Thermal Effects of Moisture in Rigid Insulation Board

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ABSTRACT

The impact of moisture in rigid roof insulation upon energy consumption is often assumed to be a simple function of the conductance. This paper will show that there are complex interactions between conductance, thermal mass, and climate. The energy performance can not be predicted from only the conductance. These results affect removal criteria for wet insulation board.

INTRODUCTION

The harmful effects of water inside of a roofing system can be broken down into two major categories: accelerated physical degradation and altered energy performance. This paper investigates the impact of differing levels of moisture in a roofing insulation system upon the energy performance of a commercial building. A special emphasis is placed on the performance of the system in warm climates. The results show that the energy performance is a complex interaction between thermal resistance, thermal mass, and climate. The data demonstrate that the energy impacts of roofing system moisture are not highly significant in warm climates. In fact, the annual cooling loads actually decrease with moisture added to the system.

The energy data have a significant implication for architects and other roofing professionals. Tobiasson and others have proposed a removal criteria for rigid insulation board based on the loss of thermal resistance[3,4]. They have generated relationships called wetting curves which relate the loss of thermal resistance to moisture content as a percentage of dry weight. They have proposed that when the thermal resistance is reduced to 80% of the dry resistance, the insulation should be removed. In other words an indirect measure of energy performance should act as the removal criteria rather than a direct measure of the amount of moisture in the insulation. The data presented in this paper shows that this removal criteria is invalid for warm climates.

THERMAL MODELING

Most of the simplified computer models in common use today can not demonstrate the interactions of conductivity, specific heat, and density of materials with sufficient flexibility. Most often these models only consider the thermal resistance of the materials with a fixed quantity of thermal mass. Water differs from other building materials in that it has 4 to 5 times the heat capacity (specific heat). This is primarily due to the weak molecular interactions between water molecules. To model these effects, the conductivity, density and specific heat of the wet insulation must be included in an hour-by-hour model which can access the dynamic behavior of buildings.

The computer simulation used for this study is titled Kelvin/295 and was programmed by the author of this paper. It is based on thermal algorithms written by Francisco Arumi-Noe, Ph.D., at the University of Texas at Austin. This program utilizes first principles of physics to calculate the thermal effects of conductance, specific heat capacity, and density of materials. The program uses an hour-by-hour methodology which allows a dynamic simulation of the external solar and air temperature and well as interior dynamic loads. The program has been validated by comparison to actual field data taken from NBS test cells[1].

For the purpose of this study, I have modeled a 10,000 square foot, single story, office building. The roofing system was composed of a built-up membrane on 2 inches of polyisocyanurate rigid insulation board supported by a steel deck. The exterior walls of the building were modeled as 3/4 inch stucco over 5/8 inch gypsum board on steel studs with R11 insulation and a 5/8 inch layer of interior gypsum board. The windows were single glazed and equally distributed on all four elevations. Glazed area was equivalent to 12% of the gross floor area.

The roof system was chosen due to the popularity of steel decks and polyisocyanurate insulation. The National Roofing Contractors Association, NRCA, does not recommend mopping a built-up roof directly to polyisocyanurate; however, this was a simplifying assumption for the purpose of this investigation[2]. Normally one would cover the polyisocyanurate with perlite or asphalt impregnated wood fiber board to prevent blistering (the polyisocyanurate releases gases when exposed to hot asphalt and will blister a mopped down membrane). However, a second layer of a different type of insulation board would complicate the thermal analysis. Therefore it was omitted.

The internal loads were held fixed. The lighting load during the occupied period was held fixed at 1.5 watts per square foot . The occupant load was 100 square feet per person. This internal load was imposed during the occupied period between 8:00 a.m. and 5:00 p.m. A one hour warm-up or cool down period was imposed between 7:00 a.m. and 8:00 a.m. before the internal loads were turned on. The thermostat was set at 72 degrees Fahrenheit for heating and 75 degrees for cooling during the warm-up and occupied period. No internal loads were imposed at night. The thermostat was set back to 55 degrees Fahrenheit during the non-occupied period. There was no air conditioning at night in the cooling season.

The thermal conductance of the polyisocyanurate was taken from Tobiasson, et.al. These values come from actual insulation samples subjected to a vapor pressure differential. The density and specific heat values were calculated from the measured amount of water in these same samples. The thermal values are presented in Table 1. The analysis was simplified by the assumption that the thermal characteristics are stable over the duration of the year.

