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**OAK RIDGE
NATIONAL
LABORATORY**

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Preliminary Evaluation of Radiation Control Coatings for Energy Conservation in Buildings

R. W. Anderson

Part of
The National Program for
Building Thermal Envelope Systems
and Materials

Prepared for the
U.S. Department of Energy
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Office of Buildings Energy Research
Building Systems Division

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FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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Building Thermal Envelope Systems and Materials

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FOREWORD

This is one of a series of reports to be published describing research, development, and demonstration activities in support of the National Program for Building Thermal Envelope Systems and Materials. The National Program involves several federal agencies and many other organizations in the public and private sectors who are addressing the national objective of decreasing energy wastes in the heating and cooling of buildings. Results described in this report are part of the National Program through delegation of management responsibilities for the DOE lead role to the Oak Ridge National Laboratory.

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PRELIMINARY EVALUATION OF RADIATION CONTROL COATINGS
FOR ENERGY CONSERVATION IN BUILDINGS*

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ABSTRACT

Radiation Control Coatings (RCCs) applied to external building surfaces can reflect about 85 percent of the solar heating from the surfaces of buildings. Since in warm climates, solar heating is the primary source of heat gain through walls and roofs, RCC technology represents an alternative or adjunct to conventional thermal control methods (e.g., thermal insulation) for opaque building components.

The primary objectives of this project were to: (1) obtain solar and infrared reflectance data for representative RCC products, (2) evaluate test methods for measurement of the radiative properties of RCCs, (3) calculate the changes in heat flow attributed to RCCs in flat roof applications in several geographic locations, and (4) compare field tests and calculated thermal performance of an RCC in a flat roof configuration.

Data are presented for the radiative properties of five commercially available RCC products as determined by several test methods. The potential energy benefits of RCCs are presented for flat roofs in both warm and cold climates.

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EXECUTIVE SUMMARY

Coating materials that have the combined properties of high solar reflectance and high long wavelength emittance can reduce heat gains through roof and wall sections. Such coatings, defined as Radiation Control Coatings (RCCs), have potential as an energy conservation material when applied to the exterior of buildings in locations where cooling loads predominate. Under certain applications, RCCs represent an alternative or adjunct to conventional thermal insulations for thermal control. Although the potential benefits of RCCs have been discussed in the literature, there are only limited data regarding the properties of RCC materials and their thermal performance in building applications.

Integrated research was conducted to first characterize current RCC products; secondly, to calculate the thermal performances of RCCs in different climatic areas by means of computer modeling; and thirdly, to measure the thermal performance of a RCC product under field conditions. The primary objectives of this project were:

1. To obtain valid radiative property data for typical RCCs for the evaluation of the thermal performance of RCCs in building applications.
2. To assess the energy conservation potential of RCCs in building applications.
3. To increase the awareness of the building industry of the potential applications of RCCs.

The objectives of the project were met by use of a three step approach;

1. Characterize the application and radiative properties of five commercially available RCC products.
2. Calculate the thermal performance of RCCs in different flat roof configurations and in different climatic areas with the BLAST computer program.
3. Measure the thermal performance of one RCC product on a flat roof configuration under summer conditions in the Oak Ridge National Laboratory (ORNL) Roof Testing Research Apparatus (RTRA).

Testing of solar and infrared reflectance properties of the products was performed in accordance to established American Society for Testing and Materials (ASTM) testing procedures whenever possible

Calculations of the thermal performance of RCCs were performed with the aid of BLAST, a computer program developed by the U.S. Army Corps of Engineers. BLAST allows the input of detailed construction parameters and calculates design day and annual heat loads based on hourly weather data for one year periods.

Characterization of five commercially available RC products showed that coating thicknesses in excess of 0.5 mm were necessary to achieve maximum solar and infrared reflectance values; thinner coatings allow measurable amounts of solar transmission through the coating. All RCC samples showed similar solar and infrared reflectances and gloss values notwithstanding differences in surface conditions and texture.

The commercially available RCC products tested have solar reflectances to 0.85 and infrared reflectances of 0.1. The high solar reflectances of RCCs is the key property for reducing solar heat loads in buildings. The low infrared reflectances of RCCs indicate that they have little value for controlling radiation heat transfer inside buildings. Observed differences in the mechanical and surface properties of commercially available RCC products indicate differences in product qualities, and some of these differences could affect the long-term performance of RCCs in field applications.

Differences in measured solar and infrared reflectance values were obtained from the different testing methods. The causes for such

differences need to be evaluated and standardized testing procedures established.

Changes in the angle of solar incidence from 7° to 45° caused about a 3% change in the solar reflectance values in two RCC products. The data indicate that solar reflectances of RCCs are, for practical purposes, insensitive to angle of solar incidence. RCC products exhibited low gloss values, thereby indicating almost all reflected energy is diffuse; in contrast, reflected energy from materials such as bright aluminum is mostly specular reflection.

