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# Refinements and Improvements to the Radiant Time Series Method

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## ABSTRACT

*This paper provides an overview of recent refinements and improvements to the Radiant Time Series Method (RTSM) as part of 1326-RP. These refinements and improvements include updating the fenestration model to be consistent with currently available manufacturers' data, development of a correction for heat losses that can be significant in buildings with high percentages of single-pane glazing on the façade, and development of compact procedures for computing radiant time factors (RTF) and conduction time series factors (CTSF). In addition, verification of the RTSM against the Heat Balance Method (HBM) with a large parametric study is also summarized.*

## INTRODUCTION

The Radiant Time Series Method (RTSM) is a simplified cooling load calculation procedure, originally developed (Spitler et al. 1997) to provide a rigorously-derived approximation to the Heat Balance Method (HBM) (Pedersen et al. 1997). It effectively replaced all other simplified (non-heat-balance) methods such as the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor Method (CLTD/SCL/CLF), the Total Equivalent Temperature Difference/Time Averaging Method (TETD/TAM), and the Transfer Function Method (TFM.)

Compared to the methods previously available, the RTSM is quite similar to the TFM. (Spitler and Fisher 1999) Like the TFM, the RTSM may be classified as a two-step method – heat gains are computed first, then cooling loads. Both methods compute loads for a 24-hour design day. In the TFM, conduction heat gains were computed with conduction transfer functions (CTF) and cooling loads were computed with weighting factors (WF); in both cases, iteration was needed to arrive at the solution for a single day. The most important difference between the two methods is that the RTSM eliminated the need for iterative solutions of conduction heat gains and cooling loads by assuming steady periodic boundary conditions and then deriving 24-term response factor series. For conduction heat gains, a 24-term series of periodic response factors (PRF) related the conduction heat gain to the 24 hourly sol-air temperatures and a constant room air temperature. The periodic response factors were later replaced with conduction time series factors (CTSF), which non-dimensionalize the PRF by dividing by the U-factor. For determination of cooling loads from heat gains, a 24-term series of radiant time factors (RTF) were derived. Elimination of the need for iteration made the RTSM well-suited for spreadsheet application.

For the TFM, CTF and WF were available from electronic databases (Falconer et al. 1993) and printed tables. For the RTSM, the Cooling and Heating Load Calculation Principles book (Pedersen et al. 1998) (Pedersen, et al. 1998) was accompanied by an HBM computer program that could calculate PRF and RTF. Printed tables of select PRF and RTF were later developed (Spitler and Fisher 1999; ASHRAE 2001). For both the TFM and RTSM, pre-tabulated factors for conduction heat gain and cooling load calculations require the user to select wall types or zone types that most closely match the actual wall type or zone type. What "most closely matches" may not be clear in all cases, even to experienced designers. Use of a separate computer program to determine PRF, CTSF, and RTF, which must then be input to a spreadsheet is also less than desirable. Therefore, one improvement to the method has been development of compact procedures for computing CTSF and RTF.

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Since the original development of the RTSM, solar heat gain coefficients (SHGC) have replaced shading coefficients (SC) as the key figure of merit characterizing window performance. Therefore, the fenestration model of the RTSM was updated to utilize SHGC. Shading coefficients gave transmitted solar radiation and inward-flowing absorbed solar radiation as separate quantities; each of which in the RTSM had different recommended values of radiant fraction. Since SHGC give the total window heat gain due to solar radiation, including both transmitted solar radiation and inward-flowing absorbed solar radiation in one quantity, a new recommendation for radiant fractions was developed based on a large parametric study.

As shown by Rees, et al. (1998), the RTSM, like the TFM, generally showed a small amount of overprediction of peak cooling load compared to the HBM. As both the TFM and the RTSM are approximations to the HBM, it is generally desirable that any inaccuracies result in overprediction rather than underprediction. However, for rooms with high percentages of the exterior façade covered with single-pane glass, the overprediction can be significant, exceeding 40% in extreme cases, in cooler climates where the room geometry approaches that of a vertical solar collector. Rees, et al. (1998) demonstrated for one extreme case with 37% peak cooling load overprediction that about 80% of the overprediction was due to heat gains that entered the room but that were then lost through the single-pane glass. Therefore, one refinement to the RTSM described here is a correction factor that can be applied for rooms where significant overprediction is possibility.

Finally, performance of the RTSM performance is verified against the HBM for a large number of cases with a parametric study. The study and results are described briefly in this paper.