TRR	WATER FRACTION BY WEIGHT	WATER FRACTION BY VOLUME	CONDUCTIVITY BTU/F*FT2*HR	DENSITY LB/FT3	SPEC.HEAT BTU/LB*F
1	0	0	0.1799	2.1	0.38
0.9	1.4	0.047	0.1998	4.94	0.74
0.8	2.62	0.088	0.2248	7.42	0.83
0.6	5.8	0.196	0.2998	13.87	0.91
0.4	10	0.337	0.4496	22.39	0.94

TABLE 1 - THERMAL PROPERTIES OF ISOCYANURATE INSULATION

Three warm climates were used to provide exterior thermal loads. Weather data was taken from: Phoenix, Arizona; Austin, Texas; and Fort Smith, Arkansas. The data was generated from a computer program written by Larry Degelman, Ph.D., at Texas A&M University. The program generates hour-by-hour data based on statistical weather parameters. This data is then averaged to produce a typical day during each month of a year. Peak days for cooling and heating represent the most extreme outdoor temperatures during each season generated by the algorithms.

THERMAL CHARACTERISTICS

Before we examine the energy performance, it will help to understand how the building's thermal properties change due to water within the roof insulation. Figure 1 shows the relationship between the thermal resistance ratio, TRR, and the total conductance of the roof. The thermal resistance ratio is the thermal resistance of the sample divided by the dry thermal resistance. A thermal resistance ratio of 1.0 represents dry insulation. This ratio decreases as water is added to the insulation, that is, moving from right to left in the figure. With the addition of water the total conductance of the roof (U*A, or

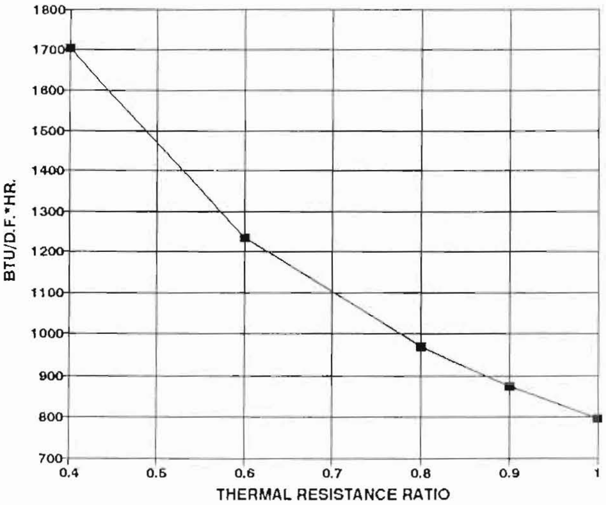

FIGURE 1: ROOF CONDUCTANCE * AREA

conductivity multiplied by the total surface area) increases. If climate and internal loads were static this would almost tell the whole story and control the energy consumption; however, reality is more complex, and thermal mass effects must be included.

Figure 2 shows one of the effects of thermal mass or thermal inertia. This property is the half time of the building. The half time is the amount of time it would take the internal temperature to change by one half of an external step change in temperature. External temperatures do not behave in this fashion; however, this gives us a comparative measure of the speed at which a building can respond to external changes. For this reason, it is often described as a thermal inertia or thermal mass effect. The longer the half time, the greater the thermal mass. The data show that as the thermal resistance decreases, the half time of the building increases. Depending on the nature of the thermal loads the building experiences, the loss of thermal resistance and the increase in thermal mass can represent opposing influences upon the energy performance of the building.

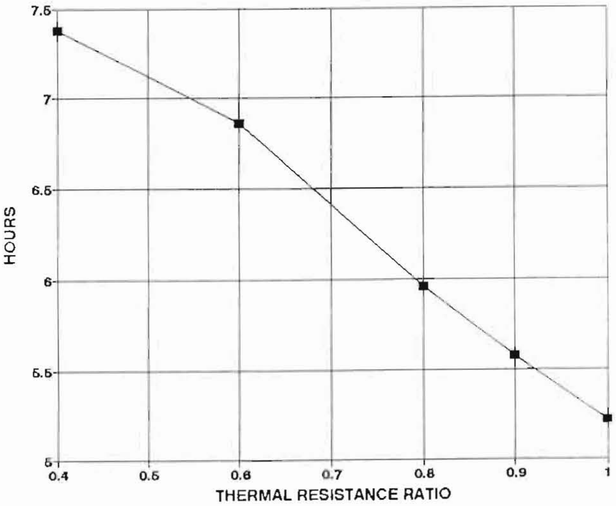

FIGURE 2: BUILDING HALF TIME

Figure 3 demonstrates the relationship between the solar admittance of the roof and the thermal resistance ratio (TRR). The admittance is the fraction of the solar heat gain which is admitted into the conditioned space. The admittance is influenced by both the conductivity and the thermal mass of the roof. Between a TRR of 0.8 and 1.0 the admittance changes very little; however, as the water content increases below a TRR of 0.6, a marked increase in admittance is seen.

