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Compressive Load Applied by the Teatcup Liner to the Bovine Teat

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Summary:

Different techniques to measure effective compressive load applied to bovine teats by the teatcup liner and the effect of varying material properties of liners on the effective compressive load during machine milking were investigated. The effective compressive load values obtained with an artificial and living teats were correlated well with a correlation coefficient of 0.894. From the experimental observations it was found that the applied compressive load to the teat was not the effect of a single liner property but the combined effect of two or more liner properties. The effect of liner tension * hardness^2 divided by wall thickness correlated well with the effective compressive load.

Keywords:

compressive load, teatcup, liner, teat

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ABSTRACT

Different techniques to measure effective compressive load applied to bovine teats by the teatcup liner and the effect of varying material properties of liners on the effective compressive load during machine milking were investigated. The effective compressive load values obtained with an artificial and living teats were correlated well with a correlation coefficient of 0.894. From the experimental observations it was found that the applied compressive load to the teat was not the effect of a single liner property but the combined effect of two or more liner properties. The effect of liner tension * hardness^2 divided by wall thickness correlated well with the effective compressive load.

INTRODUCTION

Pulsation consists of alternate collapse of the teatcup liner beneath the teat, when air at atmospheric pressure is admitted to the pulsation chamber of the teatcup, and re-opening when the pulsation chamber is re-evacuated (Thiel and Mein, 1977). The main purpose of pulsation is to limit the development of congestion and oedema in the teat tissues during machine milking by the cyclic compressive load applied to the teat by the collapsed liner (Mein, 1992). Due to the complexities of measuring the force and the area over which the force is applied, compressive load is generally expressed in terms of the pressure, above atmospheric, applied to the teat apex by the closed liner.

Thiel (1968) noted the lack of information on the magnitude of the pressure applied by the collapsing or collapsed liner to the teat apex. Since that time, attempts have been made to measure the load applied to live teats (Thompson, 1978; Mein and Williams, 1984; Gates and Scott, 1986; Mein et al., 1987) or artificial teats (Caruolo, 1983; Gates and Scott, 1986) or to calculate the compressive load on the teat apex from the geometry of the collapsed liner (Mein et al., 1973; Williams and Mein, 1980). Mein et al. (1987) described three different methods designed to estimate the cyclic load applied to the teat apex by the liner and reported some of the characteristics of the applied loads. Butler (1993) developed a mathematical model to predict the force applied to a cow's teat by the teatcup liner during milking. The model was not verified with experimental results, however, because there was no way of measuring the force applied to a cow's teat.

The collapsed liner applies little or no load to the teat barrel above the teat apex, and does not close the teat sinus at any stage of milking, because there is little or no pressure difference between the teat sinus and the teatcup pulsation chamber (Mein, 1978; Mein, 1992). However, liners normally compress the teat apex during the collapse phase in each pulsation cycle. The compressive load results from the relatively stiff liner, which is usually in longitudinal tension, bending around

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the teat apex in the longitudinal and transverse planes. Based on this physical concept, it is expected that thin-walled, soft rubber liners will apply a relatively low compressive load and that load will increase with increasing wall thickness, increasing rubber hardness and increasing liner tension up to some maximum level. However, further increase in wall thickness or hardness may result in lower compressive loads. Clearly, a liner that is too thick to be collapsed by the pressure differences normally applied in a teatcup may not apply a compressive load to the teat.

In this paper, we report results of a study to develop different techniques for measuring the effective load and point load applied to bovine teats by the teatcup liner during machine milking.

OBJECTIVES

The specific objectives of this study were to:

(1) measure the effective compressive load applied to an artificial teat by a range of commercial and experimental teatcup liners and also to live teats during normal milkings,

(2) determine the effects of varying the pressure difference across the teatcup liner, and of varying material properties of the liner such as tension, wall thickness, buckling pressure, hardness, bore, modulus of elasticity on the effective compressive load and

(3) develop mathematical models to predict the effective compressive load with varying liner material properties.

MATERIALS AND METHODS

Techniques to Measure the Compressive Load

Force Sensors:

Several thin-film commercial force sensors were tested for measuring the compressive load (average and profile) applied to the bovine teat by different teatcup liners. The sensors namely Tekscan and Pressurex supplied by the Sensor Products, Inc. were tested but were found to be unsatisfactory. Significant error was introduced by bending of the Tekscan sensor around the teat. The Pressurex sensor did not have sufficient sensitivity for measuring teat loads. This sensor also exhibited a high degree of hysteresis.

Extruded Clay Ribbon:

A thin ribbon of clay (about 0.6 mm in diameter) was used to measure the compressive load. The clay was extruded from a plunger apparatus that controlled uniformity of width over the specimen's length. The extruded clay was placed between two sheets of paraffin and inserted between the teatcup and an artificial teat. During pulsation, the compressive load applied by the liner to the artificial teat deformed the clay strip. The clay strip was then removed and the width of the deformed specimen at different locations was measured using an image processing system (Optimas, 1990). The calibration curve of applied load versus deformed width was obtained by applying a range of dead weights to a piece of clay ribbon and measuring the corresponding deformed width.

Artificial Teat

A method described by Mein (1987) was adapted to measure the pressure developed within a liquid-filled, floppy, non-distensible artificial teat. The artificial teat was made using a standard plastic teatcup plug (ISO, 1983), a surgical glove finger, and a cloth glove finger (Figure 1). The hard plastic teatcup plug was cut off 25 mm above its tip and the open end shaped by heat and pressure to form a smooth ellipse. The major and minor diameters of this ellipse, 21.6 and 16.5 mm, were chosen to simulate the shape of the teat apex in a collapsed liner. The surgical glove finger was inserted into the cloth finger and tied to a rubber stopper. The whole system was pressed into the plastic teat so that the flexible glove fingers protruded about 14 mm from the end of the hard plastic teat plug. The other end of the stopper was connected to a pressure transducer (Omega pressure transducer) and a water reservoir. Air was bled from the system. Before each measurement, the system was sealed by means of a three-way tap.

Measurements were made in the following way:

a) The "teat" was inserted into the teatcup assembly and pulsated normally for 6 cycles. Then the liner was stopped in its open position by stopping the pulsator so that the pulsation chamber vacuum (PCV) = liner vacuum (LV) = 40 kPa. The water reservoir was connected to the "teat" cistern to equilibrate the internal liquid pressure and to set the pressure transducer to +4 kPa "intra-mammary" pressure, and to remove any air bubbles from the measuring system.

b) The 3-way tap was adjusted to connect the teat cistern directly to the pressure transducer and to disconnect the water reservoir. The liner was collapsed by switching PCV to atmospheric pressure (with LV held constant at 40 kPa) and the internal teat pressure recorded as P1.

c) The liner was opened by disconnecting the liner vacuum so that LV = PCV = atmospheric pressure, and the new internal teat pressure was recorded as P2. The change in internal teat pressure, P1 - P2, reflects the compressive load, or pressure above atmospheric pressure, applied by the collapsed liner to the teat.