Solar exposures of the equivalent of one year caused small (from 0 to 3%) decreases in the solar reflectance values of the RCC products. The data indicate the solar reflectance properties of the RCC products are, for practical purposes, resistant to long-term solar exposures of at least one year.

Computer analyses showed that the highest solar reflectances result in the lowest annual cooling loads, roof surface temperatures and maximum hourly cooling demands for areas in both hot and cold climates. The data also indicate that for cold climates, the benefits of high solar reflectances would not necessarily cause penalties in terms of annual heating plus cooling roof loads.

As compared to black flat roofs, the application of RCCs significantly reduces both the annual and peak cooling loads for roofs with insulation levels up to 4.4 kJ/m^2 . The reductions in annual cooling loads are offset to varying degrees by increases in heating loads depending on climatic conditions; the greatest benefits of RCC application are in areas where cooling loads are predominate. Whereas the application of RCCs does reduce the hourly cooling demand requirements, its application has no effect on the hourly heating demand requirements.

The data show that for both warm and cold climatic areas, RCCs and thermal insulation can be combined to reduce seasonal cooling loads, combined heating and cooling loads, and cooling equipment capacities. The benefits obtained from RCCs are directly related to the level of solar reflectance of the RCC.

Compared to black roofs, RCCs are effective for reducing summer roof surface temperatures and temperatures of insulation placed below roofing membranes. Reduced roof and insulation temperatures provide additional benefits, such as increased roof life and improved thermal performance of the insulation.

Whereas the measured and calculated summer roof temperatures were in good agreement, differences in summer heat flow and ceiling temperatures were found. Additional research is needed to identify the reasons for the differences. Also, computer algorithms are needed that are able to adjust the R-values of thermal insulation and other building materials in accordance with the temperatures experienced. The variation of the thermal resistance with temperature should be included in thermal modeling programs to improve the thermal resistance values being used.

There is a need for evaluation of the effects of extended field exposure, e.g. the combined effects of rain, dust/dirt and possibly fungi on the radiative and mechanical properties of RCCs, and how long-term exposure to the environment effects thermal performance.

INTRODUCTION

Coating materials that have the combined properties of high solar reflectance and high long wavelength emittance can reduce heat gains through roof and wall sections. Such coatings, defined as Radiation Control Coatings (RCCs), have potential as an energy conservation material when applied to the exterior of buildings in locations where cooling loads predominate. Under certain applications, RCCs represent an alternative or adjunct to conventional thermal insulations for thermal control. Although the potential benefits of RCCs have been discussed in the literature [1-3], there are only limited data regarding the properties of RCC materials and their thermal performance in building applications.

Under this project, integrated research was conducted to first characterize RCC products; secondly, to calculate the thermal performances of RCCs in different climatic areas by means of computer modeling; and thirdly, to measure the thermal performance of a RCC product under field conditions. The primary objectives of this project were:

1. To obtain valid radiative property data for typical RCCs for the evaluation of the thermal performance of RCCs in building applications.
2. To assess the energy conservation potential of RCCs in building applications.
3. To increase the awareness of the building industry of the potential applications of RCCs.

This paper summarizes the major results of the project.

The type of RCC products selected for testing were limited to commercially available white elastomeric coatings formulated with acrylic latex resin binders. It should be noted that in addition to this class of RCC products, other products formulated with different resin bases, such as epoxies or polyurethanes, are also commercially available. Since the radiative properties of these other products were not tested, characteristics of such other products cannot be made from the test data described in this project.

EXPERIMENTAL APPROACH

The thermal performance of RCCs is dependent on their radiative properties. Only limited radiative property data are available from manufacturers. Although there are some standardized testing procedures for measuring radiative properties, such testing methods have not been evaluated for RCC materials, nor have manufacturers been consistent in the use of test methods.

To meet the objectives of the project, a three step approach was taken to evaluate the potential thermal performance of RCCs in building applications:

1. Characterize the application and radiative properties of five commercially available RCC products.
2. Calculate the thermal performance of RCCs in different flat roof configurations and in different climatic areas with the BLAST computer program.
3. Measure the thermal performance of one RCC product in a flat-roof configuration under summer conditions in the Oak Ridge National Laboratory (ORNL) Roof Testing Research Apparatus (RTRA).

Five commercially available RCC products were obtained for testing; three products were obtained directly from the manufacturers and two were purchased from commercial retail stores. According to product

label or other literature, each product was white in color, was an "elastomeric acrylic" coating material, had a water-based formulation, and made claims as to the product's ability to reflect solar heat or otherwise conserve energy in buildings.

Testing of solar and infrared reflectance properties of the products was performed in accordance to established American Society for Testing and Materials (ASTM) testing procedures whenever possible. For the preparation of test samples for measurement of radiative properties, material was brush-applied at three thicknesses on both aluminum foil and black rubber roofing membrane (ethylene propylene diene monomer or EPDM) substrates. The aluminum substrate had high reflectance and low emittance and the black rubber had low reflectance and high emittance; these differences in radiative properties assisted in the interpretation of the test data, that is, to assure that the thicknesses of the RCCs samples were sufficient to mask the radiative properties of the substrates.