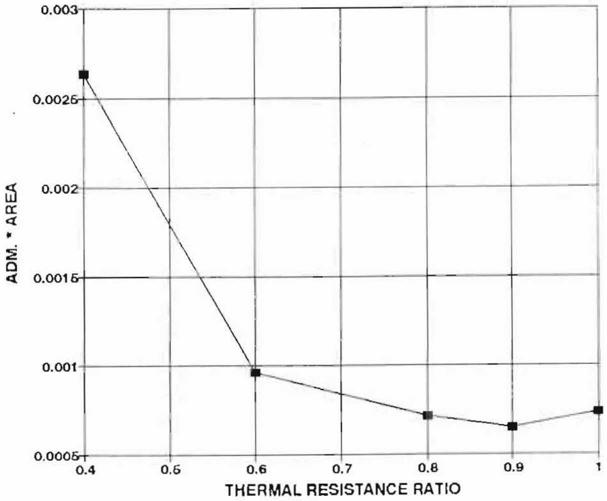

FIGURE 3: ROOF ADMITANCE * AREA

ENERGY PERFORMANCE

The energy performance was anything but predictable from consideration of the thermal conductivity alone. Figure 4 shows the relationship between the total annual sensible cooling load and the thermal resistance ratio. The data show that the annual cooling loads actually decrease as water is added to the insulation. The amount of this decrease is fairly uniform across climates (note how parallel the lines are). This implies that the effect is independent of extremes in climate. This decrease is primarily due to the benefit of added thermal mass in the system and the passive cooling effects of lower thermal resistance during mild weather conditions. This is because during cool but mild weather, air conditioning is required due to the internal heat sources from people and lighting. With a low thermal resistance, this internal heat can be rejected to the outdoors and reduce air conditioning loads.

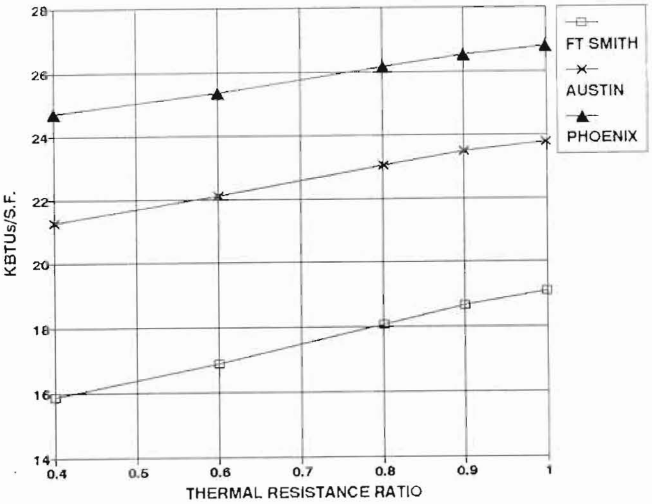

FIGURE 4: TOTAL COOLING LOADS

The results of Figure 4 were investigated further for the Austin, Texas climate. Figure 5 shows the total cooling loads for each month. Between May and September the total cooling load is increased with the addition of moisture. However, the remainder of the year demonstrates a decreased cooling load. These results are examined on an hourly basis in Figures 6, 7, 8, and 9 using average weather conditions for two months. Figure 6 shows the hourly loads for August. Figure 7 is taken

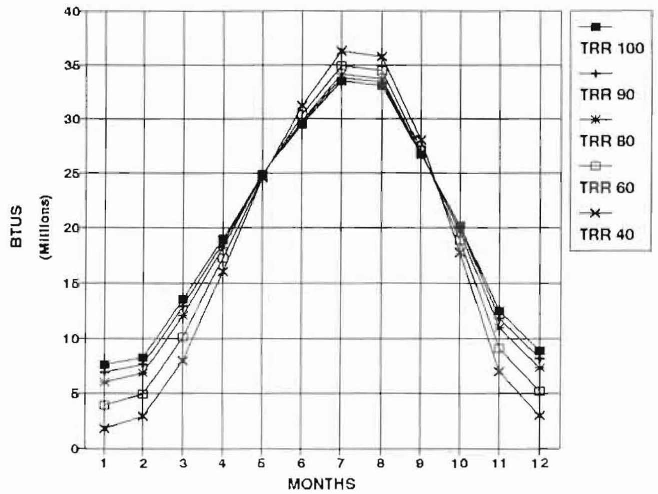

FIGURE 5: TOTAL MONTHLY COOLING LOADS
AUSTIN, TEXAS

from the same data in Figure 6; however, the difference in load between the dry and wet conditions are plotted on the Y axis. Figures 8 and 9 display the same relationships as Figures 6 and 7 for the month of March.