The effect of varying the liner vacuum on teat pressure was measured by holding PCV constant at 0 kPa while the LV was raised in steps of 5 kPa. The corresponding teat pressures were recorded. The investigation was repeated for different liners. Similarly the effect of varying the pulsation chamber vacuum on teat pressure for different LV level was investigated. In this case, LV was held constant at 30, 40 or 50 kPa while the PCV was raised in steps of 5 kPa.

Dynamic Tests During Milking

Measurements of the pressure difference across the liner wall, at which milk flow just starts or stops can provide a dynamic test for the compressive load applied by a particular liner to any teat. The point at which the milk flow is just stopped by the collapsing liner occurs when the distending force due to the LV is just offset by the compressive force of the closing liner. Starting from this equilibrium point, the maximum load applied to the teat is about equal to the incremental change in air pressure in the pulsation chamber when this chamber is at atmospheric pressure (Mein et al, 1987).

For the experimental milkings, a small hand-operated vacuum pump and digital gauge were connected into the long pulse tube (between the pulsator and the front pair of teatcups) by means of a 3-way tap. The teatcups were applied to the udder for 1 minute of normal milking. Then the liner was stopped in its closed position by adjusting the 3-way tap and switching PCV to atmospheric pressure. The PCV was increased slowly using a hand vacuum pump and the vacuum at which the milk just started to flow was read from the digital vacuum gauge. The same procedure was repeated at 3 minutes from the start of milking.

The right front (RF) and right hind (RH) teats of 20 cows at the Dairy Cattle Research Center (UW-Madison) were milked with any one of a series of commercial and experimental liner types used in this study. The left side teats were milked with the standard teatcups normally used in the dairy, to serve as half-udder controls. The pulsation chamber vacuum at which milk just started to flow from the two front teats was measured at 1 minute and 3 minutes from the start of milking. Because some cows milked faster than others, the data measured at 3 minutes from the start of milking were affected by availability of milk in the quarter. Therefore, only the data measured at 1 minute from the start of milking were used for further data analysis.

Liners

Seven commercial liners (arbitrarily designated as A,B,C,D,E,F, and G) were tested. The wall thickness of liner D was reduced from 3.2 mm to 1.6 mm by grinding the outer surface of the barrel (designated as DTH). All liners were tested mounted in the manufacturers supplied shells. Liners C and D were also tested mounted in a shell other than the manufacturers supplied (designated as CS2 and DS2). This shell was 7 mm longer than the manufacturers supplied shell.

Measurements of Liner Characteristics

Buckling Pressure (BP, kPa): An artificial teat was inserted in the liner mounted under tension equal to the tension of the liner when mounted in its shell. The vacuum was slowly increased inside the liner until the liner walls touched each other. At that point, the pressure difference across the liner walls represented a measurement of the buckling pressure in standardized conditions. The buckling pressure for different liners ranged from 11.1 to 20.5 kPa.

Wall Thickness (WT, mm): The wall thickness of the liner barrel was measured using a micrometer at about 75 mm from the top of the liner. The wall thickness for different commercial liners ranged from 2.1 to 3.2 mm, and the wall thickness of liner DTH was 1.6 mm.

Shore Hardness (H, Shore A): Hardness was measured using a Shore A pocket durometer. Three measurements were done on each liner on the outside surface of the barrel and average value was used for data analysis. The hardness for different liners varied from 41 to 48 Shore A.

Liner length (LL, mm): Liner length was measured using slide calipers. Liners were removed from their shells to measure the distance between the upper and lower points where the liner was supported in its own shell.

Shell length (SL, mm): The distance between points of support by the shell for the liner was measured using slide calipers and was termed as shell length.

Liner elongation (EL): The liner elongation was expressed by the ratio of shell length to liner length and varied from 1.11 to 1.28 between different liners.

Liner Tension (T, N): The liner tension was defined as the force required to stretch the liner length to the corresponding shell length and ranged from 24.5 to 103.7 N between different liners.

Liner Bore (B, mm): The liner bore was measured in the shell using inside calipers at a distance of 75 mm from the top of the liner (ISO, 1983) and varied from 18.8 to 23.6 mm between different liners.

Modulus of Elasticity (ME, N/m^2): The force required to stretch the liner when mounted under tension with no vacuum difference across it was measured using an Instron Testing Machine. The stress (force/(wt*bore*pi)) divided by strain ((SL-LL)/LL) was termed elasticity.

Modeling

Linear and second and third order polynomial models were fitted (SGPLUS, 1992) to the data to describe the effect of different liner properties on the PCV values.

RESULTS AND DISCUSSION

Extruded Clay Ribbon

A calibration curve for the extruded clay ribbon technique is presented in Figure 2. The variation in width of the clay ribbon with applied pressure followed a polynomial relationship. The pressure applied to an ISO plastic plug by two different liners at two different tensions (standard (ST) and lower (LT)) at a milking vacuum of 50 kPa is shown in Figure 3. In general the maximum pressure was applied within 1 or 2 mm from the tip of the teat and the applied pressure decreased progressively over the upper 3 or 4 mm of the teat apex. This technique to measure the compressive load was difficult to apply with live teats and was not used further.

Artificial Teat

Effect of Liner Vacuum and Pulsation Chamber Vacuum on the Effective Compressive Load

The variation in teat pressures with the liner vacuum for liners F and D is shown in Figure 4. Liners F and D liners were tested at 10% elongation. For both the liners there was an initial fall in teat pressure which reflected the fall in ambient pressure until the liner buckled and started to apply a compressive load. The differences in teat pressure between liners F and D were due to variations in liner material properties.

The variation in teat pressure with pulsation chamber vacuum in liner D for three different LV levels is presented in Figure 5. As PCV was raised, the teat pressure decreased linearly up to the point when the liner became fully open. After this point the teat pressure was approximately constant for all three LV conditions. The teat pressure became positive (above atmospheric pressure) only when the PCV had fallen below 11.6 kPa for a LV of 50 kPa, or below 3.7 kPa for a LV of 30 kPa. The final teat pressure when PCV was at atmospheric pressure represents the effective compressive load. e.g. + 11.6 kPa for a LV of 50 kPa.

Comparison between artificial and live teat tests

The effective compressive load is about equal to the PCV when the milk just starts to flow from the teat (Mein, 1992). Effective load values obtained after 1 min of milking with the live teats are closely correlated with the teat pressure values obtained with the artificial teat. The comparison between the laboratory and dairy tests is shown in Figure 6. The correlation coefficient of this relationship was 0.894. In general, the teat pressure values were about 1.75 times higher than the effective load values for the same liners tested. From an extensive investigation with different artificial teats, it was found that the teat pressure values were dependent on the shape, effective teat volume and the materials used for the construction of the artificial teats. Although it may be possible to make an artificial teat which would produce absolute values similar to those for living teats, the high correlation coefficient indicates that the laboratory method could be used as a convenient and repeatable technique.

