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Within the last year the Division has received many reports of wooden roof trusses deflecting upwards in the winter. This is contrary to the normal expectation that if any significant deflection did occur it would be downward because of dead and live loads. In the reported cases deflection effect became noticeable when large cracks opened between the ceiling and partitions which could not be explained through foundation or partition settlement.

It was suspected that moisture contributed to the problem and DBR was asked for an opinion. Probing calculations were made which indicated that under some conditions, and certainly for the cases reported, seasonal changes in the moisture-temperature regime could cause an upward movement.

VARIABLES

A fully developed laboratory and field research project into this phenomenon would require several seasons. Variables that would have to be explored would be:

- (i) span of trusses
- (ii) size of members
- (iii) types of truss
- (iv) amount of insulation
- (v) type of joint connections
- (vi) local outdoor environment
- (vii) moisture content of wood when installed
- (viii) ventilation of attic
- (ix) effectiveness of vapour barrier
- (x) kind of wood
- (xi) snow loads on roofs

In the present study the first six variables were fixed by selecting two specific designs from those parts of the country in which the problem occurred. The remainder of the factors were investigated to a limited extent by estimating a reasonable range of values or conditions.

TYPES OF ROOFS INVESTIGATED

Two types of roofs were investigated: mobile home roof in the Lethbridge area; and metal gusset plate Howe truss roof on a house in the Montreal area.

MOBILE HOME ROOF

Description of Roof

The shape, span and timber member sizes of the mobile home roof as well as the insulation are shown in Figure 1. Its shape and construction is that of a tied arch. Because of the "foamcore" insulation over the top chord it was assumed that the metal roofing is not attached rigidly enough to participate in the arch action.

Arch Deflection Formula

The complete derivation of formulae for moisture and thermal deflections of a tied arch are lengthy (1). For the given configuration and dimensions however they reduce to the following simple expression:

$$y = 1032\ (\alpha t + \Delta s)$$

where

- y = the deflection (negative when downwards)
- α = the coefficient of thermal expansion
- t = the difference between the top chord temperature and the bottom chord temperature (negative for temperature decrease)
- Δs = movement of top chord relative to movement of bottom chord due to moisture change (negative for shrinkage)

Assumptions and Results of Calculations

Because the real thermal-moisture conditions within the roof space are in general unknown, calculations were made for three assumed situations.

Calculation A

It was first assumed that the roof space had enough ventilation to allow the thermal-moisture conditions of the air and timber arch members to come into equilibrium with outdoor conditions. Daily fluctuations were ignored since the wood moisture content would depend on changes in the daily average temperature and relative humidity over periods of weeks or months.

Published research results (2,3) indicate that in December, January, and February both the moisture content of wood and the relative humidity in a location exposed to outdoor temperatures, but not to rain and snow, tend to remain fairly constant. During the Spring months they drop but become stable again at a lower value during June, July and August. In this investigation, therefore, the outdoor mean temperatures and relative humidity for January and July were used in the calculations. If the upward deflection of roofs is due to thermal-moisture movements a lot would depend on the time of year of construction but the foregoing assumptions were expected to predict the maximum potential range of possible movements.

From climatological records (4) the following weather data was obtained for Lethbridge:

Mean January Temperature	-	14.5°F
Mean January R/H	-	71%
Mean July Temperature	-	65°F
Mean July R/H	-	50%

Further assumptions had to be made regarding the air temperature in the roof space because it is, in general, unknown. In winter the mean temperature was taken to be 0, 5, 10 or 20F degrees above the mean outside temperature; in summer, 0, 20 or 40F degrees.

Values for the relation between relative humidity and wood moisture content which are probably average for the common species were taken from previously published data (5,6). Moisture content vs shrinkage relations were also taken (7). Shrinkage parallel to the grain from fibre saturation to oven dry was taken as 0.2 per cent (8).

As the bottom chords of the trusses are insulated on both sides, the mean temperature of the truss chord was estimated on the basis of a one-dimensional heat flow assumption. The temperature of the top chord was taken to be the same as that of the air space because of the insulation between it and the metal roofing.

In this calculation it was also assumed that the vapour barrier in the ceiling was perfect and the interior temperature 72°F.