The August data, Figure 6, show an increase in load with increase in moisture level. A close examination of the data shows that the peak load was shifted approximately one hour by the addition of moisture. The difference between dry and wet insulation is further illustrated in Figure 7 by plotting the "Delta" or difference between the loads in the dry case and each wet case. This figure shows that the greatest increases in load were experienced at two times during the day, first between 9:00 and 10:00 a.m. and next at 6:00 p.m. The initial cool down period from 7:00 to 8:00 a.m. shows a very minor decrease in load with added moisture. However, at the highest moisture level test, a minor increase in load is seen.

The corresponding March data in Figures 8 and 9 show a different trend. Figure 8 shows a significant decrease in cooling load for all hours of the day with the peak load being shifted from 4:00 p.m. to 6:00 p.m. along with a delay in onset of load. Figure 9 shows the differences between the dry and wet conditions. At low moisture levels the largest decrease in load is seen at 11:00 a.m. As the moisture level increases, the largest difference shifts to 12:00 Noon.

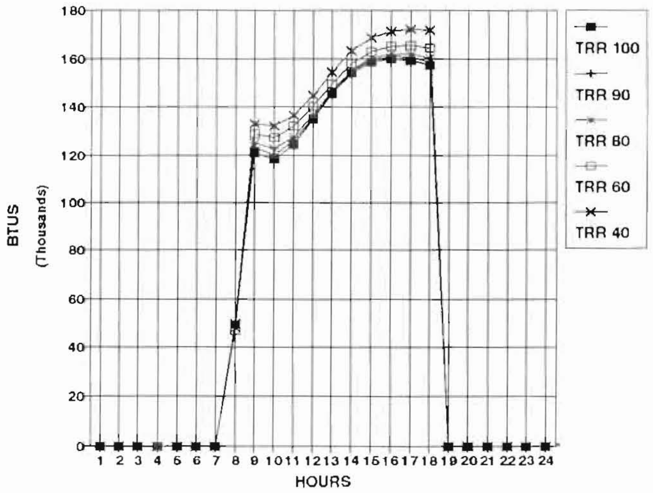

FIGURE 6: AVERAGE AUGUST COOLING LOAD
AUSTIN, TEXAS

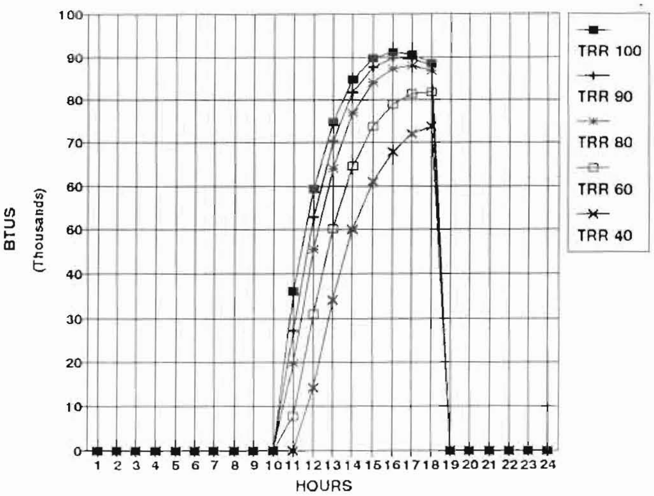

FIGURE 8: AVERAGE MARCH COOLING LOAD
AUSTIN, TEXAS

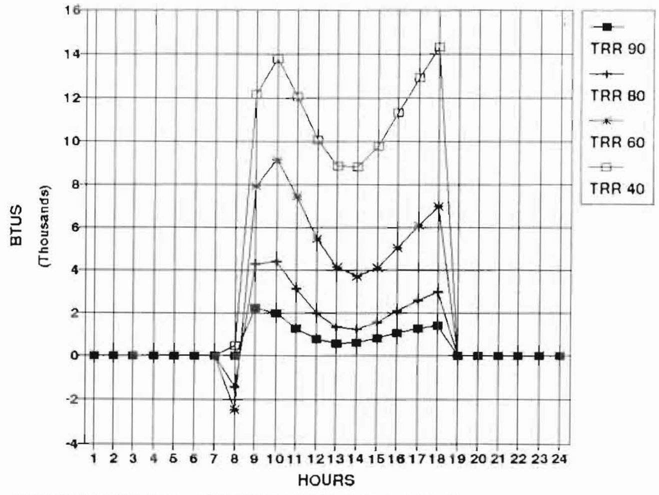

FIGURE 7: DELTA AUGUST COOLING LOADS
AUSTIN, TEXAS

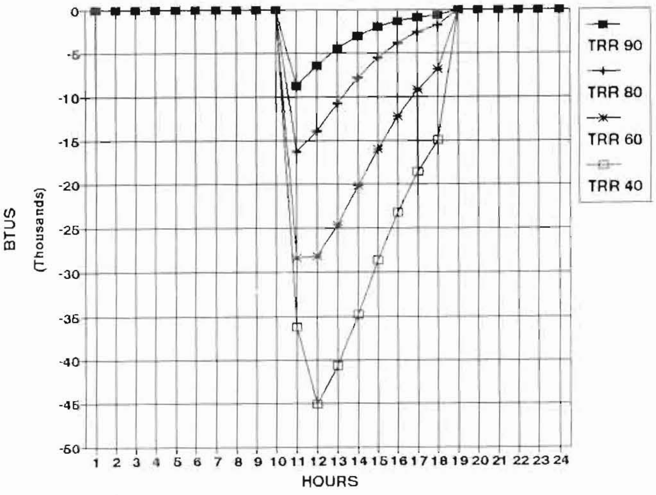

FIGURE 9: DELTA MARCH COOLING LOADS
AUSTIN, TEXAS

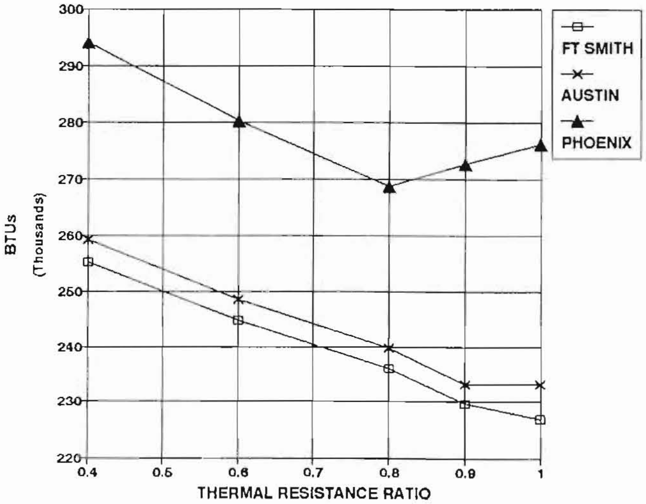

FIGURE 10: PEAK AUGUST COOLING LOADS

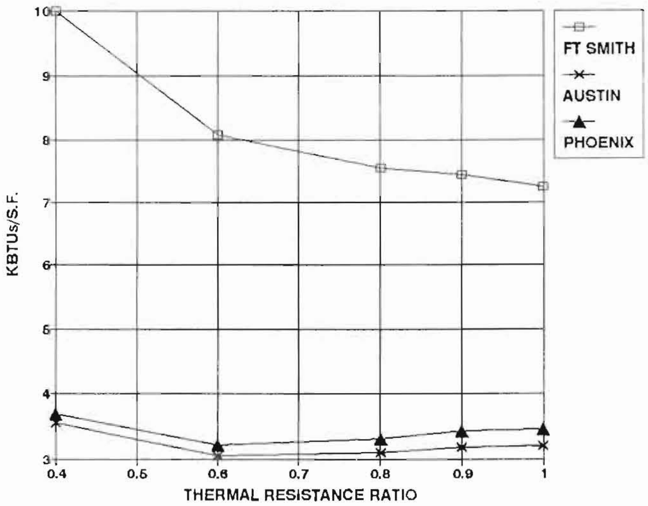

FIGURE 11: TOTAL HEATING LOADS

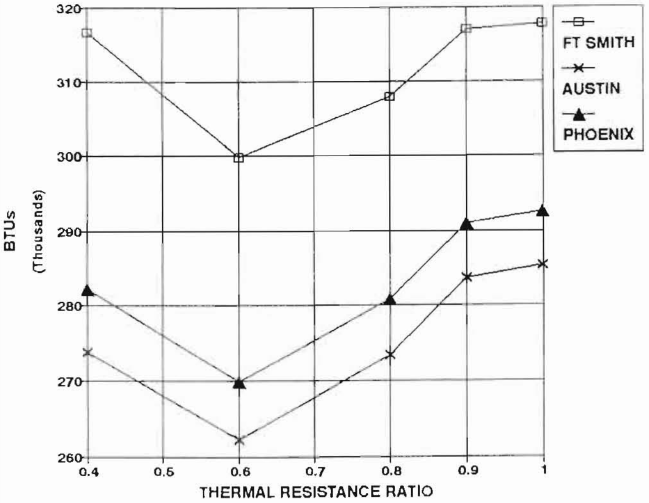

FIGURE 12: PEAK HEATING LOADS

Figure 10 shows the relationship between peak cooling load and thermal resistance ratio. This data is taken from the day with the highest peak temperature generated by the weather generation program. In general, these results are more intuitive in that the peak loads increase as the thermal resistance decreases. However, there is an exception, the Phoenix data show an initial decrease as water is added