Effect of Liner Material Properties on the Effective Compressive Load

Liner material properties were correlated with the effective load values obtained in the dairy. The effect of the liner wall thickness on the effective load is shown in Figure 7. In general, as the wall thickness increased the corresponding effective load values decreased (Correlation Coefficient, $R^2 = 0.220$). However, the means for the liners C and B appeared to be exceptions to this general trend. Liners with wall thickness less than 1.6 mm could be investigated to see the effect of very thin wall on the applied compressive load. The correlation between the liner tension and the effective load values is shown in Figure 8. The effective load increased with increased liner tension

($R^2 = 0.312$). In this case the D, G and A liners did not conform to the relationship. Other analyses (not shown here) indicated that increased buckling pressure tended to decrease effective load, increased elongation tended to increase effective load, while liner hardness, bore or elasticity did not show a clear trend. From these observations it is clear that the applied compressive load to the teat did not depend on any single liner property but on the combined effect of two or more liner properties.

The effect of some combinations of the liner properties on the effective load values was investigated. Results for three of the higher correlations are presented here. The effect of tension divided by wall thickness (T/WT) on the effective load is shown in Figure 9. As T/WT increased, the corresponding effective load values increased, but the distribution was not uniform ($R^2 = 0.621$). When the liner hardness was included into the model (Figure 10) the correlation was improved ($R^2 = 0.677$). When liner elasticity was included into the model, the correlation was poor compared to the previous case ($R^2 = 0.651$). Of the different models, the effect of tension*hardness^2/wall thickness on the effective load values resulted in the highest correlation coefficient ($R^2 = 0.720$, Figure 11).

Mathematical Model

Among various models fitted it was found that the linear models fitted very well the liner properties with the effective load values for most cases. For some cases it was found that the second and third order polynomials fitted very well. But for simplicity and ease of use of models, the linear models were selected to predict the effective load values for the known liner properties. The model which best described the effect of liner tension, hardness and wall thickness on the effective compressive load at any given milking vacuum level is,

$$EffectiveLoad = 8.933E-05*[T*H^2/WT]+9.55335$$

Where

T = Liner Tension, N
H = Liner Hardness, Shore A
WT = Liner Wall Thickness, mm

The model predicted effective load values for a given liner material properties is also presented in Figure 11. The correlation coefficient for the model was 0.720.

CONCLUSIONS

(1) The effective compressive load values obtained with an artificial and living teats were correlated well with a correlation coefficient of 0.894,

(2) Applied compressive load to the teat was not the effect of a single liner property but the combined effect of two or more liner properties,

(3) The effect of liner tension * hardness^2 divided by wall thickness correlated well with the effective compressive load.