The results of the calculations are shown in Figure 2. The predicted upward deflection was found to be due to the higher moisture content of the top chord relative to the bottom one and its variation with seasonal temperatures and relative humidity. Calculated deflections caused by temperature changes and the coefficient of expansion were relatively minor and in the opposite direction but were included in the analysis. The maximum deflection obtained was about 3/4 in. reached when the roof space temperature was the same as outdoors. For an attic temperature of 34.5°F (10° above outdoors) the calculated deflection was about 75 per cent lower. In general, deflections are more sensitive to winter temperature assumptions than to summer attic space temperatures.

The reported deflection in the mobile home was 1 1/2 in. or about twice that calculated under the foregoing assumptions. This may be due to some sort of ratcheting action between the trusses and the partitions with the trusses riding up on the partition installation screws. It is more likely, however, that the assumptions for the calculations were wrong.

Calculation B

As a second trial it was assumed that the roof space was completely sealed and that the wood was installed at a moisture content of 10 per cent. With an assumed winter attic temperature of 20°F and a bottom chord temperature of 42°F, the redistribution of moisture between the lower and upper chords (equalization of vapour pressures) was investigated along with an estimate of the accompanying deflections.

For this calculation it was necessary to assume a linear relationship between relative humidity and wood moisture content. From inspection of graphs by Hedlin (6) it was taken that for relative humidities above 10 per cent:

moisture content (%) = K (RH) + 3
where K = 0.18 to 0.22

Although the assumptions were rather crude, it was found that upward deflections of only about 1/2 in. could be accounted for by this mechanism.

Calculation C

A further assumption to be explored was that small breaks or leaks in the ceiling vapour barrier permit moisture-laden air into the roof space which would increase the moisture content of the wood. This would be a fairly continuous process and might result in free water or hoar frost on some members. Such a situation is not amenable to calculation but to explore the possibilities the following procedure was adopted.

It was assumed that enough moisture entered the space to raise the RH at the top chord to 100 per cent and the moisture content to the fibre saturation point. The system was then assumed sealed and the top and bottom chords allowed to come to moisture equilibrium.

On this basis, upward truss deflections of 1.1 to 1.4 in. were predicted depending on whether fibre saturation was taken as 30 or 24 per cent moisture content respectively. This is approximately equal to the reported deflections.

Conclusions re Mobile Home Roofs

The calculations made are speculative and dependent on the assumptions made. It seems a reasonable conclusion, however, that the upward deflection of the mobile home roofs can be accounted for by moisture considerations caused primarily by differences in temperature between the top and bottom chords. There is every possibility also that moisture entering the roof space from the interior contributes to the problem.

Deflection is controlled mainly by the movements of the top chord and there seems to be no possibility of holding the roof down by screwing or nailing it onto the partitions. The forces required would exceed the roof design load by a factor of four or more.

A solution to the problem would require an extensive research project to determine the actual conditions and to explore the mechanisms further. One set of moisture content measurements taken in March in an occupied mobile home, for example, gave higher moisture contents of the wood in the bottom chords.

This is the reverse of what was predicted herein for January.

It seems likely that the solution to the problem lies in keeping the temperatures and moisture contents of the upper and lower chords approximately equal. One way of achieving this might be to suspend the insulation below the bottom chord, but this may not be practical.

RESIDENTIAL METAL GUSSET PLATE HOWE TRUSS

The second roof investigated incorporated Howe trusses 27 ft 8 in. in span having a 5:12 slope. Members were 2 by 4's and the joints were made with metal plate connectors of unknown design. The ceiling of the house had 6 in. of insulation assumed to be rockwool installed so that the lower chords of the trusses were completely buried (Figure 3).

It was reported that the ceiling of this house and other similar ones deflected upward 1/4 to 1/2 in. in winter. This became evident as cracks appeared at the junction of the ceiling and partition walls, cracks which could not be explained by settlements.

Calculation Assumptions

In order to study the possibility of temperature and moisture being responsible for the deflections it was necessary to make the following assumptions:

(1) Location - Montreal

(2) January and July were taken as the extreme conditions and from Ref. (3) the following data was obtained:

Mean January Temperature	- 14°F
Mean January RH	- 75%
Mean July Temperature	- 70°F
Mean July RH	- 67%

(3) Attic space ventilated but mean winter temperature unknown. Values 0, 5, 10 and 20°F above outdoor temperature assumed.

(4) Attic assumed to attain peak summer temperature of 105°F but mean temperature taken as average of 105°F and a 70°F outdoor temperature, i.e., 87.5°F. The effect of assuming

that the mean summer attic space temperature was 100°F was also examined.

(5) Slopes of 4:12 and 3:12 were examined as well as the actual 5:12 slope.