## COMPACT CTSF AND RTF GENERATION

All simplified cooling load calculation procedures rely on some type of pre-calculated factors to compute conduction heat gains and cooling loads. Prior to the advent of the RTSM, the Cooling Load Temperature Difference / Solar Cooling Load / Cooling Load Factor Method (CLTD/SCL/CLFM) relied on tabulated CLTDs to determine the cooling load resulting from conduction heat gain, tabulated CLFs to estimate cooling loads resulting from internal heat gains, and SCLs to estimate cooling loads resulting from solar heat gains. The Transfer Function Method (TFM) relied on tabulated conduction transfer functions (CTFs) to estimate conduction heat gain and weighting factors to convert all types of heating gains to cooling loads. The last ASHRAE load calculation manual to feature the CLTD/SCL/CLFM and TFM (McQuiston and Spitler 1992), was accompanied by software that could look up CTFs and WFs from a database developed by Falconer, et al. (1993). Software that could compute CLTDs, SCLs and CLFs, using the database CTFs and WFs also accompanied the manual. In every case, some judgment is required on the part of the user to match actual wall constructions or actual room constructions to those tabulated in the database.

Although tabulated values may be useful for many cases, it is highly desirable to have the capability to compute wall response factors, CTSF, and room response factors, RTF, based on physical descriptions of the wall and room, respectively. As the RTSM is intended as a spreadsheet application, it is also desirable that the CTSF and RTF be computable by the spreadsheet rather than an external program. As part of this project, the first approach that was attempted involved the use of Fortran programs, adapted from the ASHRAE Load Calculations Toolkit (Pedersen et al. 2001), and compiled as dynamic linked libraries (DLLs) that could be called from the spreadsheet. Initial testing of this approach revealed that the speed of computation was excellent, but occasional problems with outside users of the software being unable to get the DLLs to work lead us to abandon this approach.

Instead, compact procedures were developed and implemented in the macro language native to Microsoft Excel, Visual Basic for Applications. These procedures are described in detail by Nigusse (2007). A brief description follows here.

### Compact CTSF Generation

Conduction time series factors (CTSF) are determined with a one-dimensional finite volume method (FVM) model. The user-provided layer-by-layer description is divided into a grid with six volumes per layer. Time steps are fixed at 60 seconds. The FVM model of the wall is pulsed with a unit heat gain triangular temperature pulse at the exterior surface. The hourly conduction heat gain at the interior surface forms a set of response factors. These response factors are combined (Spitler et al. 1997) to give PRF, then divided by U to give CTSF. As shown by Nigusse (2007), for 83 typical wall and roof constructions, the maximum difference in peak conduction heat gain computed with CTSF generated by this procedure and CTSF generated by the state space method (Seem et al. 1989) provided with the ASHRAE Loads Toolkit is 2.2%; the average difference is 0.03%. More refined gridding procedures might be introduced to improve the accuracy of the method, but the current accuracy is sufficient for cooling load calculation procedures, where conduction heat gains almost always make up only a small fraction of the peak cooling load.

The 1-d FVM procedure has the further advantage of being very compact. The procedure is implemented in about 500 lines of VBA or F90 code, compared to about 2000 lines of F90 code used to implement the state-space method.

### Compact RTF Generation

Similar to the situation with CTSF, it is convenient to have a procedure for generating RTF within the spreadsheet. In order to make this a reality, a new RTF generation procedure was developed that is much simpler than the full heat balance method (HBM) utilized in HBFORT. The so-called "reduced heat balance method" (RHBM) requires only inside surface heat balance equations and takes advantage of the periodicity of the problem. The RHBM eliminates the following procedures that are part of the full heat balance method: outside surface heat balance, solar radiation calculations, shading calculations, infiltration and ventilation.

A further simplification tested for the RHBM and found to work well is the use of a fixed radiation heat transfer coefficient. The RHBM utilizes the Carroll (1980) MRT network method for radiation interchange between surfaces. Carroll defines a preliminary estimate of the radiation coefficient which may be calculated for each surface. Use of this estimate, without further iterative improvement, can be shown to give excellent results. Figure 1 shows peak cooling loads computed with RTF based on fixed radiation coefficients compared to peak cooling loads computed with RTF based on variable radiation coefficients for 13,440 zones of mixed construction type and aspect ratio. The maximum difference error caused by the fixed radiation coefficient is 0.2% in peak cooling load and the average over all cases is 0.03%. The simplification considerably speeds up the calculation of RTF, so use of this assumption is recommended.