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Figure 1. Artificial teat

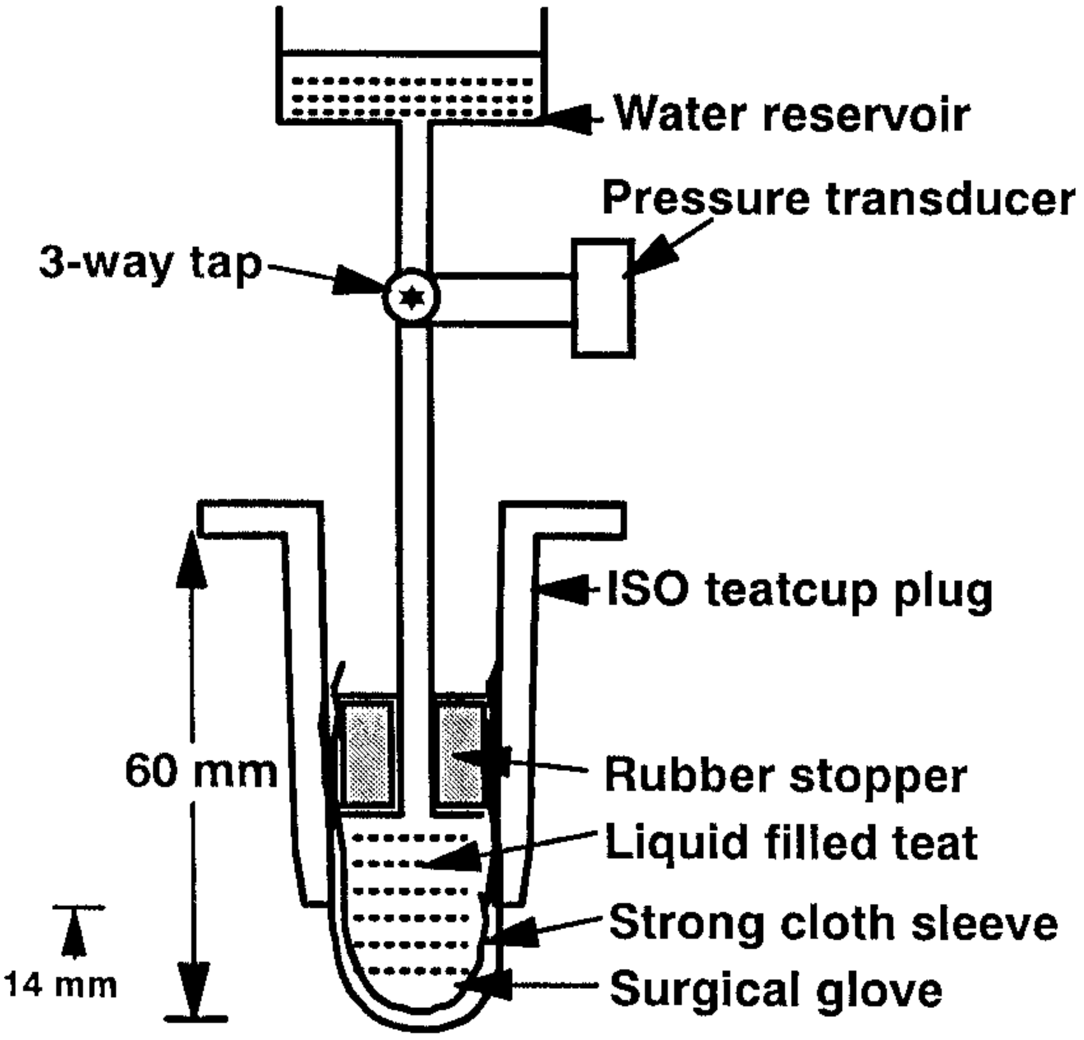


Figure 2. Calibration curve of extruded clay ribbon

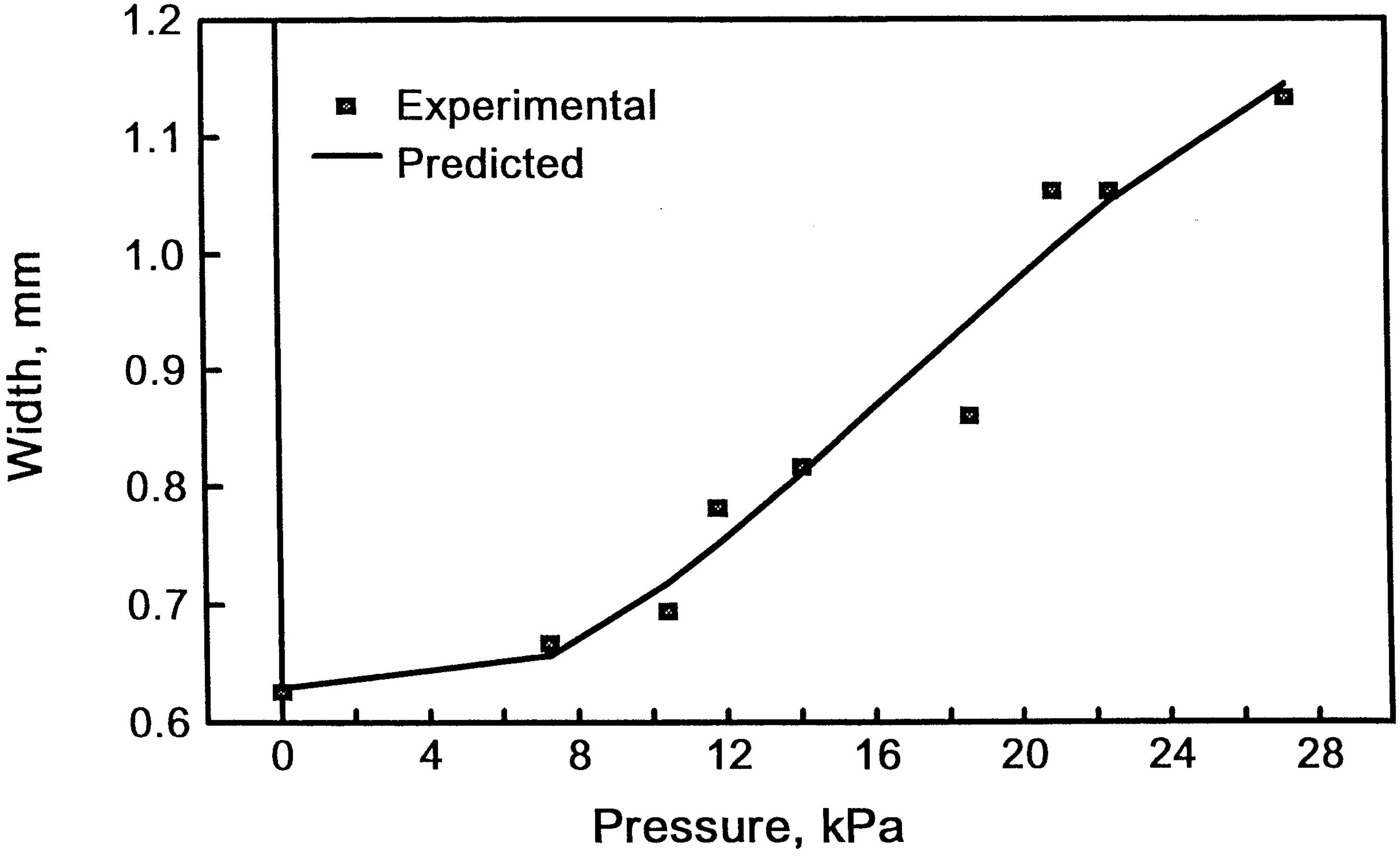


Figure 3. Variation of pressure with location from tip of an ISO plug

