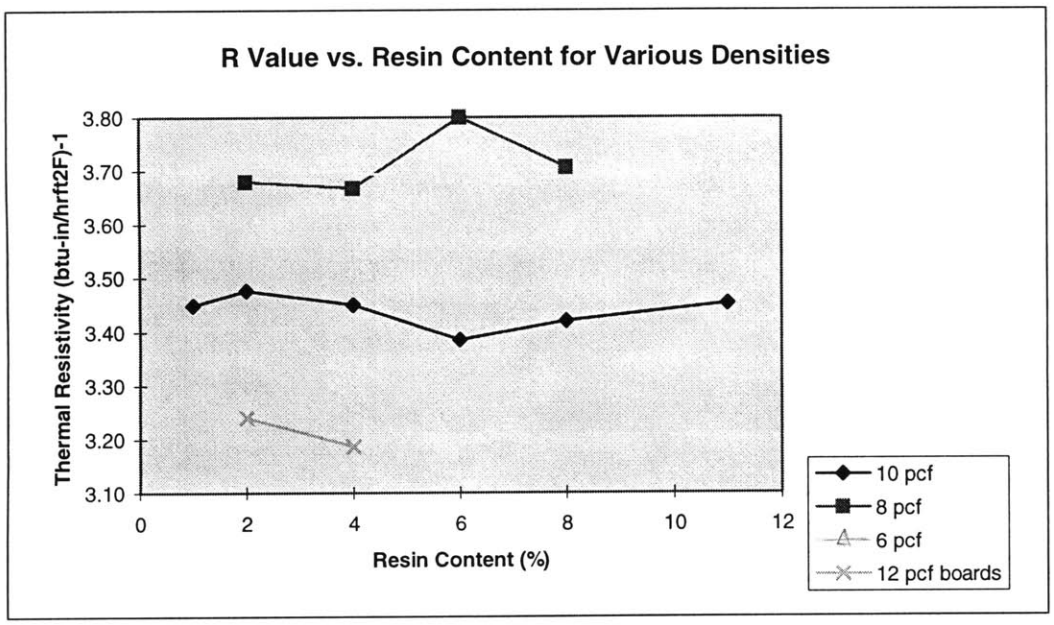

Figure 9. R Value vs. Resin Content for Various Densities

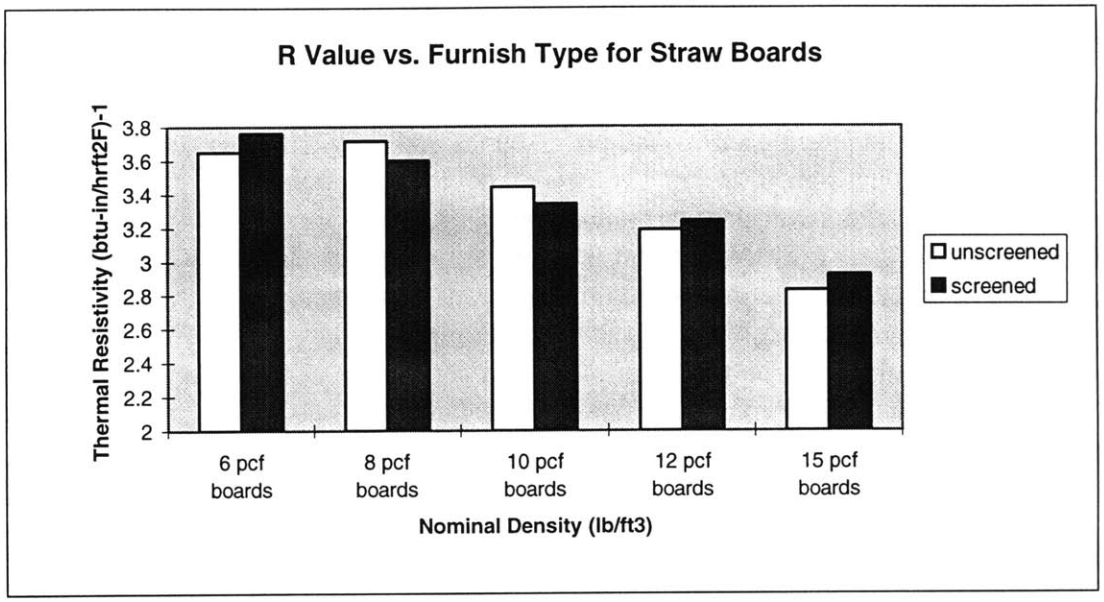

Figure 10. R Value vs. Furnish Type

In figure 11 resistivity is graphed against density, where different resin contents and furnish types are all included, as these two variables have, as shown, little effect. The density has, of course, a strong effect on the thermal conductivity. Values for other kinds of insulation board are also shown in the figure.