A procedure analogous to that described in the previous section for obtaining CTSF is utilized to compute periodic response factors that give the conduction heat gain at the inside surface due to a temperature pulse at the inside surface. This model of conduction heat gain is coupled with fixed convection coefficients and the MRT network procedure with fixed radiation coefficients, the interior surface heat balance equations for 24 hours can then be cast in matrix form and solved with a single matrix inversion. A full derivation of the RHBM is given by Nigusse (2007). A key feature is that the resulting code is very compact – about 500 lines in VBA or F90, compared to about 4000 lines of F90 code for an implementation of the full HBM used to generate RTF. The compact coding made feasible by the RHBM has the advantages (all other things – documentation, clarity, etc. – being equal) of being easier to understand, maintain, and port to other environments.

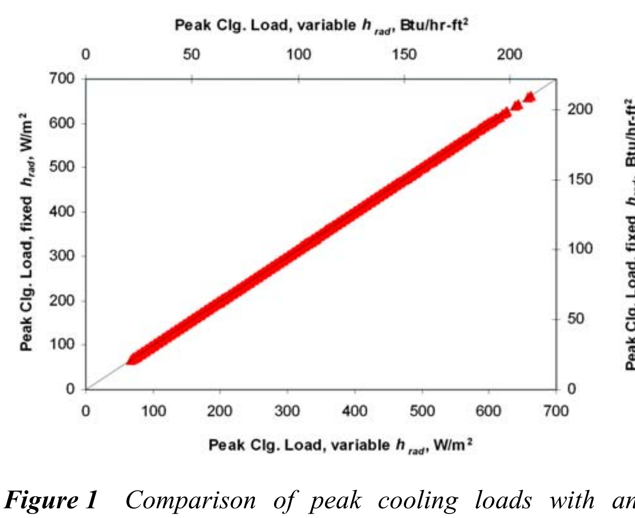


***Figure 1*** *Comparison of peak cooling loads with and without fixed radiation coefficient assumption.*

## UPDATING THE FENESTRATION MODEL

In the original development of the RTSM, shading coefficients were utilized for fenestration heat gain and no procedure was recommended for windows with interior shading, e.g. Venetian blinds. Since that time, the ASHRAE Handbook (2005) treatment of fenestration has shifted to the use of solar heat gain coefficients (SHGC) and, for interior shading, the interior attenuation coefficient (IAC). Window manufacturers have also begun reporting SHGC; these data are available from the National Fenestration Rating Council (NFRC).

Accordingly, the RTSM has been revised to use solar heat gain coefficients instead of shading coefficients and has been expanded to include interior shading with the use of the IAC. Previously, with shading coefficients, the transmitted and absorbed inward flowing components of solar radiation were estimated separately. With solar heat gain coefficients, the transmitted and absorbed components are lumped together. This, in turn, required further investigation of radiative/convective splits since the splits appropriate for transmitted radiation and absorbed radiation could not be readily combined to form a single radiative/convective split. In addition, with windows that have interior shading, the radiative fraction of the heat gain is reduced substantially, but this was not treated at all in the original development of the RTSM.

Adoption of SHGC and incorporation of interior shading required determination of additional recommended radiative/convective splits, which are summarized in Table 1. The recommended radiative/convective splits for windows were determined with a large parametric study, described below in the section "Verification of the RTSM". The parametric study was used to find radiative/convective splits that minimized overprediction of cooling loads (compared to the HBM) without leading to significant underprediction for a wide range of cases.

## OVERPREDICTION CORRECTION

The radiant time series method (RTSM) generally performs as desired for a simplified cooling load calculation procedure – it has a small but acceptable amount of over prediction of peak cooling loads compared to the heat balance method (HBM). However, as shown previously by Rees, et al. (1998), for zones with a significant amount of single-pane glass, the RTSM can over predict the peak cooling load as much as 44%. To a lesser degree, zones with significant amounts of double-pane glazing (Nigusse 2007) can have overprediction as high as 14%. In theory, this could also be the case for other high conductance surfaces, such as a tent.