followed by a significant increase with additional wetting. The initial decrease is probably due to the larger diurnal temperature swing in the Phoenix climate. This would lead to night time cooling of the thermal mass. The data demonstrate how complex interplay between thermal resistance, thermal mass, and climate can occur in peak load calculations.

Figure 11 shows that the total heating load does not significantly change with moisture content for mildest heating climates. The lack of an impact on total heating load may be caused by thermal storage of heat within the water. Heat generated within the building as well as solar heat gain can be stored by the thermal mass within the wet insulation. This heat can counteract the effect of the lower thermal resistance during the night setback conditions and during warm-up on the next day. However, for the coldest climate tested, Fort Smith, Arkansas, the total heating load increased due to the much colder night time temperatures and the loss of thermal resistance with increasing moisture levels.

The peak heating loads are shown in Figure 12. In general, the peak heating load drops as moisture is added to the roof insulation for mild heating climates. The peak heating load occurred between 7 a.m. and 8 a.m., that is, during the warm-up period. This data further demonstrates how thermal resistance and thermal mass may act as opposing forces. The addition of water decreases the peak heating load by storing heat. As the resistance to thermal flow decreases, where the TRR becomes 0.4, the peak heating load increases.

IMPLICATIONS

The data show the complexity of the thermal effects due to increased moisture content within rigid roof insulation. Heat storage within rigid insulation affects thermal loads in ways not easily predicted by the loss of thermal resistance. In fact, thermal loads can actually decrease. The results of this study have several significant implications.