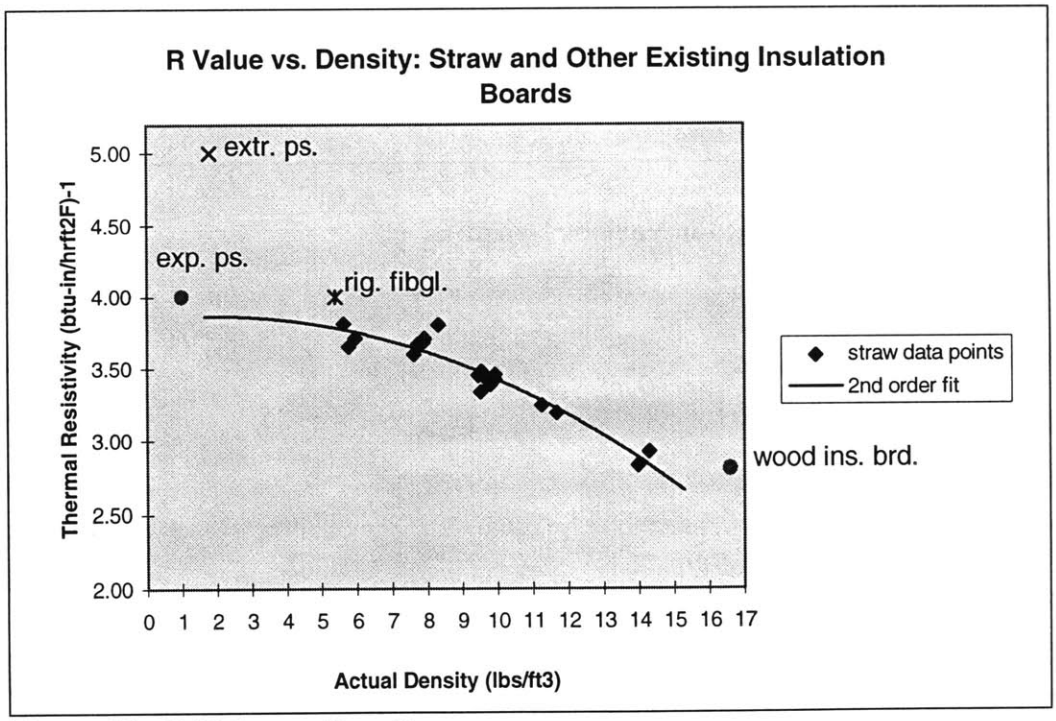

Figure 11. R Value vs. Density

As density rises, conduction through the solid straw pieces becomes greater as conduction through the entrapped air decreases. We do not have a measurement of solid straw conductivity, however we can look at other lignocellulosic materials, such as wood. The thermal resistivity of softwood in the 30 pcf range is R1.4/inch perpendicular to the grain, and R.6/inch parallel to the grain (ASHRAE 1981). We never see straw in a form this dense, as it grows in slender, hollow stalks, but the base material should have a resistivity in this range. This is much less than the R5.4/inch of still air. So we expect the lower densities to insulate better, up to the point at which pore size becomes so great that convection occurs. At low densities radiation may also become important. From figure 11, this must be at a point lower than 6 pcf.

Any of these boards insulate well enough to improve living conditions in Pakistan. For a given material we wish to maximize the R value both to make the installed board less bulky, and to cut cost per insulating unit. Since polystyrene at R4 per inch is available, we would like to at least approach that value, although cost is more important than the R per inch. At densities above 10 pcf, thermal qualities drop off, and more straw is required, driving cost up. However less resin is needed, so boards 45-Q and 45-H group show excellent structure at less than 3¢ per unit insulation. It is unclear whether or not we should recommend use of insulations in the R2.9 to 3.2 per inch range.

An important question then is whether on not the 8-10 pcf density boards are strong enough, or can be made strong enough. Figure 12 shows compressive strength versus resin content for unscreened straw boards. The flat curves show little correlation. We assume that the resin helps hold things together when pulled apart, but does not make them stronger when crushed. In figure 13 the compressive strength of screened and unscreened boards is contrasted for the 2% resin content. We can conclude that removing the fines improves compressive strength significantly. In these cases the gain was on the order of 20% for the 10 pcf boards, and by nearly a factor of two for the 8 pcf boards. This corresponds with the advice of the ICI chemists, who had found that the fines, which represent a large surface area, soak up the resin, and prevent it from binding the larger pieces. Their clients therefore screen the straw for the higher density straw particle board that they make.

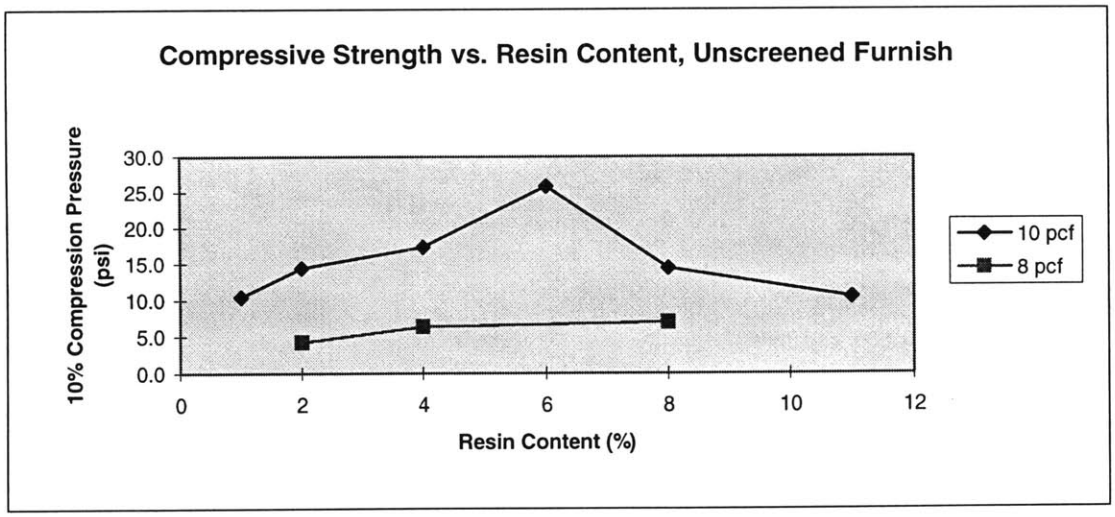

Figure 12. Compressive Strength vs. Resin Content

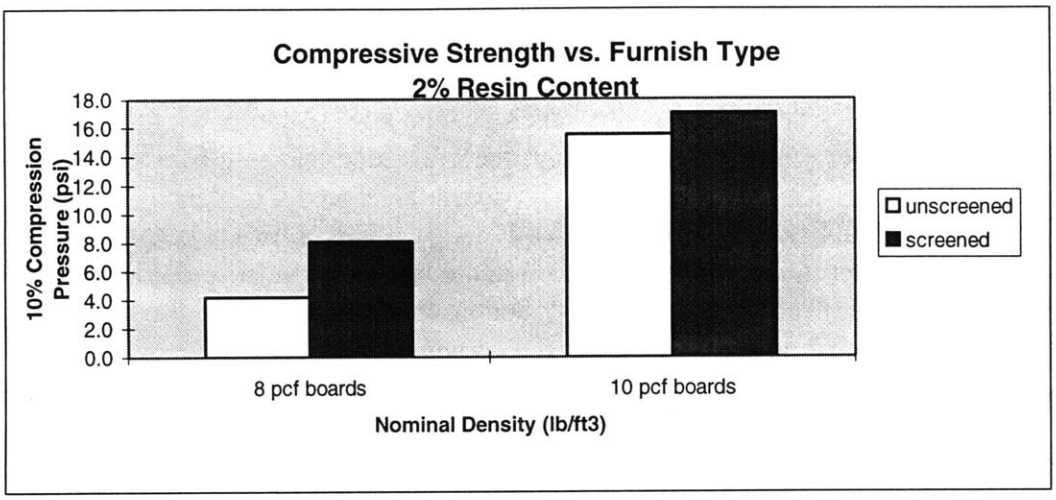

Figure 13. Compressive Strength vs. Furnish Type

Figure 14 shows compressive strength as a function of density for unscreened boards at all resin contents. Included are points for the five other kinds of board that we tested. Compressive strength is a very strong function of density, although it is not clear from this data what sort of function. A linear fit is possible for the points shown. If compressive strength goes to 0 at density equal to 0 pcf, then a power fit is more reasonable.