Nigusse (2007) has developed a correction for zones that can be applied to the RTSM. It has been tested for a very wide range of test zones and can be applied to all zones, or only to zones where significant over prediction is expected. The correction factor takes the form of a dimensionless conductance that is computed from the zone geometry, inside combined conductance, and the overall U-value of the fenestration. In addition, a slightly different value of radiative fraction is recommended for window solar heat gain. The correction factor has been tested

**Table 1. Recommended Radiative/Convective Splits for Internal Heat Gains**

| Heat Gain Type | Recommended Radiative Fraction | Recommended Convective Fraction | Comments |
|---|---|---|---|
| Occupants—typical office conditions | 0.6 | 0.4 | Radiative/convective splits for other conditions are given in Table 6.1 of the Load Calculation Applications Manual. |
| Equipment | 0.1–0.8 | 0.9–0.2 | Recommended radiative/convective splits for motors, cooking appliances, laboratory equipment, medical equipment, office equipment, etc. are given in Chapter 6 of the Load Calculation Applications Manual |
| Office equipment with fan | 0.10 | 0.9 | |
| Office equipment without fan | 0.3 | 0.7 | |
| Lighting | | | Recommended radiative/convective splits, taken from Fisher and Chantrasrisalai (2006), are given in Table 6.3 of the Load Calculation Applications Manual. |
| Conduction heat gain through walls and floors | 0.46 | 0.54 | |
| Conduction heat gain through roofs | 0.60 | 0.40 | |
| Conduction heat gain through windows | 0.33 (SHGC>0.5)<br>0.46 (SHGC≤0.5) | 0.67 (SHGC>0.5)<br>0.54 (SHGC≤0.5) | |
| Solar heat gain through fenestration w/o interior shading | 1.0 | 0.0 | |
| Solar heat gain through fenestration w/ interior shading | 0.33 (SHGC>0.5)<br>0.46 (SHGC≤0.5) | 0.67 (SHGC>0.5)<br>0.54 (SHGC≤0.5) | |
| Infiltration | 0.0 | 1.0 | |

for a very wide range of test zones and can be applied to all zones, or only to zones where significant over prediction is expected. The correction factor takes the form of a dimensionless conductance that is computed from the zone geometry, inside combined conductance, and the overall U-value of the fenestration. In addition, a slightly different value of radiative fraction is recommended for window solar heat gain.

Derivation of the dimensionless loss conductance is described in some detail by Nigusse (2007). In the simplest form, for a room with one window, the dimensionless loss conductance is given as:

$$U^* = \frac{U_{window}}{h_{i,\,window}} \times \frac{A_{window}}{A_{room}} \tag{1}$$

Where

$U_{window}$ = is the U-factor for the window, Btu/hr·ft$^2$°F or W/m$^2$K

$h_{i,window}$ = inside surface conductance for the window, Btu/hr·ft$^2$°F or W/m$^2$K

$A_{window}$ = the window surface area, ft$^2$ or m$^2$

$A_{room}$ = the total interior surface area of the room including furniture, ft$^2$ or m$^2$

For a room with $M$ windows, the dimensionless heat loss conductance is given by:

$$U^* = \left(\frac{1}{A_{room}} \sum_{j=1}^{M} \frac{U_j A_j}{h_{i,j}}\right) \tag{2}$$

Where

$U_j$ = is the U-factor for the $j$th window, Btu/hr-ft$^2$°F or W/m$^2$K

$h_{i,j}$ = inside surface conductance for the $j$th window, Btu/hr·ft$^2$°F or W/m$^2$K

$A_j$ = the $j$th window surface area, ft$^2$ or m$^2$

$A_{room}$ = the total interior surface area of the room including furniture, ft$^2$ or m$^2$

For windows with interior shades, the U-factor would include the resistance of the shade and the air gap. For zones with two exterior facades, the dimensionless loss conductance, depending on the glazing fraction, may range from 0.01 to 0.14. Figure 2 shows sample values of dimensionless loss conductances for zones with different types of glass as a function of the exterior façade glazing fraction. The possible overprediction without correction is roughly correlated to the dimensionless loss conductance. As may be inferred from Figure 2, the overprediction is most significant for zones with a large amount of unshaded single-pane glass.

## VERIFICATION OF THE RTSM

The RTSM is validated against the HBM for a wide range of zone types, locations, etc. with a large parametric study, as described by Nigusse (2007). A short summary follows here.