Calculations of the thermal performance of RCCs were performed with the aid of BLAST, a computer program developed by the U.S. Army Corps of Engineers [4]. BLAST allows the input of detailed construction parameters and calculates design day and annual heat loads based on hourly weather data for one year periods. BLAST was used to evaluate the thermal performances of RCCs in different flat roof construction configurations and in different climatic areas. BLAST was also used for the comparison of the calculated thermal performance of roof sections to values measured in the RTRA for summer field testing.

For the RTRA tests, the heat fluxes and surface temperatures were compared for side-by-side flat roof sections of the following construction: Section 1 - Black 1.1 mm EPDM over fir plywood 3.8 cm thick; and Section 2 - Same as Section 1, except that the black EPDM was coated with 0.9 mm of a RCC. A detailed description of the RTRA test configuration is given by Courville and Childs [5].

CHARACTERIZATION OF RCC PRODUCTS

OBJECTIVES.

The objectives of the characterization of commercially available products were; to obtain valid radiative property data, to identify a representative product for field testing, and to evaluate different methods for measurement of radiative properties.

TEST DATA.

Characterization of the five commercial RCC products included the following properties:

- application characteristics,
- effect of coating thickness on apparent solar and infrared reflectances,
- solar and infrared reflectances of the RCC products,
- effect of angle of incidence on the solar reflectance, and
- surface gloss.
- effect of one year equivalent solar exposure on the solar reflectance.

Application characteristics shown in Table 1 are based on visual observations during preparation of samples of the five RCC products. Bonding to the rubber substrate was defined as "good" if the bond remained after stretching and twisting of the substrate. Flexibility was defined as "good" if the RCC did not crack when the substrate was bent back on itself; "poor" flexibility was an indication of cracking. A "ripple" surface showed the brush marks from application; a "smooth"

surface was self-leveling after brush application. A "smooth" surface texture of the dry RCC had no surface irregularities attributed to the composition of the RCC; a "granular" texture showed the outlines of large particles contained within the RCC.

Table 1 -- RCC coating characteristics.

Product Code	Bond to rubber	Flexibility (bending)	Surface	Texture
S	good	good	ripple	smooth
H	good	poor	smooth	granular
E	good	poor	smooth	granular
P	good	good	ripple	smooth
K	good	good	ripple	smooth

The effect of thickness on the apparent solar reflectance of RCC product "S" was tested at coating thicknesses from 0.08 to 1.14 mm using a solar spectrum reflectometer [6]. As summarized in Table 2, coating thicknesses in excess of 0.5 mm exhibited the maximum reflectance values.

Additional tests of the five RCC products applied to both bright aluminum and black rubber substrates, demonstrated that coating thicknesses in excess of 0.5 mm resulted in maximum solar reflectance values and thicknesses in excess of 0.35 mm resulted in maximum infrared reflectance values (infrared reflectance was not tested for coating thicknesses less than 0.35 mm).

Table 2 -- Effect of thickness on solar reflectance.

Coating thickness mm	Reflectance TTU ^a
0.08	0.59
0.13	0.68
0.15	0.68
0.19	0.72
0.36	0.77
0.51	0.80
0.66	0.79
0.89	0.80
1.14	0.80

^a Tennessee Technological University, Cookeville, TN

Solar and infrared reflectance data were obtained for freshly prepared samples of the five RCC products plus two samples of single-ply rubber roofing membrane materials - a black rubber (EPDM) membrane manufactured by Firestone and a white rubber membrane manufactured by Goodyear. The following tests were conducted:

- Solar reflectance in accordance with ASTM E 903; tests conducted by DSET Laboratories, Inc., Phoenix, AZ.
- Solar reflectance in accordance with ASTM E 1175; tests conducted by DSET Laboratories, Inc.
- Solar Reflectance as measured with a solar reflectometer manufactured by D&S, Inc.; tests conducted by Tennessee Technological University (TTU), Cookeville, TN.
- Infrared reflectance in accordance with ASTM E-408, method A; tests conducted by DSET Laboratories, Inc.
- Infrared reflectance in accordance with ASTM E 408, method B; tests conducted by TTU.

Note: With this method, reflectance is determined indirectly by the measurement of emittance and

assuming reflectance is equal to emittance. Also, test results can be effected by the thermal resistance of the sample. The samples tested had small, but unknown thermal resistances; no corrections for thermal resistances were made.

Solar and infrared reflectance data, at near normal angle of incidence (about 7°), are summarized in Tables 3 and 4 respectively, and solar data for different angles of incidence are given in Table 5. Coating thicknesses were in excess of 0.51 mm to assure that there was no transmission of radiation through the coatings.

Table 3 -- Solar reflectance (near normal).