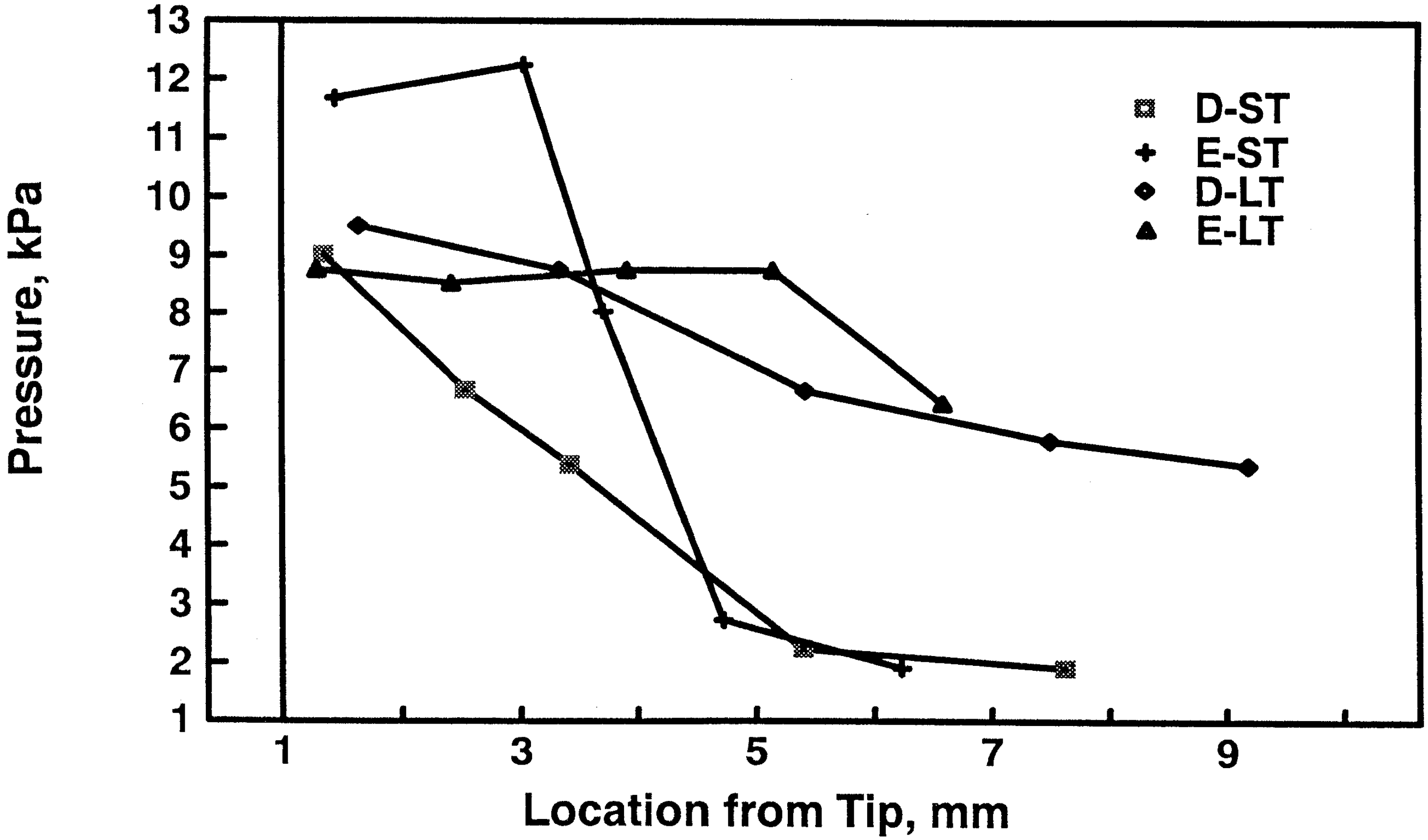
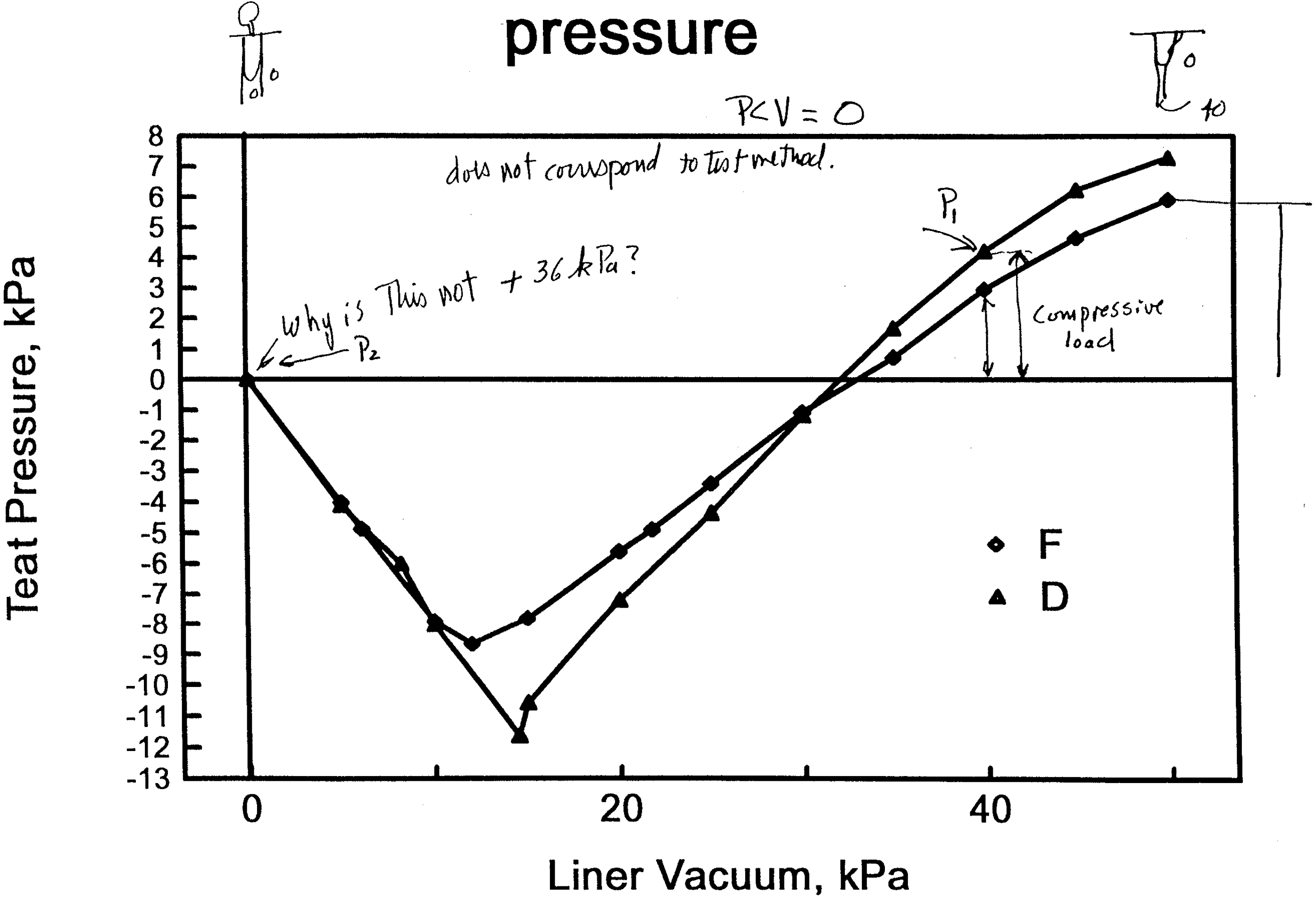


Figure 4. Effect of liner vacuum on teat pressure



does not correspond to test method.

why is This not + 36 kPa?

compressive load

Figure 5. Effect of pulsation chamber vacuum on teat pressure for different liner vacuum