Also evident from figure 14 is the fact that even our 8 pcf boards, at 4-8 psi, have greater strength in compression than such widely used boards such as expanded polystyrene (4.6 psi) and rigid fiberglass (1.6 psi). Although we foresee the straw boards being most often used with a plaster finish, the material may be durable enough to place on a wall with minimal covering.

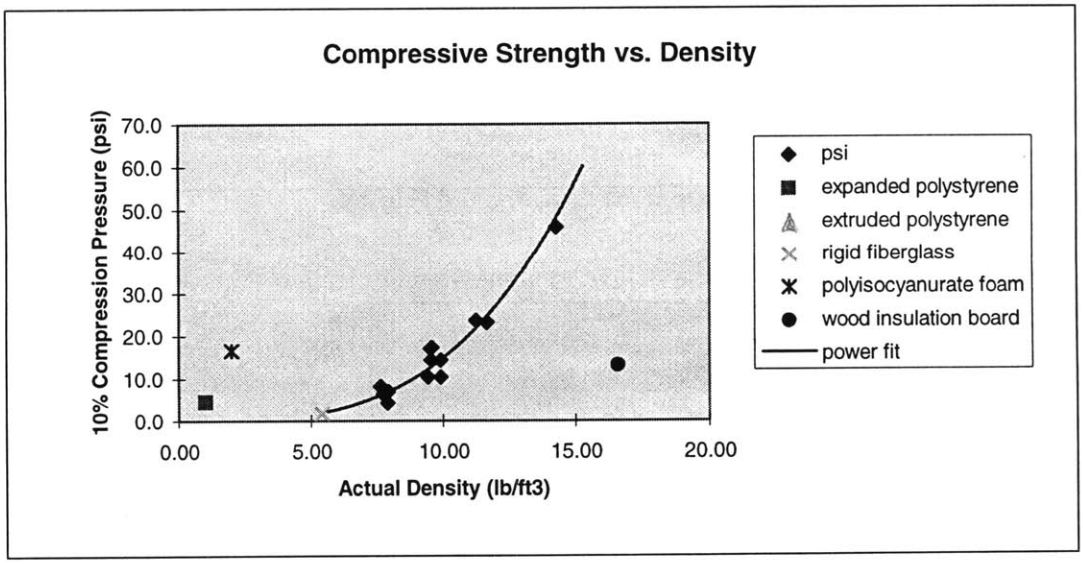

Figure 14. Compressive Strength vs. Density

The strength of the boards in bending, which involves compression on one face, and tension on the other, should be a more meaningful structural criterion for our purposes, giving a

sense of how well the boards can span studs or rafters, and how easily they can be carried. Figure 15 shows the impact of MDI resin percent on the modulus of rupture (MOR), which is a measure of bending strength, for the unscreened boards in two density ranges. We expect to see a positive correlation, as the resin should increase tensile strength which figures in bending, and in the data we see an erratic but definite enhancement of board strength with rising resin amount. This may be a case where the relatively few number of data points, and the large deviations in the bending data, make the results unclear. The effect might be more obvious in the case of the screened furnish, however in a given density range we only have one screened board type, and so can not examine the effect.