Product Code	DSET ^a ASTM E 903	TTU ^b	% difference ^c
S	0.766	0.797	- 4
H	0.764	0.815	- 7
E	0.770	0.787	- 2
P	0.816	0.817	0
K	0.789	0.827	- 5
Black rubber	0.067	0.071	- 6
White rubber	0.769	0.783	- 2

^a DSET Laboratories, Phoenix, AZ

^b Tennessee Technological University, Cookeville, TN

^c (DSET - TTU) X 100 / DSET

Table 4 -- Infrared reflectance (near normal).

Product Code	ASTM E 408, A DSET	ASTM E 408, B TTU
S	0.10	0.15
H	0.09	0.11
E	0.10	0.19
P	0.11	0.14/0.20
K	0.10	0.18
Black rubber	0.15	0.17
White rubber	0.13	0.20

Table 5 -- Solar reflectance at near normal (about 7°) and 45° angles of incidence.

Product Code	ASTM E 1175, 7° DSET	ASTM E 1175, 45° DSET	% difference
S	0.85	0.82	3
H	0.86	0.84	3

Measurements of surface gloss reported in Table 6 were made for each of the ROC products and the black and white rubber membranes. The purpose of these tests was to assess the amount of specular reflection that may occur from the surfaces of the products. Gloss units are reported on an arbitrary scale commonly used in the paint industry; as a point of reference, gloss measurements were made on the bright surface of aluminum foil.

Table 6 -- Surface gloss (gloss units).

Product Code	ASTM D 523, at 60° angle of incidence; DSET
S	4-5
H	2
E	3
P	6-8
K	4
Black rubber	6
White rubber	4
Aluminum foil	>100

The effects of one year equivalent solar exposure on the solar reflectances were measured for the five RCC products and the white single-ply roofing membrane. The samples received a total solar exposure of 12,709 MJ/m² (333 MJ/m² of UV radiation) during the period January 26, 1991 to April 20, 1991 at DSET's "EMMA" accelerated weathering test facility; the exposure tests were conducted in accordance with the ASTM G 90 test method. During the exposure period, the samples were mounted to prevent any exposure to moisture and to minimize any accumulation of atmospheric borne dust or dirt. Hemispherical reflectance measurements were performed (ASTM E 903) on the samples before and after the one year equivalent solar exposure; the resulting solar reflectance test data are given in Table 7.

Table 7. Effect of one year equivalent solar exposure on solar reflectance

Product code	Solar reflectance, ASTM E 903 Before	After	% Change
S	0.782	0.783	0.0
H	0.764	0.749	-2.0
E	0.793	0.788	-0.6
P	0.803	0.797	-0.8
K	0.800	0.773	-3.0
White rubber	0.749	0.753	+0.5

DISCUSSION OF TEST DATA.

There were observable application differences between the five RCC products. Whereas all products exhibited good adhesion to rubber and aluminum substrates, the products fell into two groups when considering flexibility and surface qualities. Products S, P and K were flexible and did not crack under stretching or bending conditions but products E and H easily cracked when bent and stretched. Likewise, products S, P and K retained brush marks from application but otherwise had smooth surfaces similar to a semi-gloss paint. In contrast, products E and H showed no brush marks from application, (e.g. were "self-leveling"), and had granular surface textures.

Coating thicknesses in excess of 0.5 mm were necessary to achieve maximum solar and infrared reflectance values; thinner coatings allow measurable amounts of solar transmission through the coating. All RCC samples and the white rubber membrane showed similar solar and infrared reflectances and gloss values notwithstanding differences in surface conditions and texture. Small differences in the measured reflectance values are probably related to differences in composition and surface conditions.

Differences in measured solar and infrared reflectance values were obtained from the different testing methods. The causes for such differences need to be evaluated and standardized testing procedures established. For measurement of infrared reflectance, ASTM test method E 408, method A (which measures reflectance directly) is suggested over test method E 408, method B (which measures reflectance indirectly).

Changes in the angle of incidence from 70° to 45° caused a 2-3% change in the solar reflectance values in the two RCC products tested. The data indicate that solar reflectances of RCCs are, for practical purposes, insensitive to angle of solar incidence. RCC products exhibited low gloss values, similar to those obtained for the white and black rubber roofing membranes. These results indicate that the specular reflection component of RCCs is low and that almost all reflected energy is diffuse.

Solar exposures of the equivalent of one year caused small (from 0 to 3%) decreases in the solar reflectance values of the RCC products. The one-year data indicate the solar reflectance properties of the RCC products are, for practical purposes, resistant to long-term solar exposures. Although the causes of the observed changes in reflectances were not determined, it is probable that the primary cause would be due to solar radiation induced changes of the indices of refraction or absorptivity of the resin matrices.

COMPUTER MODELING OF RCC THERMAL PERFORMANCE

The objectives of the modeling with BLAST were to: assess the maximum effects due to RCC applications by comparing the thermal performance of RCCs with black roofs, e.g. EPDM rubber membranes; assess the effects due to RCC applications to roofs in different climatic areas, and assess the effects of RCCs applied in conjunction with thermal insulation.