The parametric run tool (Spitler and Rees 1998) developed for ASHRAE 942-RP was modified for use in this study. A total of 2,867,200 zones were utilized for comparisons. Parameters varied included: zone orientation, zone aspect ratio, % of exterior façade glazed, type of glazing, type of interior shading, zone envelope construction, zone thermal mass construction, location, month of the year, interior heat gain quantities and schedules. 14 US locations combined with 7 months (June-December) gave a wide range of outdoor boundary conditions. (In the temperate zone latitudes of the northern hemisphere, peak cooling loads can occur at any month between July and December, depending on the relative dominance of air temperatures and solar angles.)

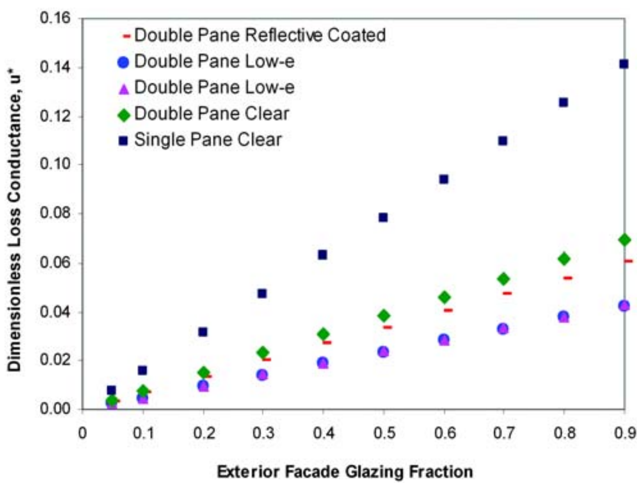


*Figure 2* *Dimensionless loss conductance for zone with two exterior façades and unshaded glazing.*

Subsets of the results are presented in the following figures, with each plot representing 358,400 combinations of zone orientation, fenestration type, geometry, % of façade glazed, zone construction, internal heat gains, thermal mass, location, and month. In each case, the peak cooling loads given by the "Current" RTSM (i.e. without the heat loss correction factor) and those given by the "Improved" RTSM (i.e. with the heat loss correction factor) are compared to the heat balance method. The results have been normalized to Watts per square meter and Btu/hr per square foot of zone floor area. The solid diagonal line shown on each figure represents a perfect match between the RTSM and the HBM. The labeled dashed lines represent the upper bounds on the overpredictions by the "Current" and "Improved" RTSM.

Figures 3 and 4 show results for lightweight and heavyweight zones with single-pane, unshaded glass. As can be seen, the improvement given by the heat loss correction factor is quite dramatic for these cases, reducing the maximum overprediction by about 2/3 for both lightweight and heavyweight zones. It should be kept in mind that the most dramatic improvement is for the spaces with the highest loads – generally highly glazed facades, usually on corners, so that two exterior facades are exposed.

In general, as the solar radiation heat gain becomes less dominant, due to shading or improved glass, and/or as the heat loss through the glazing becomes less important, due to multiple panes of glass, the overprediction of the current RTSM is