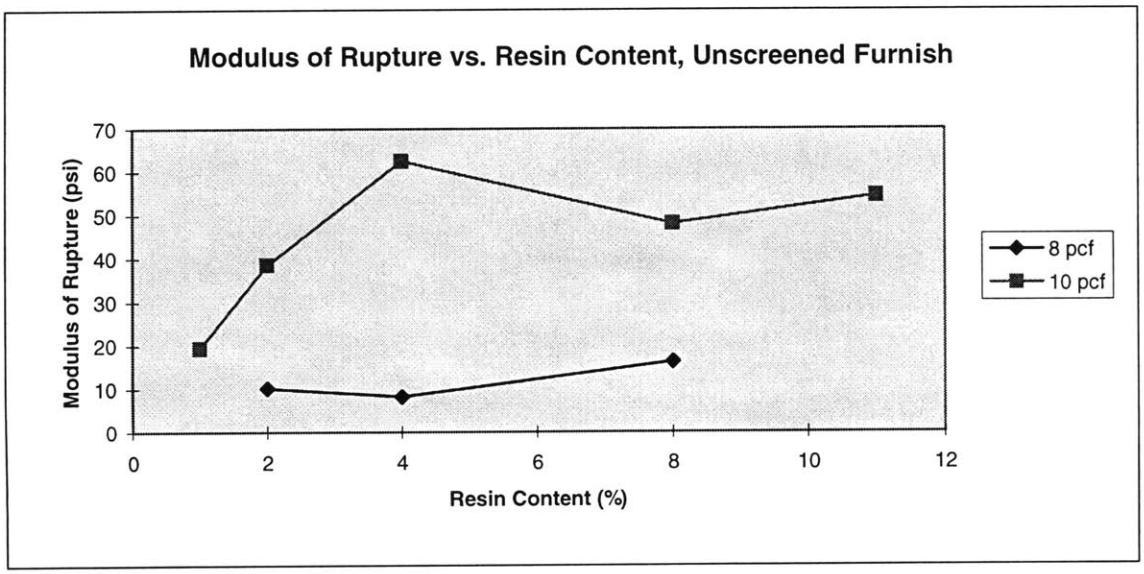

Figure 15. Modulus of Rupture vs. Resin Content

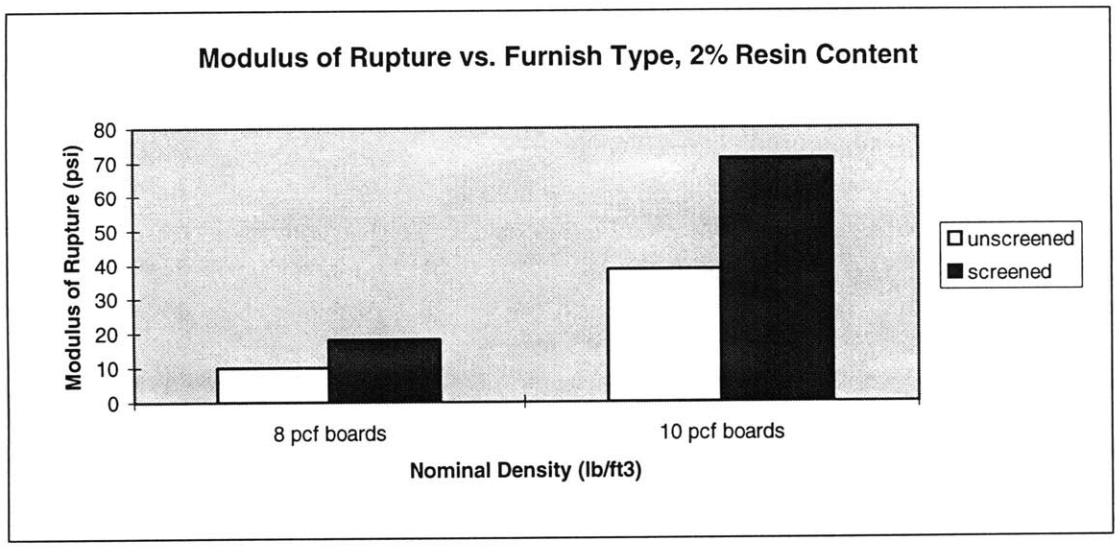

Figure 16. Modulus of Rupture vs. Furnish Type

From figure 16 it is apparent that screening the straw furnish has a major impact on bending strength, presumably for the same reasons cited above in regard to compression: the resin binds more effectively when the fines are removed. Bending is also a strong function of density as shown in figures 16 and 17. This makes sense given that there is a strong increase in compressive strength with density; and we assume that tensile strength also increases with rising density.

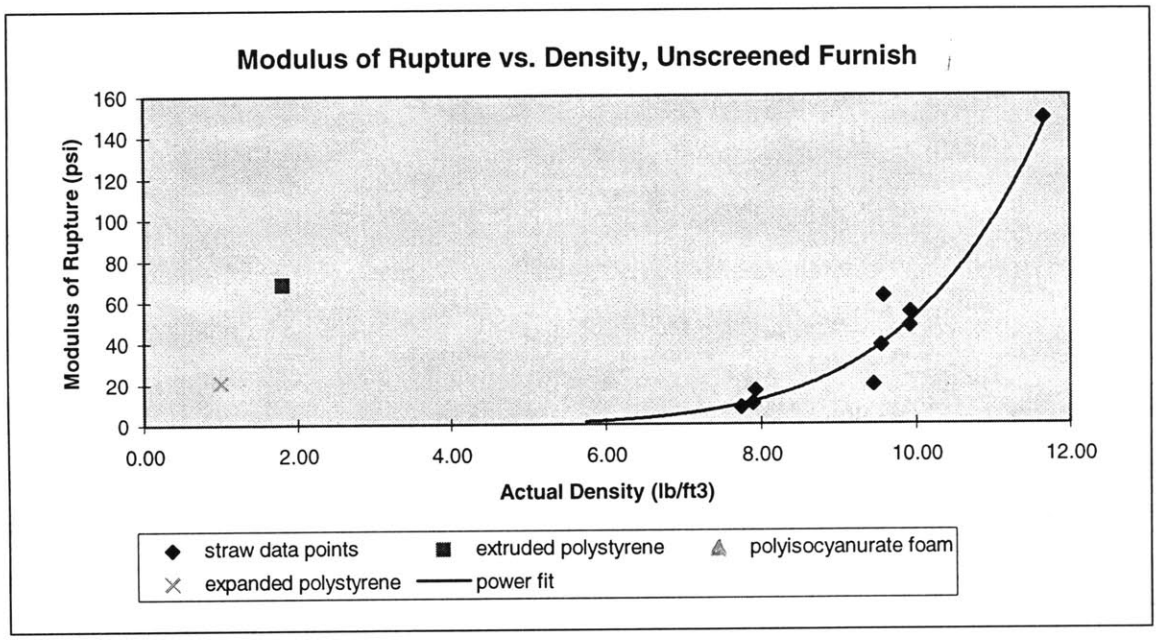

Figure 17. Modulus of Rupture vs. Density

From the foamed polymer insulation board points also shown in figure 17 we see the virtue of the plastics in giving good structural properties at low densities. However this also shows that a common, useful board such as expanded polystyrene, only has a MOR of 21 psi. Our 10 pcf boards are stronger than that, with the exception of those made at 1% resin content. Extruded polystyrene, which has remarkable structural properties and is used in forming concrete foundations, and under footings, only has a MOR of 69, which we achieved with screened furnish in a 10 pcf board. On the other hand, the foamed plastic boards are clearly superior to the straw boards in resisting flaking or dog-earing. We observed considerable degradation of this sort just in the course of moving our straw boards about the lab. This could be quantified in further work by measuring impact strength.

The final graph of the data in figure 18 shows cost versus density for various levels of resin content, in unscreened furnish. Since density is the primary determinant of both thermal and structural performance, this plot provides a neat summary of the boards. So far we have only achieved acceptable structure in boards of 10 pcf or greater. We have no exact target for thermal performance, other than to maximize it, which means using as low a density as possible. We may take 2¢/R-ft^2 as a rough upper limit for materials cost, so that with the added expense of labor, overhead, retail markup, etc., the boards can still cost less than the polystyrene currently available for 6¢/R-ft^2. Figure 16 then defines an operating range, which would be a narrow rectangular region in the center bottom of the plot. Three of our current boards fall into that region, although the 10 pcf boards at 1% resin are structurally unacceptable (by inspection, and as shown by the

low MOR of 19 psi). Ten pcf boards at 2 or 4% resin (groups 45-A and 45-I) meet the cost criteria, have moderate thermal performance, and are strong enough, or could be made so with minor improvement.