(6) Calculations were made assuming only 4 in. of insulation was used.

(7) The plywood roof deck was assumed not to participate in the truss action because of joints, higher shrinkage and minimum nailing.

Calculation Method

Deflections of trusses due to linear changes in length caused by temperature and moisture movements were calculated by the virtual work method (9) and as exemplified by Hansen for wood trusses (10). It was considered that joint slip, if any, under dead load would occur when the trusses were installed and for zero and small live load conditions joint slip would not enter the calculation of subsequent potential movements.

RESULTS

Figure 4 shows the predicted upward deflections under the assumptions described. Curve A is the basic case for a span of 28 ft 6 in., 5:12 slope, 6 in. insulation, and a summer attic temperature of 87.5°F. Curves C and D illustrate the suppression of deflections likely because of an increase of the downward dead load deflection caused by creep and due to a light 10 psf snow load. Curve B illustrates the effect of assuming a 100°F mean summer attic temperature.

All of the values obtained are about the same magnitude as the deflections reported.

Figure 5 shows the probable relative effects, and in general:

(a) A decrease of slope results in greater upward deflection.

(b) A reduction of the insulation from 6 to 4 in. on the bottom chord decreases the deflection because it allows the chord to have a lower winter temperature and thus a higher moisture content.

(c) The calculated deflections for a 20-ft span, 5:12 slope, and 6 in. of insulation were lower than for a span of 28 ft 6 in.

DISCUSSION OF RESULTS

None of the factors studied suppressed the potential upward movement to any great degree, although it is evident that a full design snow load of 50 psf would substantially prevent the upward truss movements.

Since there are many houses where upward deflection of the ceiling is not evident, there must be other factors not explained by this study. Some may be:

(a) Trusses and partitions installed in Spring or Fall would probably exhibit movements on the average of about one-half those calculated;

(b) The deflections would probably be unnoticed in a house with no partitions and the incidence of cracking would probably depend, to some degree, on the partition layout;

(c) Tight wedging of partitions against the trusses would, in some instances, prestress the trusses and prevent differential movements; and

(d) Improper assumptions. Obviously, actual cases and thermal-moisture regimes would have to be studied to establish all the facts.

CONCLUSION

This Technical Note was written with the hope that it would help to explain the upward deflection of wood trusses observed in some roofs. It is also hoped that it will encourage the reporting of other cases of this problem so that its prevalence can be evaluated.

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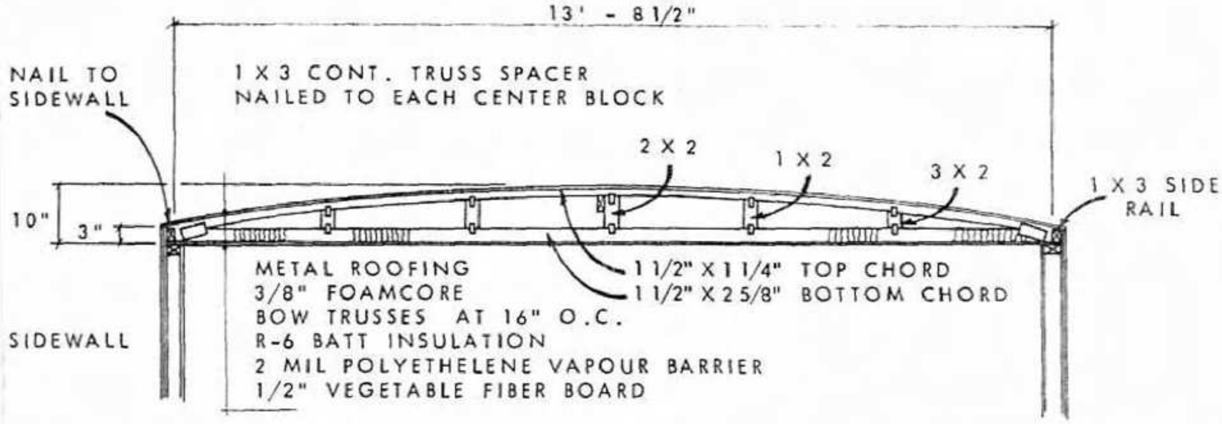

NOTE:

INTERIOR PARTITIONS
ARE SCREWED TO RAFTERS
OR TO LADDERS SPACED
24" O.C. BETWEEN RAFTERS

FIGURE 1

MOBILE HOME ROOF

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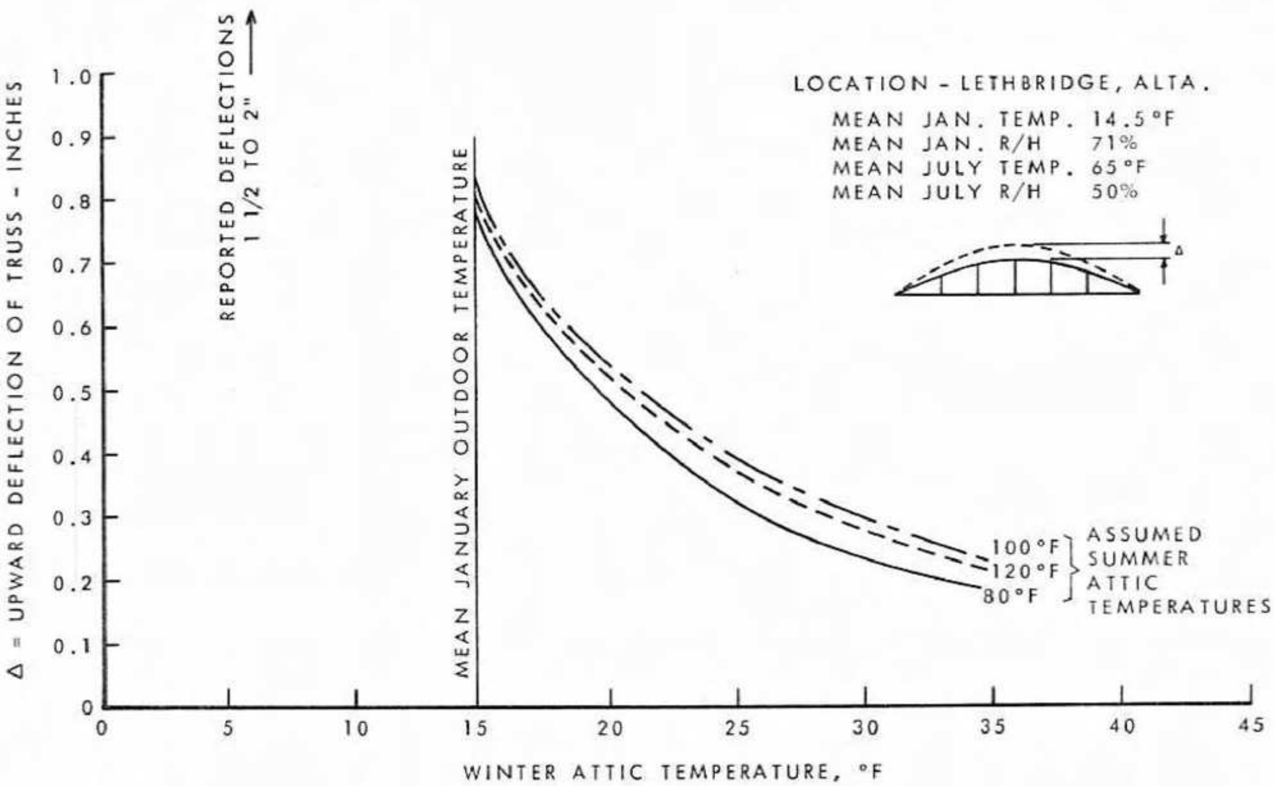