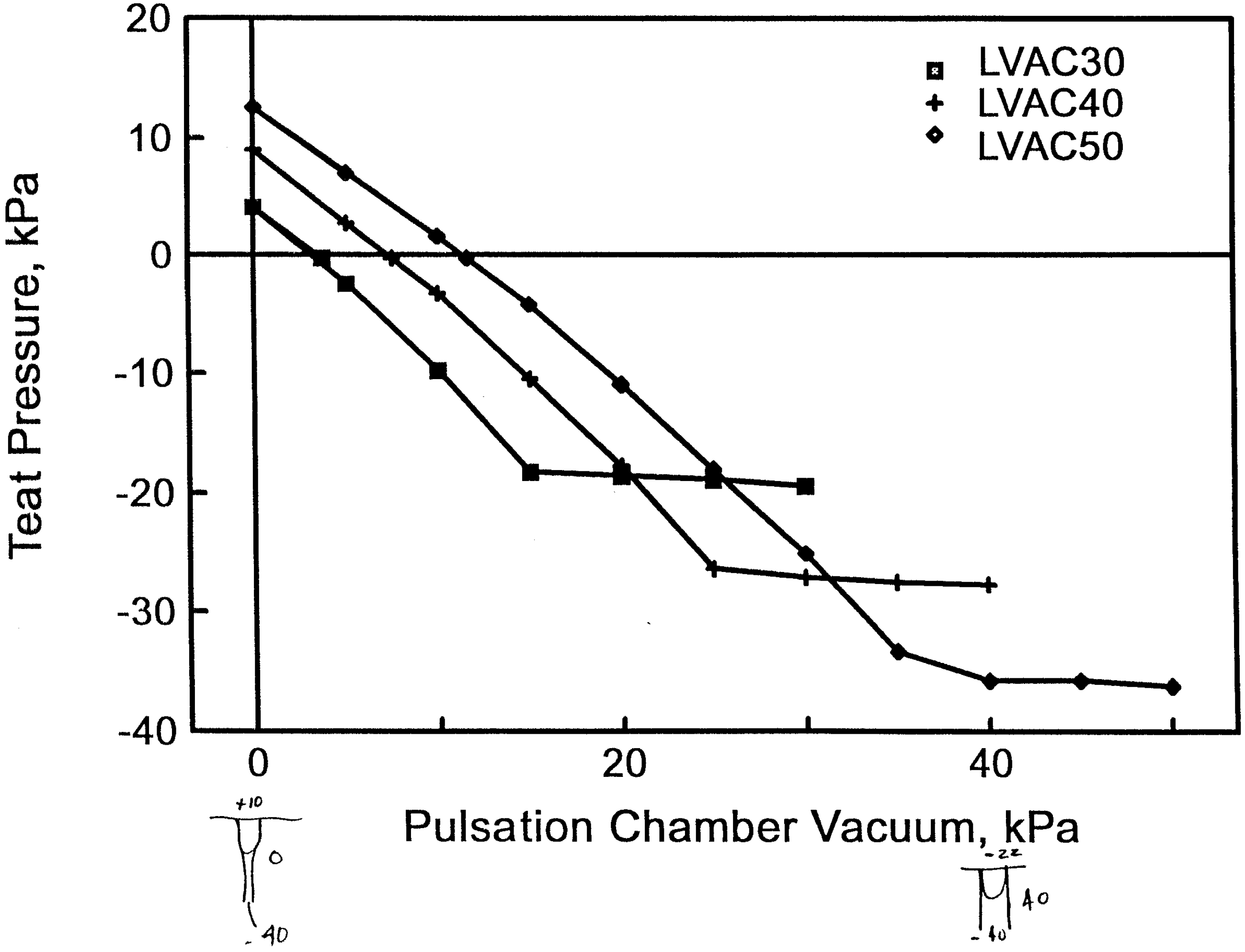
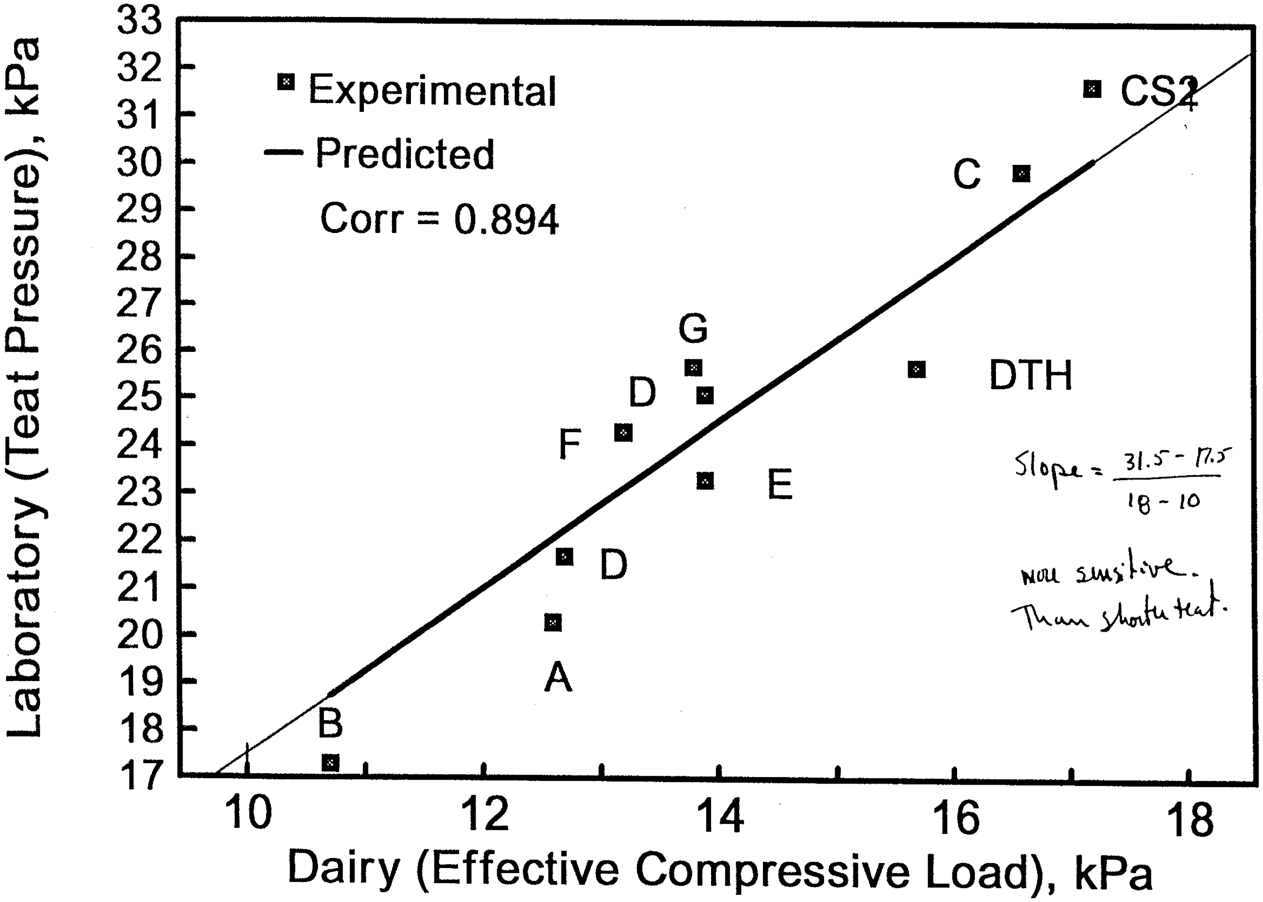


Figure 6. Comparison between artificial and live teat tests



$$\text{Slope} = \frac{31.5 - 17.5}{18 - 10} = \frac{14}{8} = 1.75$$

More sensitive.
Than shorter teat.