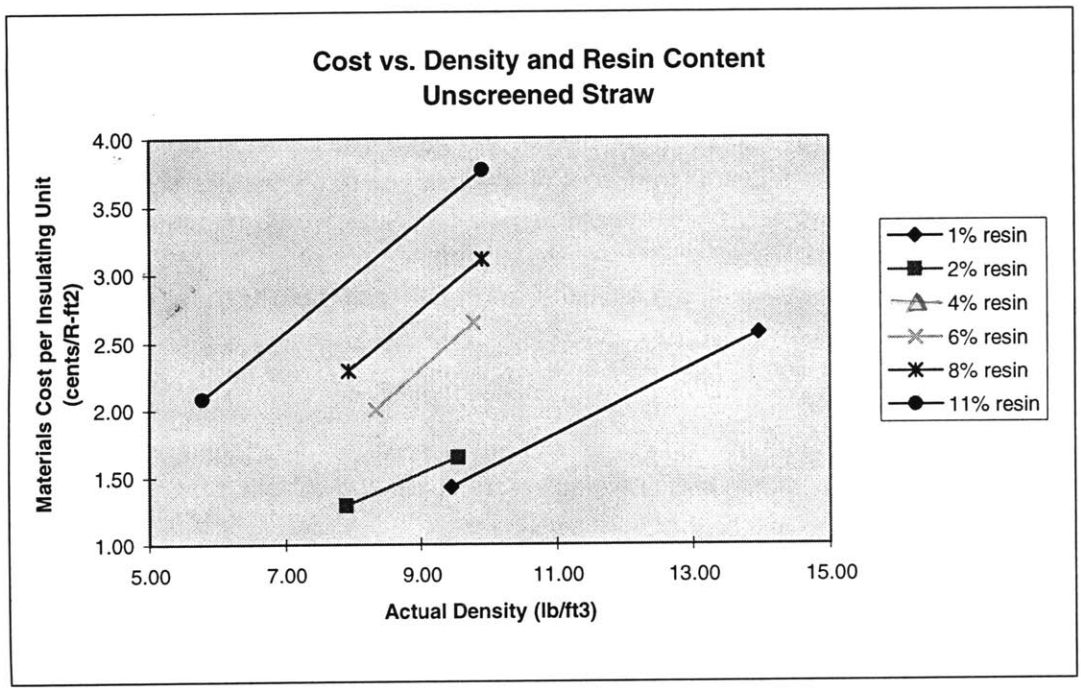

Figure 18. Cost vs. Density for Straw Boards

If better thermal performance were desired, we could push the envelope of that operating range by going to 8 pcf boards with either screened furnish, or higher resin content. Figure 18 does not show the additional variable of screening the furnish, which may increase straw costs and therefore unit insulation costs, depending on whether or not the fines can be sold. However we can see in table 13 that an 8 pcf, 2% resin, screened board (45-U group) would cost 1.9¢ per insulating unit if the fines are discarded, and 1.3¢ if the fines have value; both figures being within our cost target. These boards are almost strong enough to use, with a MOR of 18 psi. On the other hand, an 8pcf, 8% resin, unscreened board costs 2.3¢ per unit (42-J group in table 13), and has a MOR of 16 psi. These boards are also not quite acceptable structurally. From the 11% curve in figure 18 we see that an 8 pcf, 11% resin, unscreened board would cost about 3¢ per unit, and would probably still not be strong enough. From these cost and modulus of rupture numbers, it is apparent that we can get more structural improvement per dollar spent by screening the straw than by increasing resin load. However we would like to ascertain the extent of the thermal penalty that is incurred by removing the fines.

If superior mechanical characteristics were the top priority, we could operate at 10 pcf density but upgrade to screened straw (as in the 45-S group in table 13). These boards have an excellent 71 psi MOR, and reasonable cost, at 2.5¢ (or 1.7¢) per unit, but lowered R3.3 per inch resistance. Presumably the 40% fines removed from the straw would find use as fuel, soil additive, etc. The cost for the screened boards may therefore be closer to the lower figure given in parentheses in tables 11 and 13.

V. Conclusions

This development process is far from complete, but we have made good progress. With the help of ICI personnel, and the use of their facility, we were able to make low cost straw insulation boards with modest thermal and structural attributes, using MDI resin. The lowest density we achieved, with acceptable strength, was ten pounds per cubic foot. If the author of this thesis had to make insulation boards in Pakistan next week, he would make MDI boards at 10 pcf density, 4% resin content, using unscreened straw as received from the thresher. These boards would have an R value of 3.5 per inch, a modulus of rupture of 60 psi, and the straw and resin going into them would cost 2¢ per R-ft^2. A tumbler, spray apparatus, and hot press would be required. The boards could be attached to the interior of walls and roofs with screws or nails, and plastered. Although this product should perform well, and is ready for small scale field testing, it is likely that with further work even better boards will be created.

After our experience with the MDI boards, it is apparent that in our earlier work with pulping and water soluble glues we were trying to work at too low a density. We did not succeed in making a sound, cost-effective board with PVA or sodium silicate, or by alkaline soaking, in the 5-6 pcf range, but it would be worth repeating these efforts in the 10 pcf range, where it should be possible to use much less adhesive. Sodium silicate, in particular, is still a promising candidate because it is noncombustible, unattractive to microorganisms, inexpensive, and the raw materials are widely available. Although it does not have tremendous adhesive power in comparison to other glues, it would probably be sufficient at a higher density, and with better technique.

Making strong boards at lower densities with straw and other fibrous materials will be feasible, as our understanding of the bonding mechanism grows. This is demonstrated by the 6 pcf recycled paper board recently developed in Germany (Homann Dammstoffwerk 1996), which uses pulping by-products as adhesives, and jute fibers as reinforcements.

In our case, we know from the microscope that the adhesive in our earlier efforts was not fully exploited. More efficient glue use could be achieved by the same methods used at the ICI research facility, namely 1) better mixing action, requiring at least a rudimentary tumbler or blender with spray capability, 2) faster drying, probably by heat, as solvents are too expensive, and 3) pressure during setting. All three of these run counter to the goals of low density and low embodied energy that we set at the start, but it appears we can still make a useful product if these requirements are relaxed somewhat.

An adhesive that penetrates the straw well enough to grab without high pressure, but still remains sufficiently thick on the surface to attach to other surfaces, should permit low density, structurally adequate boards to be made. This is presumably how the MDI operates.

The following topics could be productively pursued.

- Find more historical information. The Bodite, balsam wool, hair felt, etc. processes mentioned in chapter I could represent cost-effective methods for making low density insulation boards. Knowledge of them might hasten product development.
- In further trials with PVA and sodium silicate, examine the benefit of higher densities (6-10 pcf), heat for more rapid setting, better foaming and spraying techniques, and the use of additives such as surfactants, fillers and plasticizers (for this, advice is needed from industry practitioners). It would be best to try these water soluble glues in a tumbler with spray head for better distribution, which could permit lower glue amounts to be used.