The structures modeled were flat roofs having the following construction features:

- Top layer - black rubber membrane or white RCC; the solar reflectance values 0.10 and 0.85, respectively. The infrared absorbance values were 0.9 for both materials.

- Second layers - thermal insulation; R-value levels of 0.9, 2.3 and $4.4 \text{ m}^2\text{K/watt}$.

- Third layer - 1.9 cm thick plywood deck.

The thermal performances of the roofs were calculated for cities in both warm and cold climates. For all calculations, the heating and cooling setpoints were 22°C . All reported loads represent only sensible loads; since no air infiltration was assumed for the roof sections, there were no latent loads. The listed R-values for the roofs represent the total surface-to-surface R-values.

The calculated thermal performances for the roofs in different climatic areas are summarized in Tables 8-11.

TABLE 8 -- Annual heating and cooling loads in 1000 kJ/m² with
R-values in m²*K/watt.

City	Black rubber			White RCC		
	R-0.9	R-2.3	R-4.4	R-0.9	R-2.3	R-4.4
Las Vegas						
heating	118.4	60.0	41.0	175.6	89.9	61.3
cooling	289.6	115.2	52.4	98.5	34.3	12.1
Tampa						
heating	48.3	28.6	24.2	70.0	42.6	36.9
cooling	206.2	75.9	31.0	62.2	16.4	3.4
Fort Worth						
heating	141.6	72.2	49.9	185.6	95.4	65.9
cooling	179.0	67.3	28.3	62.6	19.5	5.6
Minneapolis						
heating	402.3	190.3	118.0	468.3	222.2	137.9
cooling	77.2	28.0	11.2	16.3	4.2	0.8

TABLE -- 9 Maximum hourly demands in kJ/m²
for summer and winter design days
(R-values in m²*K/watt)

City	Black rubber			White RCC		
	R-0.9	R-2.3	R-4.4	R-0.9	R-2.3	R-4.4
Las Vegas						
heating	88.9	41.0	23.9	88.9	41.0	23.9
cooling	242.8	106.0	54.7	75.2	30.8	14.8
Minneapolis						
heating	180.1	79.8	45.6	180.1	79.8	45.6
cooling	112.0	47.3	23.2	34.9	13.8	5.1

TABLE -- 10 Maximum roof surface temperatures (°C)
for summer design day, July 21
(R-values in m²*K/watt)

City	Max. ODB ^a °C	Black rubber			White RCC		
		R-0.9	R-2.3	R-4.4	R-0.9	R-2.3	R-4.4
Las Vegas	42	84	85	86	46	47	47
Tampa	33	69	70	70	38	38	38
Minneapolis	32	50	51	51	33	34	34

^a outside air dry bulb temperature

TABLE -- 11 Maximum ceiling temperature ($^{\circ}\text{C}$)
for summer design day, July 21
(R-values in $\text{m}^2\text{K/watt}$)

City	Black rubber			White RCC		
	R-0.9	R-2.3	R-4.4	R-0.9	R-2.3	R-4.4
Las Vegas	33	27	25	26	24	23
Tampa	30	26	24	25	23	22
Minneapolis	28	25	24	24	23	22

Calculated summer design-day profiles of cooling loads, roof-surface temperatures and ceiling temperatures for roofs located in Las Vegas, NV are shown in Fig. 1 for the white RCC roof, and Fig. 2 for the black rubber roof.

The results show that RCC roofs had lower cooling loads than the corresponding black roofs having similar levels of thermal insulation; however, the magnitude of reductions of cooling loads were greater for the warm climates (see Table 8). Compared to black roofs with low levels of insulation, the reduction of cooling loads by the RCCs is "equivalent" in effect to thermal insulation levels in the R-value range of 2.3-4.4 $\text{m}^2\text{K/W}$. However, the equivalency of RCCs to thermal insulation varied for different climates.

RCCs can effectively reduce the annual cooling loads of roofs having a wide range of level of thermal insulation. The benefits from reductions of cooling loads are balanced by increases in heating loads; the greatest net benefits are to be gained in warm climates where cooling loads are predominate. For each climate, optimized levels of thermal insulation in conjunction with RCCs need to be determined based on relative costs for heating and cooling energy sources and/or energy use policies.

For all levels of thermal insulation examined, the application of RCC significantly lowers maximum hourly cooling demands for the black roofs for a wide range of climates. In contrast, the RCC roofs did not increase the maximum hourly heating demands compared to black roofs since maximum heating demands occur during night time hours when solar reflectance has no effect (see Table 9). Hence, RCC application reduces cooling equipment capacity requirements without corresponding increases in heating equipment capacity requirements.