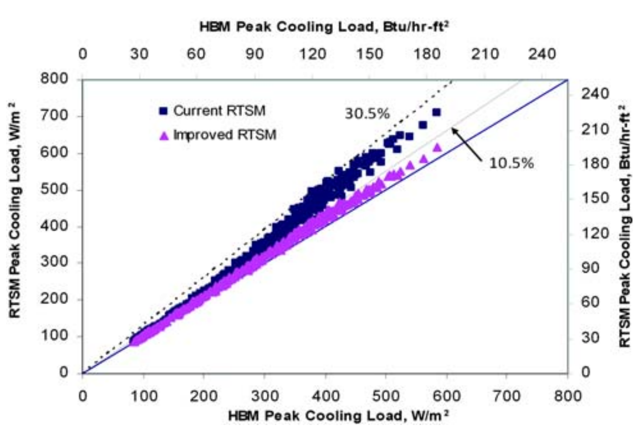


*Figure 3* *Results for lightweight zones with unshaded single-pane glass.*

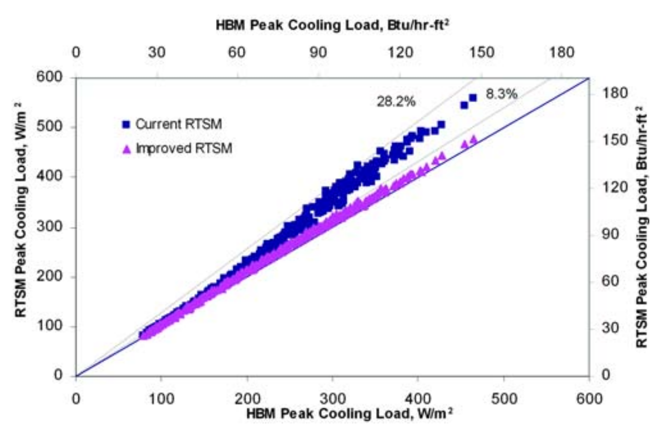


*Figure 4* *Results for heavyweight zones with unshaded single-pane glass.*

less important and the heat loss correction factor has a smaller effect. Figures 5 and 6 are for similar subsets of the results as Figures 3 and 4, except that the single-pane glass is now shaded with one of three types of interior shade: medium color Venetian blinds, dark roller shades, or close-weave dark-color drapery. As can be seen, the overprediction of the current RTSM is significantly lower, as is the effect of the heat loss correction factor.

It may also be observed that the lightweight zone has less overprediction than the heavyweight zones. This is an indirect consequence of the choice of radiative/convective splits. Choosing higher values of the radiative fraction results in lower overprediction; choosing lower values results in higher overprediction. But the amount of overprediction will vary with the effective mass of the zone. Heavyweight zones are naturally more sensitive to the radiative fraction. The values given in Table 1 above were chosen to give minimum overprediction over a wide range of cases without ever giving significant underprediction. While it might be possible to further refine Table 1 based on the weight of the zone, it was judged to further complicate the method without a significant increase in accuracy.

Tables 2 and 3 summarize the maximum overprediction for all five glass types, with and without interior shading. As discussed above, the overprediction is mainly problematic for single-pane clear glass, although it can be as high as 17% for double-pane glass. This would occur for cases with high glazing fractions. Figure 7 illustrates this for a smaller subset of 1100 zones, with maximum overprediction plotted against glazing fraction. For these cases, the maximum overprediction exceeds 10% when the double-pane glass takes up 50% of the exterior façade area.

## CONCLUSIONS

This paper has described a series of refinements and improvements to the Radiant Time Series Method:

- Compact procedures for generating conduction time series functions and radiant time factors are suitable for implementation in the macro language environment of a spreadsheet. The compact nature of the algorithm facilitates implementation in other environments. The use of fixed radiation coefficients within the MRT network model increases computational speed with very little impact on accuracy.
- The RTSM was adapted to use solar heat gain coefficients instead of shading coefficients as input data for fenestration. This allows ready use of the RTSM with currently available manufacturers' data. Interior shading, not previously explicitly accounted for in the RTSM, may now be included.
- It has been previously shown that the RTSM generally has a small but acceptable amount of overprediction of peak cooling loads, except for rooms with significant amounts of single-pane glass. A dimensionless loss conductance has been developed that can be applied to all zones, or only zones where significant overprediction is expected. For the zones with significant amounts of single-pane glass, the overprediction is reduced by about 2/3.

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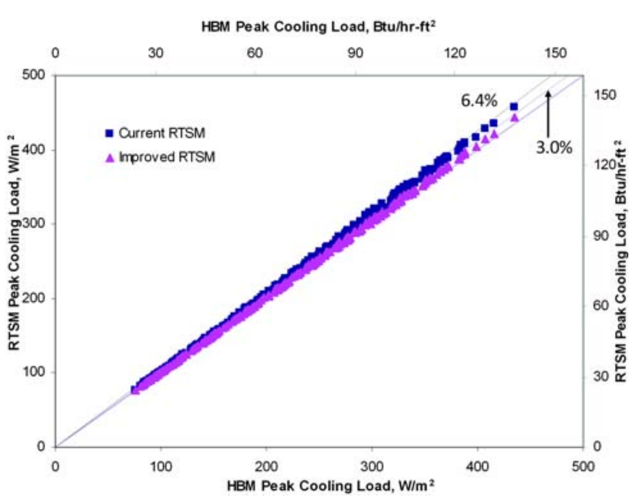