- Reinforce the boards with fine jute, hair, glass or plastic fibers, etc.
- Obtain pulping by-products such as Tall oil and test for binding properties. The manufacturers of Homatherm might be willing to advise.
- Make pulped wet process boards, starting with hammer-milled particles. Examine the difference between those made at room temperature, those heated to the boiling point of water, and those heated to the softening point of lignin. Determine feasibility of making the boards at 10 pcf or lower. Estimate the cost of the equipment, water, and energy. If necessary try adding a small amount of disk refined pulp, which could come from waste paper. This could perhaps be best accomplished by one of the six US producers of wood insulation board.
- In the case of chemical pulping, look at lime and wood ash as low cost sources of alkali.
- For MDI boards, attempt to achieve adequate strength in the 6-8 pcf range. One place to begin is with 6 and 8 pcf boards made from screened furnish. These showed promise in our tests; perhaps with greater resin loading, or filament reinforcement, they would work. For the 10 pcf boards, start testing water, fire and rot resistance, and try adding boric acid as a biocide and fire retardant. Test volatile emissions.
- Obtain asphalt powder or emulsion, and wax, and test in straw boards. This should confer moisture resistance and improve strength.
- Develop heat transfer model. Determine density of the solid straw using a pycnometer. Find the solid conductivity in a crushing cylinder with transient hot wire method. Measure radiative properties, and model the morphology of the straw boards.

As we develop boards with acceptable insulative and mechanical properties, by whatever method, other parameters, such as volatile emissions, and resistance to water, biological agents, and fire, will have to be tested. We will also need tensile and impact strength tests for a more complete profile of structure. These will play an important role in determining possible applications for the boards, and in encouraging acceptance.

These boards, even the ones we have in hand, could provide substantial benefit to the economy and environment of Northern Pakistan in the immediate future. It would be appropriate to begin field testing now in houses or simple shelters, while further study and refinement goes on at MIT.

In the long term, the methods engendered in this work can be applied to materials other than straw, although straw is certainly of critical importance as it is found in quantity in many parts of the globe. The fundamentals of shredding, applying binder, and forming a strong porous sheet will be transferable, so that inexpensive, environmentally benign insulation can be made in all parts of the world-- rural, urban, developing or developed-- with whatever low-value materials are available. This could be significant in efforts to provide shelter, slow global warming, and alleviate pollution.

Acknowledgements

The author would like to thank Bill Newman and Joe Marcinko of ICI Polyurethanes' West Deptford, New Jersey, facility, as well as Tony Cunningham of ICI's Everburg, Belgium, headquarters, for their interest in the work and for providing facilities and support for making the MDI boards. Acknowledgement is also due to Peter Herriday and Bob Xavier of Northern Products of Woonsocket, Rhode Island, who gave advice and donated adhesives that we used in the

first part of the project. A number of other people were generous with their time and counsel over the telephone, including Lewis Wagner of the American Fiberboard Association, and Gary Myers and Charlie Vick of the Forest Products Laboratory.

Many thanks also to Professors Glicksman and Norford for their careful supervision of the work, for thoughtful critiques of the thesis, and for keeping the project on track.

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Photo 1. Pakistani Straw, Threshed