Figure 7. Effect of liner wall thickness on effective compressive load

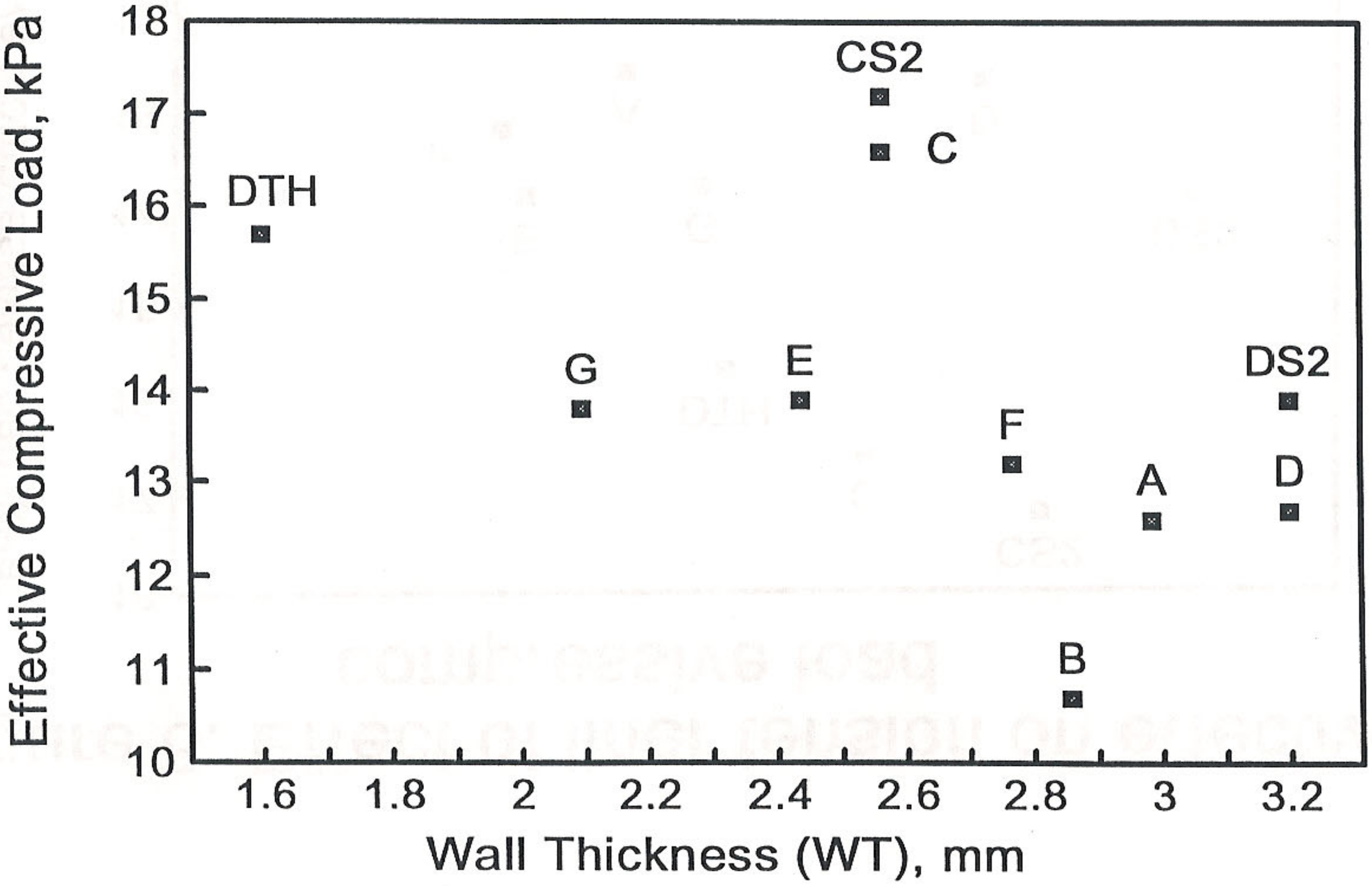


Figure 8. Effect of liner tension on effective compressive load

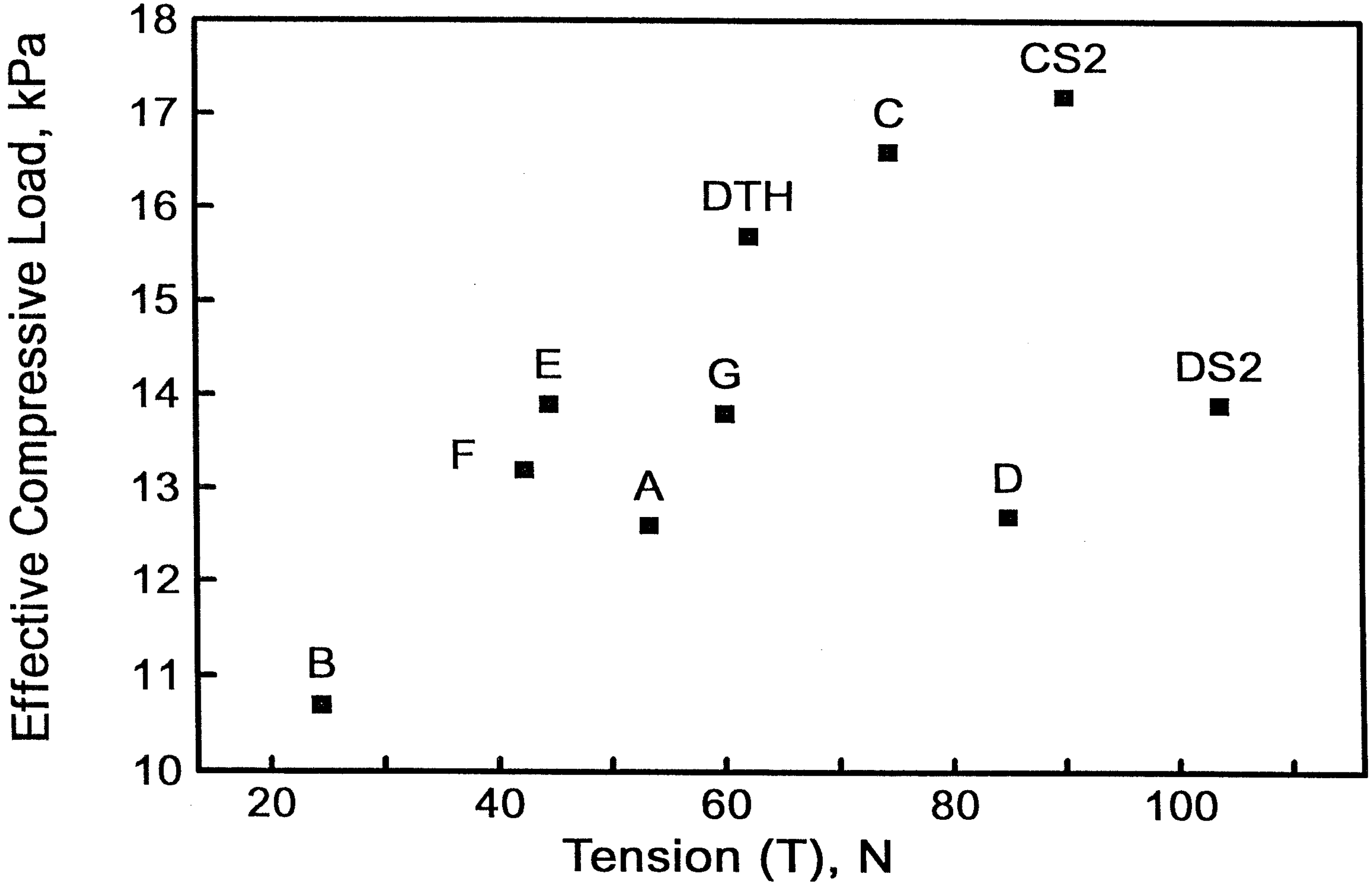


Figure 9. Effect of tension over wall thickness on effective compressive load