For black roofs, the maximum roof surface temperatures calculated for summer design days ranged from 51 $^{\circ}\text{C}$ for Minneapolis to 86 $^{\circ}\text{C}$ in Las Vegas; higher levels of thermal insulation increased the maximum surface temperatures only slightly (see Table 10). In contrast, for RCC roofs, maximum roof surface temperatures for summer design days ranged from 34 $^{\circ}\text{C}$ for Minneapolis to 47 $^{\circ}\text{C}$ for Las Vegas. The maximum roof surface temperatures for RCC roofs were 3-5 $^{\circ}\text{C}$ above the maximum outside air temperatures for all locations. The high surface temperatures on black roofs indicate maximum temperatures of thermal insulation placed below the roof membrane can reach similar temperatures. Also, average temperatures within the thermal insulation can reach 55 $^{\circ}\text{C}$ or more. High insulation temperatures have several important energy related implications:

- 1) High roof temperatures can exceed some insulation manufacturers' recommended service conditions for their products, and premature loss of thermal and mechanical performance can be expected.
- 2) Building thermal design is generally based on insulation R-values determined at an average temperature of 24 $^{\circ}\text{C}$. Since the

R-values of all insulation materials decrease with increasing temperatures, the designed thermal performance overstates the actual summer thermal performance, that is, greater than expected heat flow will be experienced. It should be noted that building thermal insulation R-value data are generally not available for average temperatures other than 24 °C.

- 3) All computerized heat load calculation methods, including BLAST, assume a constant R-value for insulation materials, typically the R-value determined at 24 °C. Consequently, calculated cooling loads are understated.

The RCC roofs had lower ceiling temperatures during summer periods than the black roofs of corresponding thermal insulation levels (see Table 11). High ceiling temperatures cause radiation heating of occupants and, for a given inside setpoint temperature, the occupants tend to lower the setpoint temperature; the result is greater cooling energy consumption.

The effects of varying the solar reflectances of roofs from 0.1 ("black"), 0.35, 0.60, and 0.85 (RCC white) were calculated for two cities in markedly different climates; Las Vegas - predominate cooling loads and moderate heating loads, and Minneapolis - predominate heating loads and moderate cooling loads. As summarized in Fig. 3, roof cooling loads for Las Vegas decreased with increasing values of solar reflectance for roof insulation levels ranging from R-0.9 to 4.4. Likewise, the sum of annual heating and cooling loads decreased with increasing values of solar reflectance; the reduction of cooling loads were greater than the corresponding increases in heating loads.

The effect of increasing solar reflectances on the Minneapolis cooling loads (Fig. 4) were similar to those seen for Las Vegas. However, unlike Las Vegas, the sum of the annual heating and cooling loads were insensitive to the range of solar reflectances, and thereby indicating that in cold climates, the savings in cooling loads with high solar reflectances would not necessarily result in increased annual heating plus cooling loads. It should be noted that the actual corresponding savings in energy and costs would have to be evaluated on a case by case basis in terms of the relative heating and cooling equipment system efficiencies and energy costs.

The effect of increasing levels of solar reflectances on maximum roof surface temperatures during summer design days were similar for Las Vegas and Minneapolis (Fig 5); maximum roof temperatures decreased directly with increasing solar reflectance values. Likewise, maximum hourly cooling demands decreased directly with increasing solar reflectance levels for both Las Vegas and Minneapolis (Fig.6). As shown in Table 9, the level of roof solar reflectance has no effect on maximum hourly heating demands since these maximum demands occur during night time periods. Hence, for even cold climates, the high solar reflectances can be used to reduce cooling demands without corresponding increases in heating demands.

In summary, the data show that the highest levels of solar reflectance result in the lowest annual cooling loads, roof surface temperatures and maximum hourly cooling demands for areas in both hot and cold climates. The data also indicate that for cold climates, the benefits of high solar reflectances would not necessarily cause penalties in terms of annual heating plus cooling roof loads.

PRELIMINARY FIELD TESTING OF THE THERMAL PERFORMANCE OF RCCs

Preliminary field tests of the thermal performance of RCCs were conducted on the ORNL RTRA from July 24, 1990 to October 15, 1990. The objectives of these tests were; to demonstrate the thermal performance of RCCs during summer conditions, to compare the measured thermal performance of RCCs to those calculated by the BLAST computer

program and, to assess changes in solar reflectance and mechanical properties due to solar and atmospheric exposure.

The RTRA is a small free-standing building with instrumented roof sections exposed to full solar and atmospheric conditions, and inside surfaces facing temperature controlled space. The roof sections were instrumented to continuously measure inside and outside surface temperatures and heat flux through the roof sections. The construction and operation of the RTRA is described in Ref. 5.

Two test sections, each 1.2 m by 1.2 m, were used for testing. Each section consisted of three sheets of 1.27 cm thick fir plywood covered on the top surface with a 0.11 cm thick black EPDM single-ply membrane. The top surface of one section was coated with 0.11 cm of a white RCC product (product code S). The surface-to-surface R-values of the test sections were 0.40 m²K/W. The air temperature at the underside of the test sections was controlled at a nominal 24 °C, however there were uncontrolled temperature fluctuations of about +/- 3 C.

