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Polyurethane Industrial Tires

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**Polyurethane Manufacturers' Association
Spring Meeting**

**April 12, 1994
Saddlebrook Resort, Wesley Chapel, Florida**

I. Introduction

The performance of polyurethane industrial tires continues to improve as tire manufacturers specialize their products to service an increasingly segmented market. Tire functionality has become more specialized (and demanding) because industrial truck manufacturers design their trucks for specific material handling operations. For example, the lift truck industry recognizes 17 types of electric trucks in three general classes: electric rider, electric narrow isle, and electric hand pallet.

Polyurethane industrial tire manufacturers have responded and have encouraged this trend with polymer improvements, greater number of chemistry offerings and in some cases controlled variation of stoichiometry. While the demands on an industrial tire increase and polymers used to make a tire improve, the design tools have been available for sometime and are readily available to PMA members. This paper will discuss the industrial tire market and several readily available design tools that have proved particularily useful to this manufacturer.

II. Market Demands

Polyurethane Industrial Tires - A Specialty Product

Of the $200 million market for all solid industrial tires, we estimate the polyurethane segment to be approximately 20%. This $40 million dollar market can be broken into tires and load wheels each with widely different performance requirements. We estimate the load wheel consumption in North America is 830,000 units and the polyurethane press-on market to be 450,000 units annually. Our guess is that 22% of this demand is attributable to new truck production. The largest and fastest growing portion of the polyurethane tire market is for electric trucks due to their low rolling resistance requirements. In our opinion, most successful of the 18 major truck manufacturers over the past decade have been Raymond and Crown - leaders in the narrow isle electric segment. To date, they appear to have been able to stay ahead of both foreign and domestic competition. In 1994, we believe that 80,000 new electric trucks will be sold in North America, 24,000 in Japan and 80,000 in Europe, with the highest growth in the narrow isle

electric truck classification. Interestingly, as of mid-1993 the percentage of electric trucks versus all forklifts produced was 54% in North America, 32% in Japan and 68% in Europe.

A market niche is the Automated Guided Vehicle market. Sales of AGV units peaked in 1985 at $167million (co-incident with the apogee of Roger Smith's career at GM). 1993 sales of AGV units is estimated at $67 million. The major producers, Demag, Eaton, FMC to name a few, are not the traditional lift truck manufacturers. Perhaps the lift truck manufacturers truly understand material handling requirements. For the polyurethane tire designer, the AGV niche tends to be lucrative because the vehicles are designed first, the wheels are considered as an afterthought. If the AGV navigation system is based on laser or sonic distance measurement and obstacle avoidance systems as opposed to dead-reckoning or wire guided systems, vehicle designers are very concerned about tire deflection and rolling resistance. In addition, AGVs have most successfully deployed in hazardous environments, such as reactor cleanup operations, offering the tire producer the opportunity to add value through solvent resistance or radiation resistance.

Recognizing the diverse performance requirements for these applications, several original equipment truck manufacturers now offer up to four chemistries of tires and wheels as replacement products. These chemistries are: TDI Ether with PPG, TDI Ether with PTMEG, MDI Ester and NDI Ester. (**Figure 1** show a matrix of these elastomers' general properties.)

In the custom market, there is an even greater degree of specialization. For example, a manufacturer may customize the stoichiometry of a tire for certain customer's application. In the following two sections, I will first discuss the performance attributes that a manufacturer must address and then the physical properties that allow the manufacturers to meet these needs.

Important Tire Performance Attributes to Customers

Below is a brief discussion of tire performance attributes important to customers. Keep in mind that market segments' needs may vary tremendously and as a consequence a tire designed for one application may be an accident waiting to happen in another. Also, most industrial trucks have no active suspension, as a result the tire has the additional duty of providing the trucks minimal suspension.