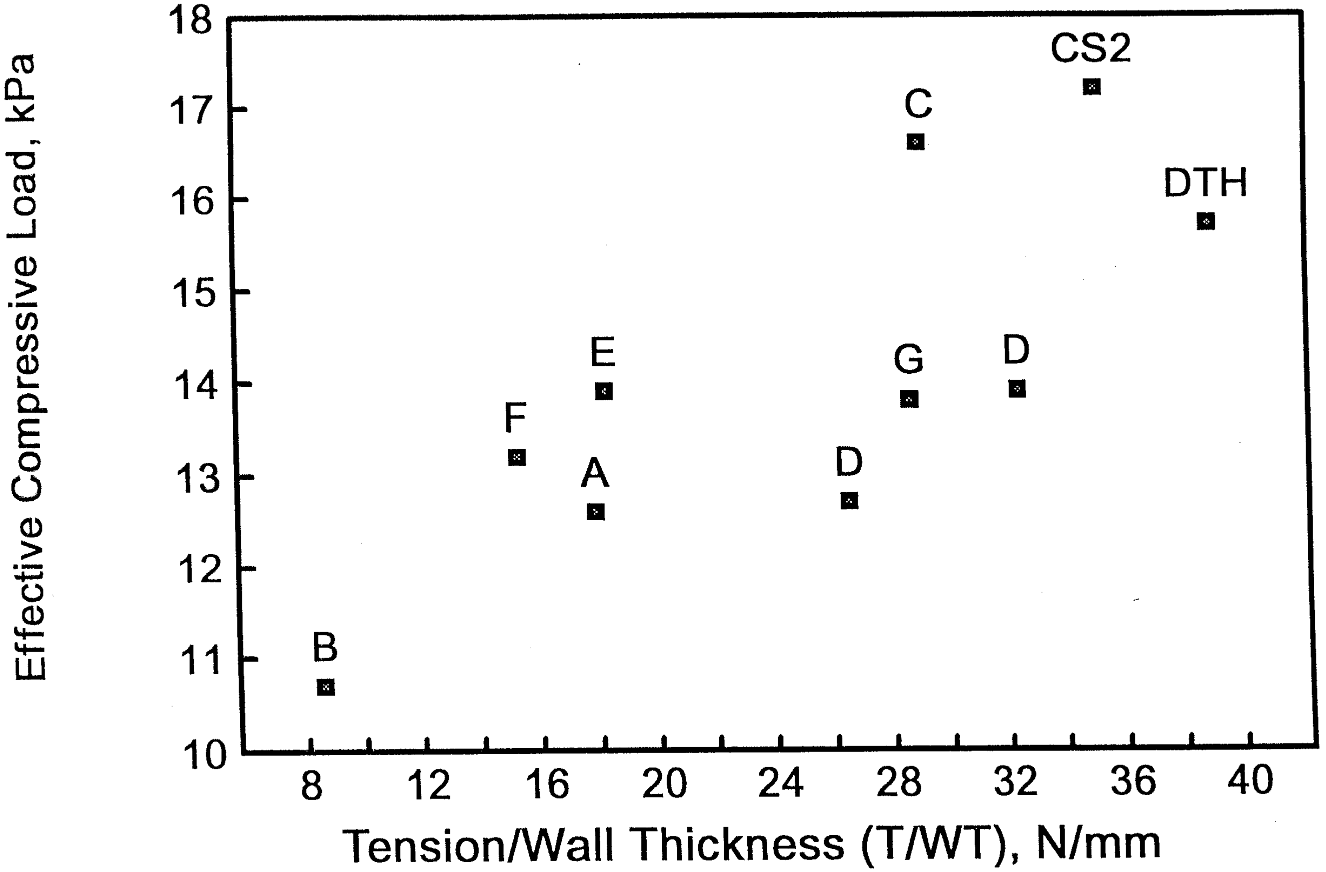


Figure 10. Effect of tension x hardness over wall thickness on effective compressive load

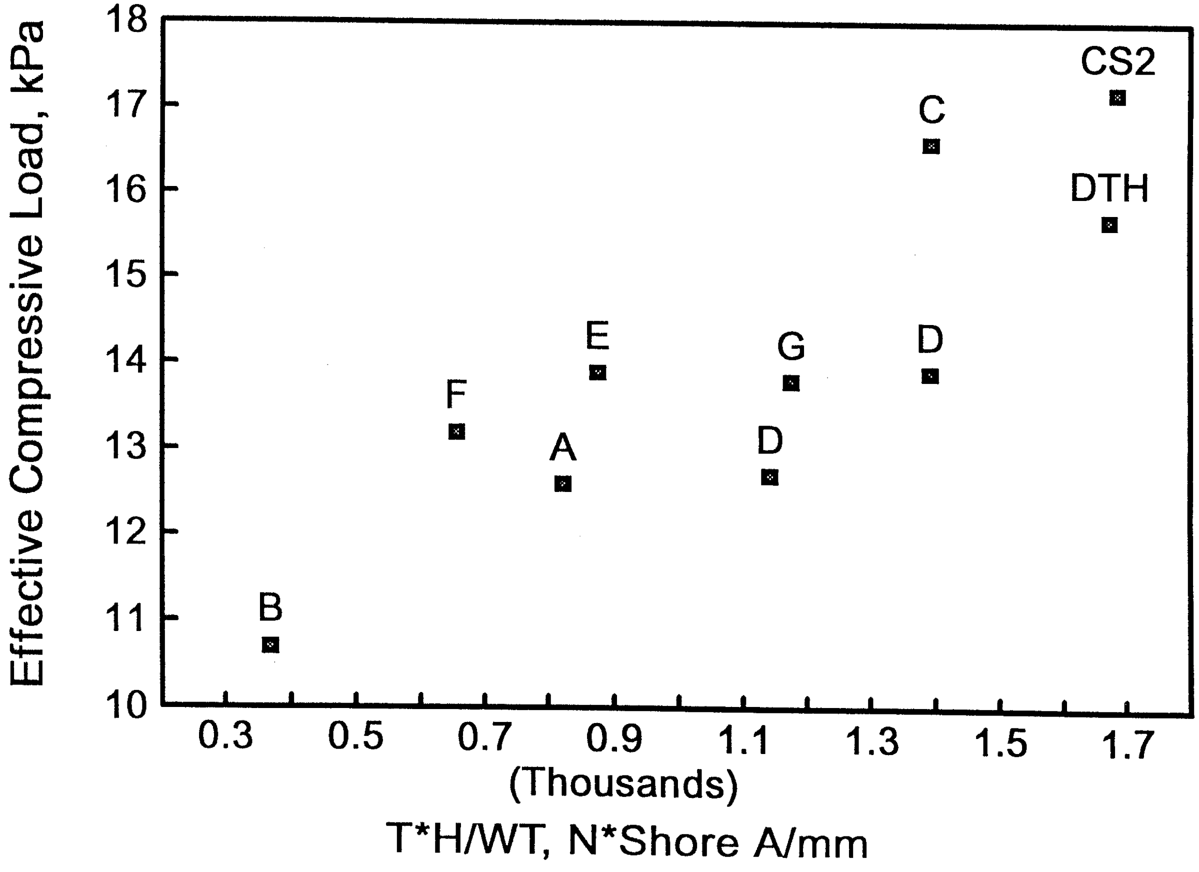


Figure 11. Effect of Liner Tension x hardness squared / wall thickness on effective compressive load