FIGURE 2

CALCULATED DEFLECTION OF TIMBER ARCH - TRUSS ROOF OF MOBILE HOME

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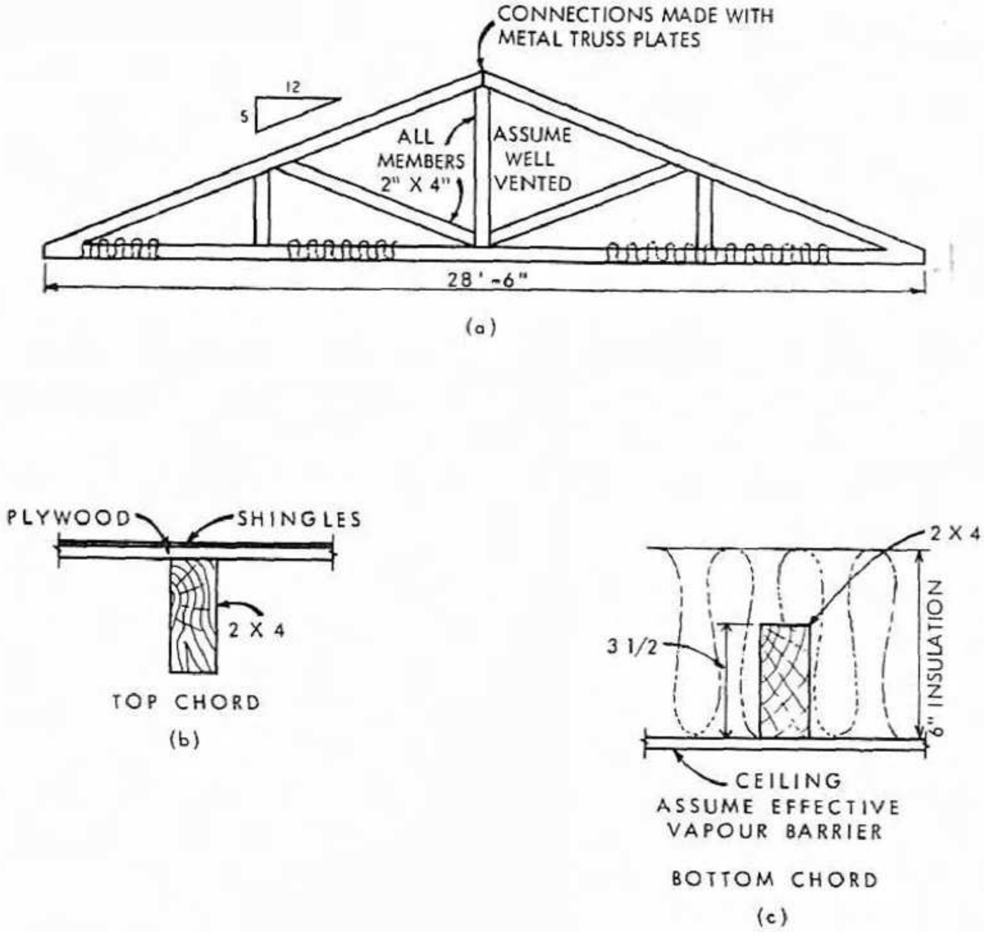

FIGURE 3
SKETCH OF HOWE TRUSS

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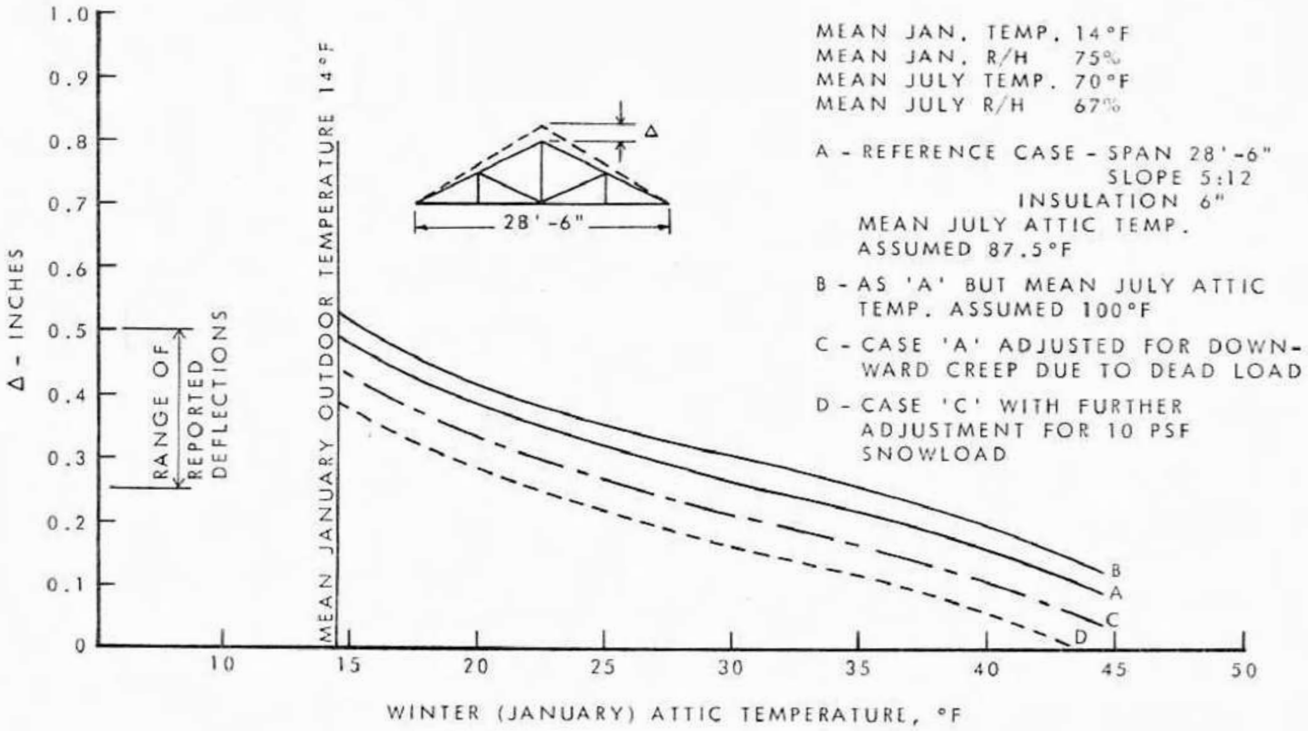