Operating Load - The Tire & Rim association specifies that a polyurethane tire is rated to carry ~ 150% of the load of a rubber industrial tire. The load carrying capacity of polyurethane tires is dependent on compound choice and process stoichiometry. Combinations of these factors may vary load capacity from 50% to 250% of a rubber tire. The standard load capacity for most general duty lift trucks is 4,000 lbs. However, the trend in electric truck design is toward higher lifting, longer operating trucks while maintaining the same wheel base and turning radius.

Operating Speed - Operation speed is generally limited by the manufacturer for safety considerations at 6 to 10 MPH loaded. Of greater concern for tire design is how the speed is reached, how long it is maintained and under what load conditions. In today's 500,000 to 1,000,000 sq. ft. distribution centers, trucks may be operating at top speed for up to 1,000 ft or more on a continuous basis.

Wear - This is a general term that more specifically includes, abrasion resistance for damage due to skidding and cut and tear for tough applications. Wear needs vary greatly among applications. In newer locations where floor conditions are good and housekeeping is vigilant, cut and tear requirements may be low. However, abrasion resistance due to skidding may be great. Conversely, in foundries, cut and tear requirements may be paramount.

Rolling Resistance - Heat build up in an industrial tire and battery energy loss due to hysteresis are the two greatest problems associated with rolling resistance. In electric trucks, poor rolling resistance can significantly curtail service life between recharging.

Physical Characteristics related to these Performance Attributes

The previous four tire performance attributes, are related, often with overlap, with the following four physical properties. As you may appreciate, these physical parameters vary with compound and with stoichiometry. Furthermore, optimization of one parameter often leads to degradation in an other parameter.

Hardness - Polyurethane chemistry and processing variability aside, this physical characteristic impacts the tire's load carry capacity. The practical range for industrial tires is 82 to 97 durometer on the Shore A scale. Generally, the harder the tire, the greater the load carrying capacity.

Furthermore, as hardness increases, the material flex is reduced, reducing the heat build up in the tire, however, ride quality suffers.

Flex Life - Flex life is one measure of a material's dynamic longevity under stress. I will use this as a general term describing dynamic performance. This is particularly important in applications where the wheel is under constant dynamic stress, such as applications with poor floor quality or the where truck suspension is primitive or nonexistent. While there are several standard tests of flex life, most manufacturers have their own methodologies for testing dynamic material performance under conditions that model tire and wheel flexing.

Abrasion Resistance / Cut & Tear - Polyurethane is best known for its abrasion resistance and cut and tear properties. Tire users are generally more interested in cut and tear than abrasion resistance. The higher resilient materials such as MDI and NDI Esters offer better performance than TDI Ethers.

Tan δ - This is a measure of the energy hysteresis in the polyurethane chemistry or how much mechanical energy is converted into heat. Tan δ (a standard measure) for an SBR rubber industrial tire may be 0.2, for a high cut resistant polyurethane tire 0.07, and for a high resilient MDI or NDI Ester polyurethane tire 0.03.

There are several other physical properties such as compression set that more exactly measure specific issues. However, the above physical parameters give an adequate definition of the parameters that must be addressed in tire selection.

Demanding Applications

Two examples of demanding applications that require very different tire performance are large Foundries and Distribution warehouses.

A foundry's tire needs are: superior cut and tear due to generally poor housekeeping, average rolling resistance because most trucks are propane or gasoline, lower durometer hardness for better ride because of poor floors and average flex life because the effective tire speed is lower due to the large size tires generally used.

Distribution warehouses tend to use fleets of electric trucks requiring smaller tire and wheels. Tires selected for this application may have the following properties; high hardness, low rolling resistance, high flex life, average cut and tear. Very often distribution centers may have circular drive patterns that result in high stress and uneven wear on one side on the truck. However, without knowledge of the end-users floor conditions a tire manufacturer can easily make a improper trade-off regarding, for example, hardness versus flex life. **Figure 2** maps a customer's performance criteria onto a chemistry's physical parameters and shows the relationship of foundries to distribution centers.

Crown TS Turret Truck at Blair Corp.