A preliminary comparison was made of the measured thermal performance of the two test sections with those calculated by the BLAST program. The test day of August 18, 1990 was selected as being typical of a clear summer day. For the computations, hourly outside air temperatures for the test day were modeled using the minimum and maximum day temperatures recorded by the ORNL weather station. The solar heat flux was determined by the BLAST program for the Knoxville, TN location using a clearness factor of 1.0. The inside air temperature was set at a constant 24 °C.

The measured and calculated outside air temperature profiles for August 18, are shown in Fig. 7. The measured and calculated hourly heat loads, roof surface temperatures and ceiling temperatures for the two test sections are shown in Figs. 8, 9 and 10 respectively.

Both the measured and calculated results show that the application of RCCs to black roof sections can significantly reduce the heat flow through the roofs during summer conditions. The measured heat flows however, were greater than those calculated. Although there was good agreement between the maximum measured and calculated black roof surface temperatures, the calculated ceiling temperatures were higher than those measured. Causes for the differences in the measured and calculated heat flow and ceiling temperatures are as yet unknown; possible causes for the differences are:

- The solar reflectance value of the RCC on the RTRA roof section was lower than it's original value due to three weeks of atmospheric exposure; a lower solar reflectance would increase the solar heating.
- The R-value of the wood substrate in the RTRA decreased when exposed to high temperatures and lower R-values would increase heat flow; a constant R-value was used in the BLAST model.
- The air temperatures inside the RTRA fluctuated during the test period and the air was moved at high velocities; the inside air boundary conditions of the RTRA were variable and could not be modelled by BLAST.
- The radiative properties of the RTRA internal surfaces, e.g. ceiling, walls and floor, were assumed; differences between actual RTRA values and those assumed for the BLAST model could affect the respective heat flow and ceiling temperature values.
- Although the algorithms used in BLAST are generally considered to be accurate, there has not been any experimental verification of the calculated results at this level of detail [7].

SUMMARY

The commercially available RCC products tested have solar reflectances in the range of 0.77 to 0.85, infrared reflectances of 0.09 to 0.11, and thermal emittances of about 0.9. The high solar reflectance of RCCs is

the key property for reducing solar heat loads in buildings. The low infrared reflectances of RCCs indicate they have little value for controlling radiation heat transfer within buildings. There are differences in the mechanical and surface properties of commercially available RCC products that could affect the long term performance of RCCs in field applications.

The solar reflectances of the five RCC products tested changed less than 3% when exposed to one year equivalent solar radiation. However, no statement can be made about the solar stability of all RCC products.

As compared to black flat roofs, the application of RCCs significantly reduces both the annual and peak cooling loads for roofs with insulation levels up to 4.4 kJ/m^2 . The reductions in annual cooling loads are offset to varying degrees by increases in heating loads depending on climatic conditions; the greatest benefits of RCC application are in areas where cooling loads are predominate. Whereas the application of RCCs does reduce the hourly cooling demand requirements, its application has no effect on the hourly heating demand requirements.

The data indicate that for both warm and cold climatic areas, RCCs and thermal insulation can be combined to provide minimum seasonal cooling loads, minimum combined heating and cooling loads, and minimum cooling equipment capacities. The benefits obtained from RCCs are directly related to the level of solar reflectance of the RCC.

Compared to black roofs, RCCs are effective for reducing summer roof surface temperatures and temperatures of insulation placed below roofing membranes. Reduced roof and insulation temperatures provide additional benefits, such as increased roof life and improved thermal performance of the insulation, even in cold climates.

Compared to black roofs, RCCs are effective for reducing summer ceiling temperatures, especially for roofs having low levels of thermal insulation. Lower ceiling temperatures reduces the levels of radiation heating of interior building space.

Whereas the measured and calculated summer roof temperatures were in good agreement, differences in summer heat flow and ceiling temperatures were found. Additional research is needed to identify and correct the causes of the differences between the measured and calculated results. Also, computer simulation algorithms are needed that are able to adjust the R-values of thermal insulation and other building materials in accordance with the temperatures experienced.

There is a need for evaluation of the effects of extended field exposure, e.g. the combined effects of rain, dust/dirt and possibly fungi on the radiative and mechanical properties of RCCs, and how long term exposure may effect the thermal performance of RCCs.

RECOMMENDATIONS FOR FUTURE WORK

Whereas it has been shown that RCC technology has the potential for wide-scale application for reducing cooling loads for buildings in warm climates in the U.S. and many parts of the world, there remain a number of barriers to the full application of the technology. The barriers to the technology become the basis for future research agendas.

BARRIER: Lack of valid radiative property data for common building materials. For energy design purposes, solar reflectance and emittance data for building materials in standard references, e.g. ASHRAE Fundamentals, are incomplete and the available data are of questionable accuracy. The lack of valid radiative property data prevents the accurate design analyses of the energy conservation benefits of RCCs.

RECOMMENDATION: That governmental and building industry professional organizations and private

industry coordinate efforts to develop and publish valid radiative property data for common building materials.