First, the data show that in warm climates a criteria for insulation removal should not be based on loss of thermal resistance; for thermal resistance is not directly related to energy performance. A removal criteria based on percent water by volume or weight of water per unit volume would reflect the quantity of water present better than percent water by weight. This is due to the variability in density of different types of rigid insulation boards. An appropriate removal criteria should be dependent on the corrosion characteristics of the deck, fasteners, and the sensitivity of the roof membrane and insulation to moisture damage. Since there are so many combinations of these elements, there may not be a single parameter that can be used as a removal criteria in all cases.

Until further research can be done on the sensitivity of roofing and deck systems to moisture, I favor a conservative approach toward formulating a removal criteria when dealing with moisture sensitive systems. For example, a criteria based on 5% water by volume could be chosen for roofing systems that are sensitive to water. Specifying a removal criteria based on a small quantity of water, could limit corrosion of mechanical fasteners, primed but unpainted steel decks, and damage to moisture sensitive roofing membranes (for example, organic felts). This criteria is much larger than the equilibrium moisture content but approximately half the 80% TRR criteria.

In addition to physical deterioration, the data presented here have implications for energy consumption and peak cooling loads. The thermal mass and the thermal conductivity of a roof can be fine tuned to minimize the thermal loads for differing climates, insulations, decks, building configurations, and budgets. Thus far, our building standards such as ASHRAE 90.1 have ignored the thermal mass effects of roof and deck systems. The standards have only focused on mass effects in wall systems. However, many of our commercial buildings are low-rise with large expanses of roof surface area. With careful consideration of first costs, thermal mass, conductivity, reflectivity and maintenance costs, it is possible to increase the present value of roof and deck systems to building owners. Experience has taught us that the cost for this type of energy analysis is minor compared to the first costs and maintenance costs of a complete roofing system.

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