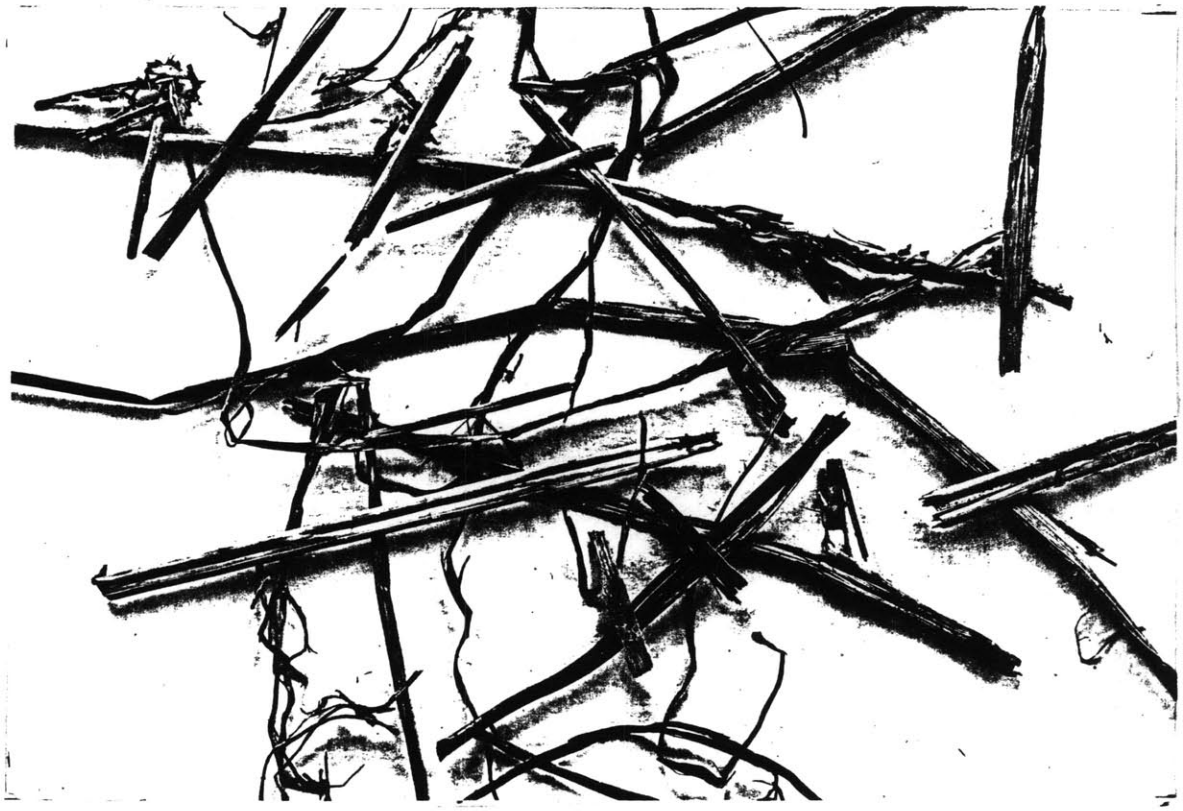


Photo 2. Whole Stalks, American Oat Straw

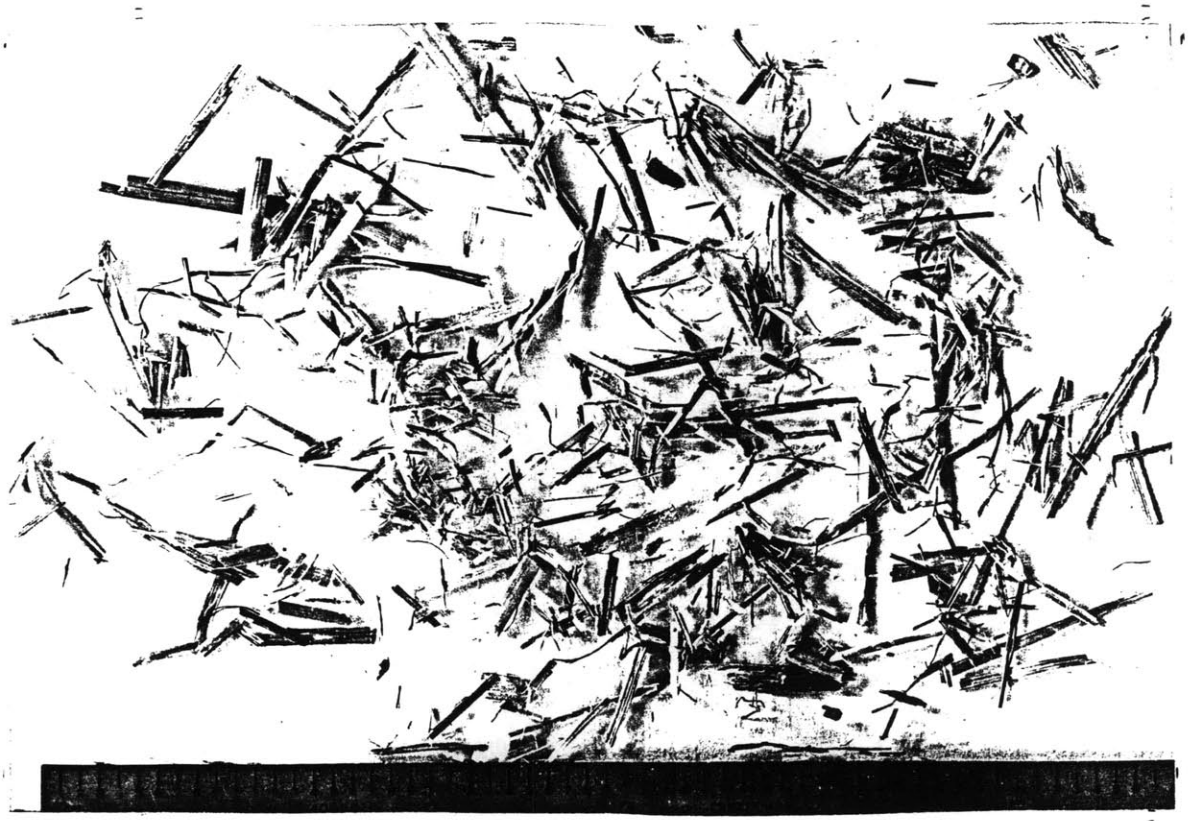


Photo 3. MIT Straw, Shredded, Unscreened

Photo 4. MIT Straw, Hammer-milled

Photo 5. MIT Straw, Shredded, Screened

Photo 6. MIT Straw, Fines

Photo 7. ICI Straw, Unscreened

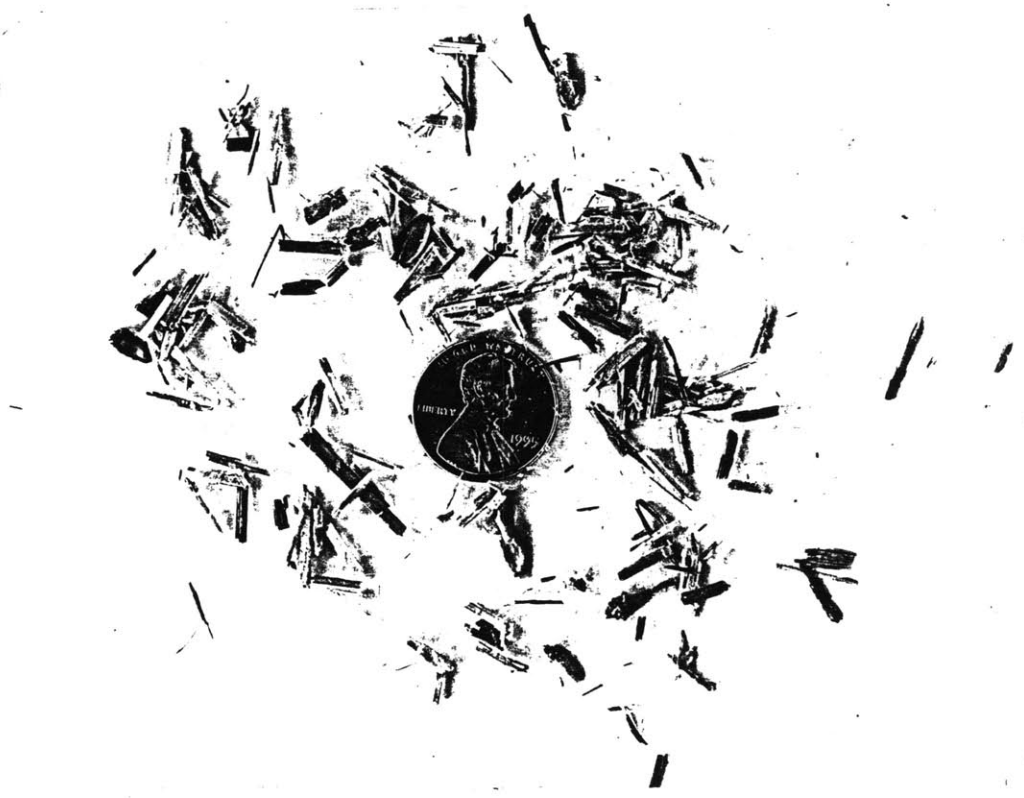
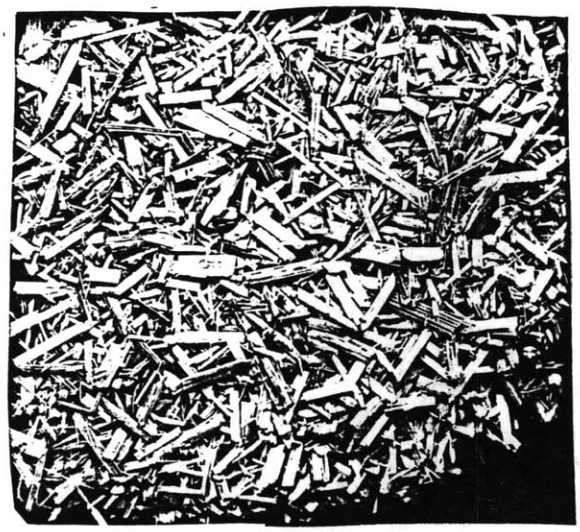
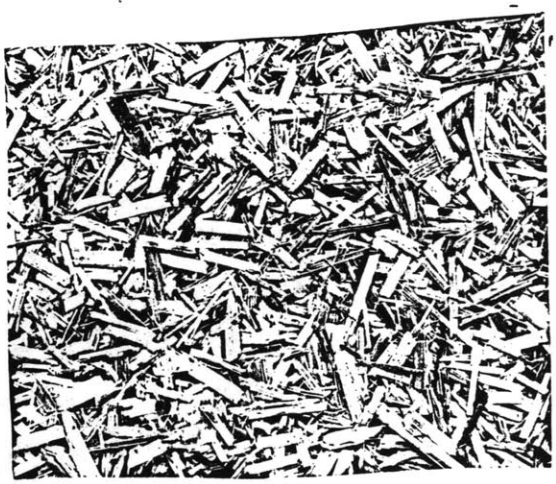