BARRIER: Lack of material standards for RCC materials. Material standards are needed to assure uniformity in testing of the properties of RCCs and to provide a basis for acceptance of RCCs as an energy conservation measure in model energy conservation codes.

RECOMMENDATION: That governmental, manufacturers and professional organizations support the research necessary for the development of ASTM standards for RCC materials.

BARRIER: Lack of demonstrated seasonal and annual energy savings for RCC applications on buildings in different climates. Demonstration data are needed to gain public acceptance of the RCC technology and to demonstrate the validity of design calculation methods.

RECOMMENDATION: That controlled demonstrations of energy savings for RCC applications be conducted on buildings in different climates.

BARRIER: Lack of commonly used methods for calculation of building envelope energy loads that address the radiative properties of building materials. Needed are improved calculation methods that allow input of detailed radiative property data of envelope surfaces and adjust the thermal resistance values of building envelope components in accordance with the temperatures experienced by the building component. Currently, calculation methods assume constant thermal resistance values for building components. For example, errors in heat loads arise when the thermal resistance of roof insulation is assumed constant for both "black" and "white" roofs, even though the surface temperature of the black roof, and hence temperature of the roof insulation, will be significantly higher than the white roof during daylight periods.

RECOMMENDATION: That improved energy load calculation methods be developed that account for the radiative properties of building envelope surfaces and the resulting effects of component temperatures on the thermal resistances of the materials in the envelope component.

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APPENDIX A: MODELING OF ROOF STRUCTURES, BLAST INPUTS.

The thermal performances of roofs were calculated with the personal computer (PC) version of BLAST, version 3.0, level 130. The BLAST computer program was developed by the U. S. Army Corps of Engineers Construction Engineering Research Laboratory in Champaign, Illinois.

Annual heating and cooling loads were calculated using weather files based on NOAA Typical Meteorological Year (TMY) data for the respective cities. Design day loads for the different cities were calculated using design day data provided in the ASHRAE Handbook - Fundamentals, ch.24.

The roofs used in the analyses were placed on a standard cubical structure consisting of four walls and a floor. The cubical structure was necessary to allow radiative coupling between the inside roof surface with the walls and floor. To eliminate the effects of other external and internal loads, such as air infiltration, solar loads through windows, lighting, etc., the walls were specified as "internal partition walls" having no conductive heat flow, and there were no internal loads placed within the cubical space. The floor was of specified as "slab concrete" and was insulated from the ground.

The following are the specifications for the standard test cubical and roof structures; the characteristics of the materials are those provided in the materials library of the BLAST program.

Dimensions:

Roof/floor - 15.24 m X 15.24 m (232.2 m²).

Wall - 15.24 m X 2.4 m (total wall area, 148.6 m²).

Roof construction:

Top layer - RCC coating, solar reflectance - 0.1 to 0.85,
thermal absorptance - 0.9,
roughness - smooth.

Second layer - expanded polystyrene insulation,
2.54 to 15.2 cm thick.

Bottom layer - 1.9 cm-thick plywood deck.

Total R-values of roofs, from 0.9 to 4.4 m²*K/watt.

Wall construction ("interior wall"):

0.2 m lightweight concrete block, thermal absorptance - 0.9,
roughness - rough.

Floor construction, slab on grade:

0.1 m high density concrete, thermal absorptance - 0.9,
0.23 m expanded polystyrene insulation.

Total R-value of floor - 6.52 m²*K/watt.

COOLING LOADS

ROOF SURFACE TEMPERATURES

CEILING TEMPERATURES

FIG. 1 Roof with white RCC surface, Las Vegas summer design day.

COOLING LOADS

ROOF SURFACE TEMPERATURES

CEILING TEMPERATURES

FIG. 2 Roof with black rubber surface, Las Vegas summer design day.

FIG. 3 Effect of roof reflectance on annual roof cooling loads and total cooling + heating loads; Las Vegas

FIG. 4 Effect of roof reflectance on annual roof cooling loads and total cooling + heating loads; Minneapolis.

Las Vegas, roof temperatures
(maximum air temperature: 42 °C)

Minneapolis, summer roof temperatures
(maximum air temperature: 32 °C)

FIG. 5 Effect of roof reflectance on maximum roof surface temperatures during summer design days; Las Vegas and Minneapolis

FIG. 6 Effect of roof reflectance on maximum hourly cooling demand during summer design days; Las Vegas and Minneapolis.

Fig 7. Measured (RTRA) and calculated (BLAST) outside air temperatures, August 18.

Fig. 8 Measured (RTRA) and calculated (BLAST) cooling loads for RTRA roof configuration, August 18.

ROOF SURFACE TEMPERATURES

AUGUST 18

Fig. 9 Measured (RTRA) and calculated (BLAST) roof surface temperatures for RTRA roof configuration, August 18.

CEILING SURFACE TEMPERATURES

AUGUST 18

Fig. 10 Measured (RTRA) and calculated (BLAST) ceiling temperatures for RTRA roof configuration, August 18.

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