FIGURE 4

CALCULATED UPWARD DEFLECTION OF TIMBER (HOWE) HOUSE ROOF TRUSSES JULY TO JANUARY, LOCATION - MONTREAL

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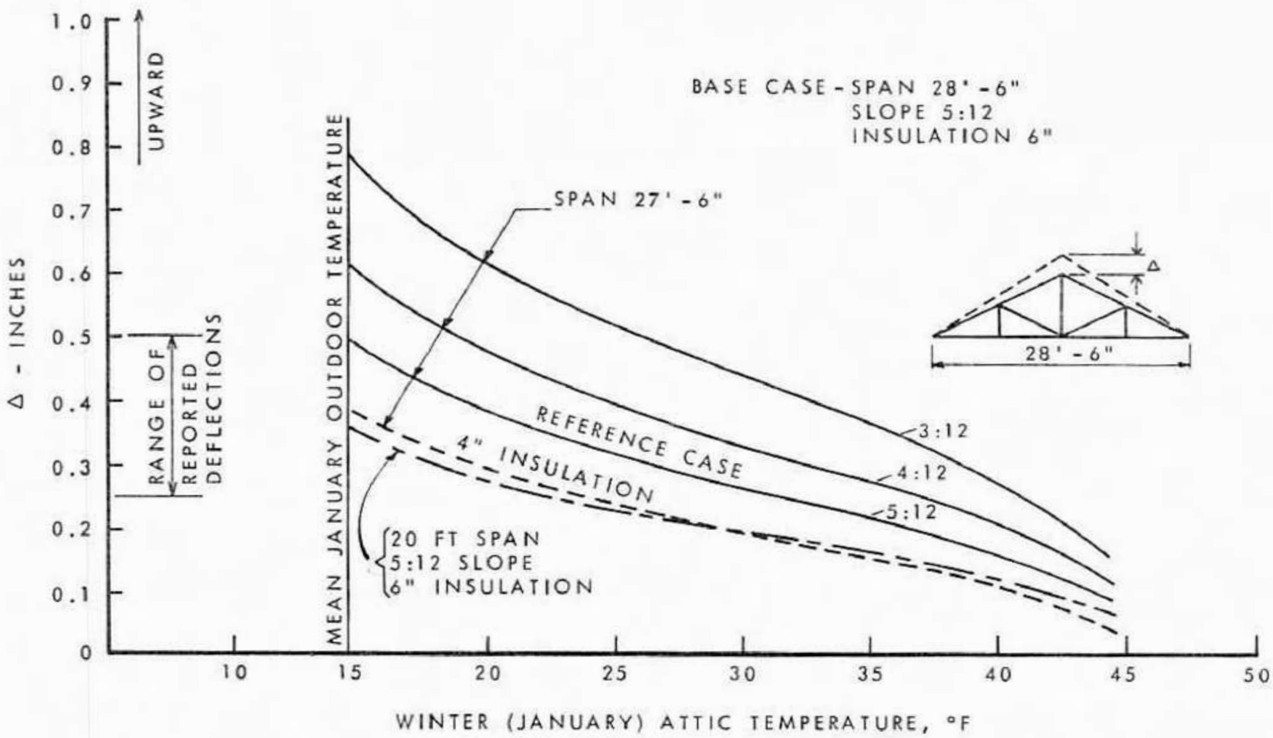

FIGURE 5

CALCULATED UPWARD DEFLECTION OF TIMBER (HOWE) TRUSSES - JULY TO JANUARY
LOCATION - MONTREAL, EFFECT OF SLOPE, SPAN AND INSULATION

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