Photo 8. ICI Straw, Screened



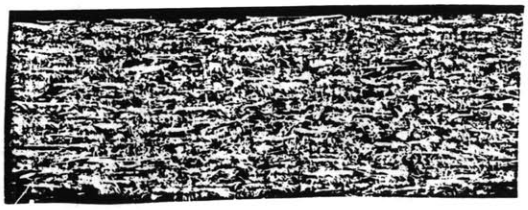
eight pound per cubic foot density



fifteen pound per cubic foot density

Photo 9. ICI Boards, Surface

eight pound per cubic foot density



fifteen pound per cubic foot density

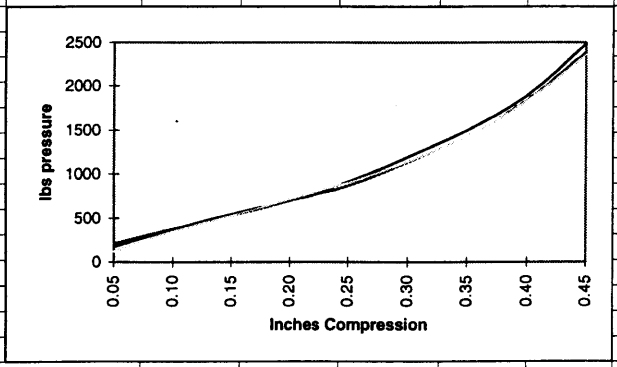
Photo 10. ICI Boards, Edge

Appendix

Sample Data Sheet
Structural Tests on ICI Board
7487-45A

7487-45A

	inches	force, pounds				thickness uncompressed						
	compression	sample #1	#2	#3			0.960	inches				
	0.05	170	205	120		Area	4.5	in.squared				
	0.10	370	380	345			20.25	sq. inches				
	0.15	545	525	525								
	0.20	705	695	710		comp-	interpolated values for pressure, psi					
	0.25	915	870	905		ression		sample number				
	0.30	1195	1135	1140			1	2	3	Mean	Std Dev	Std Dev
	0.35	1500	1430	1435		10%	17.6	18.2	16.3	17.4	1.0	5%
	0.40	1890	1840	1830		20%	34.2	33.0	33.7	33.6	0.6	2%
	0.45	2485	2390	2360								



Rupture

sample	rupture force		deflection	modulus of rupture			span	6	inches
	Newtons	pounds	mm	psi			width	2.75	inches
1	101.90	22.91	3.56	81.3			thickness	0.96	inches
2	99.73	22.42	3.12	79.6					
3	48.72	10.95	2.67	38.9					
4	62.82	14.12	2.66	50.1					
mean				62.5					
standard deviation				21.3					
st. dev. as percent				34%					

Appendix

Sample Data Sheet
Thermal Tests on ICI Board
7487-45A
(first page)

Foam is calibrated at R =		5.2	(hr ft^2 F/ Btu)/ inch				
Qtotal	21.13	Btu/Hr	q_{total}	8.89	Btu/Hr ft^2		
Qfoam	8.38	Btu/Hr	q_{foam}	3.53	Btu/Hr ft^2		
Qtop	12.75	Btu/Hr	q_{top}	5.37	Btu/Hr ft^2		
			$q_{top, measured}$		Btu/Hr ft^3		
Exper. Area	**2.376**	ft^2					
Experimental				**Control**			
Qtop	12.75	Btu/hr		Qfoam	8.4	Btu/hr	
L, top	0.960	inches		L, bottor	1.00	inch	
deltaT	**17.5**	F		**deltaT**	**18.3**	F	
R-panel	**3.27**	**hr sq.ft F/ Btu**		R	5.2	**(hr sq.ft F/ Btu)/ inch**	
R/inch	**3.41**	**(hr sq.ft F/ Btu)/ inch**					
k panel	0.29365846	btu-in/hr-ft2-F					
Cost	$/ft3	$/ft2 1" thick	cents/R-ft2		Estimated Overhead		
Straw	0.4959	0.04	1.21		as Percentage of Cost		
Resin, heat cure	0.3898	0.03	0.95		15%		
Subtotal Material 1a	0.8857	0.07	2.17				
					Margin Percentage		
Resin, air temp. cure	0.5848	0.05	1.43		30%		
Subtotal Material 1b	1.0806	0.09	2.64				
Overhead	0.1621	0.01	0.40		Retail Markup		
Cost Total	1.2427	0.10	3.04		20%		
Price	1.7753	0.15	4.34				
Sales Markup to Dealer	1.8464	0.15	4.52		Sales Markup		
Dealer Markup to Retail	2.2156	0.18	5.42		4%		
			$/lb				
Unit Cost of Straw - Northern Pakistan			$0.053	per pound			
Unit Cost of Straw - US			$0.053	per pound			
Unit Cost of Resin - Heat Cure			$1.000	per pound			
Unit Cost of Resin - Air Temp. Cure			$1.500	per pound			

Appendix

Sample Data Sheet
Thermal Tests on ICI Board
7487-45A
(second page)

Foam is calibrated at R =		5.2	(hr ft^2 F/ Btu)/ inch				
Qtotal	21.13	Btu/Hr	q_{total}	8.89	Btu/Hr ft^2		
Qfoam	8.38	Btu/Hr	q_{foam}	3.53	Btu/Hr ft^2		
Qtop	12.75	Btu/Hr	q_{top}	5.37	Btu/Hr ft^2		
			$q_{top, measured}$		Btu/Hr ft^3		
Exper. Area	**2.376**	ft^2					
Experimental				**Control**			
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L, top	0.960	inches		L, bottor	1.00	inch	
deltaT	**17.5**	F		**deltaT**	**18.3**	F	
R-panel	3.27	**hr sq.ft F/ Btu**		R	5.2	**(hr sq.ft F/ Btu)/ inch**	
R/inch	3.41	**(hr sq.ft F/ Btu)/ inch**					
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