***Figure 5*** *Results for lightweight zones with shaded single-pane glass.*

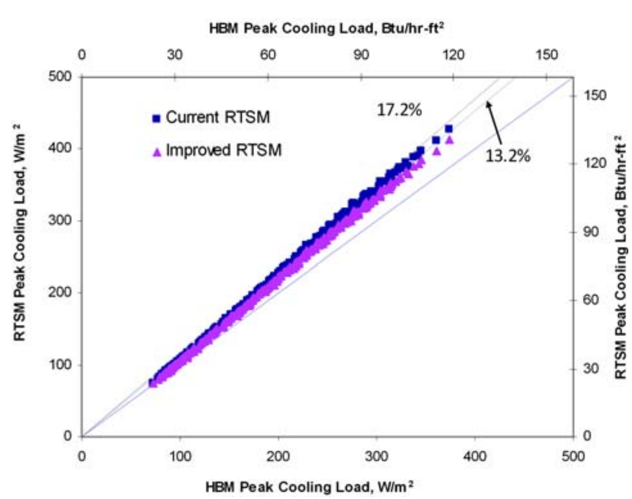


***Figure 6*** *Results for heavyweight zones wit hshaded single-pane glass.*

**Table 2. RTSM Peak Cooling Load Maximum Overprediction for Glazing Without Shade**

| Glazing Types | Current RTSM Maximum Over Prediction, % | | Improved RTSM Maximum Over Prediction, % | |
|---|---|---|---|---|
| | Lightweight Construction | Heavyweight Construction | Lightweight Construction | Heavyweight Construction |
| Single-Pane Clear Glass (SHGC =0.80) | 30.4 | 28.2 | 10.5 | 8.3 |
| Double-Pane Clear Glass (SHGC =0.76) | 14.0 | 13.1 | 5.9 | 6.9 |
| Double-Pane Low-e Glass (SHGC =0.65) | 8.5 | 7.8 | 4.1 | 5.8 |
| Double-Pane Low-e Glass (SHGC =0.39) | 10.4 | 7.9 | 6.0 | 5.7 |
| Double-Pane Reflective Coated Glass (SHGC =0.21) | 18.5 | 14.5 | 11.7 | 9.0 |

**Table 3. RTSM Peak Cooling Load Maximum Overprediction for Glazing with Interior Shade**

| Glazing Types | Current RTSM Maximum Over Prediction, % | | Improved RTSM Maximum Over Prediction, % | |
|---|---|---|---|---|
| | Lightweight Construction | Heavyweight Construction | Lightweight Construction | Heavyweight Construction |
| Single-Pane Clear Glass (SHGC =0.80) | 6.4 | 17.2 | 3.0 | 13.2 |
| Double-Pane Clear Glass (SHGC =0.76) | 7.1 | 19.9 | 4.8 | 17.1 |
| Double-Pane Low-e Glass (SHGC =0.65) | 7.3 | 19.6 | 5.7 | 17.7 |
| Double-Pane Low-e Glass (SHGC =0.39) | 8.2 | 14.2 | 6.1 | 11.7 |
| Double-Pane Reflective Coated Glass (SHGC =0.21) | 11.4 | 14.2 | 8.6 | 11.1 |

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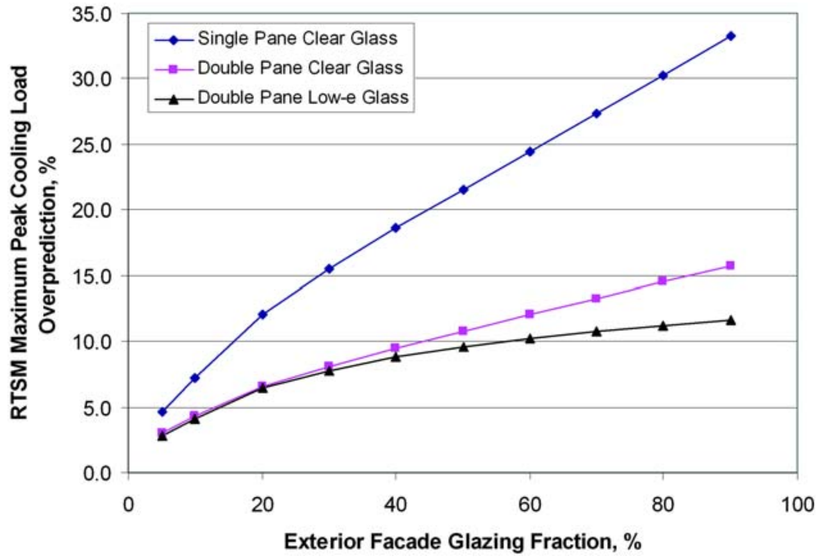


***Figure 7*** *Maximum RTSM peak cooling load overprediction versus glazing fraction and type.*

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