The award winning Crown TS is state of the art for a stock picker that might be used at a large distribution center. This machine was named by the Industrial Designers Association as the product of the Decade in 1990. The machine can lift 4000 lbs to 41' with a loaded speed of 6 MPH. A truck such as this might sell for $100,000.

Blair Corporation is a $500 million dollar discount mail order company located at a 500,000 sq. ft. mailing and merchandise distribution center in Irvine , Pa. The company markets primarily clothes and some household items. While much of the material handling is accomplished using fixed conveyor equipment and there is an extensive fleet of counter-balanced material handling trucks, Blair has recently invested in a fleet of 8 Crown TS trucks for its new mailing building which was designed specifically for this class machine.

The trucks operate in a clean environment with a high quality F100 floor. This truck is equipped with four wheels, each with solid suspension. The trucks are driven up and down aisles not exceeding 200 ft in length. Due to the height of much of the operations, the truck does not see continuous high speed runs. Loads reach the truck maximum of 4,000 lbs. Maximum truck weight loaded is 20,000 lbs.

Two 15"x8"x10.5" high capacity polyurethane tires are the load tires and two 13"x5.5"x8" steer tires are in the back. The standard material for these wheels is a 95A high hardness Low Free TDI Ether. An example of the greater demands on polyurethane industrial tires is the .030" out of

round specification for this wheel, well below the .100" specified by the Tire and Rim Association. Tire problems most frequently reported at this location are primarily flat spotting and some material chunking. These problems could be addressed though alternate compounds such as a 92A MDI Ester or NDI Ester.

Blair engineers expect future trucks to accommodate 60' reach heights with the same or increased loads. In fact, their new mailing center was designed to be used to this height. Given the degree of electronic sophistication of the current generation of turret trucks, it is not hard to imagine adaptive electronic suspensions providing leveling at this height. What does this mean for the tire? Greater load carrying capability and tighter dimensional tolerances.

III. Design Tools

The PMA's Engineering Design Manual is a rosetta stone for tire design. The attached bibliography lists a few of the papers that we have found particularly useful for modeling the performance of polyurethane tires. Rather than reiterate in detail what many PMA members have previously done so well, I will highlight calculations that our customers' design engineers have found useful in their effort to understand tire design trade-offs.

ASTM Data for Deflection, Footprint and Ground Pressure Calculation

Two of the most frequently asked questions for a custom application are: What will be the deflection of the tire? What is the ground pressure for a given load? The method with which to calculate these parameters is clearly defined in paper IX of the PMA Design Manual. In order to use the deflection Equation:

$U = [.75W(b-a)/(E_c S(8b)^{1\ 2})]^{2\ 3}$ where:

U = Deflection (in.)

W = Weight (lbs.)

b = Outside Radius

a = Inside Radius

E_C = Compressive Modulus

S = Tire Width at Tread

The significant unknown in this equation is E_c. Using a ASTM standard button measurements to calculate young's modulus, paper X, gives an easy to follow example to calculate the compressive modulus for any form factor. The footprint and ground pressure can then be easily calculated:

$P = 2S(b^2-(b-U)^2)^{1/2}$ and $L = W/P$ where P is the footprint in square inches and L in the ground pressure in pounds per square inch. **Figure 3** is an example of a simple spreadsheet we use at Superior to make these calculations quickly for our customers. Note that there are several columns as Young's modulus is not constant with load.

Rebound Data as Function of Temperature for Calculation of Rolling Resistance

Rolling resistance and the accompanying battery drain are of particular concern for the industrial truck market. This is also a notoriously difficult parameter for the small processor to measure directly even if they have a dynamometer. Many people measure the change in current load or have torque sensors on their dynamometer, but this is prone to error or beyond the resources of many processors. In addition, field conditions and driving habits may result in actual rolling resistance values (and battery performance) much worse than those predicted. However, Paper XVIII of the design guide documents an excellent effort to do this testing properly. Often it is sufficient for our customers' engineers to review the relative predicted performance of different polyurethane and rubber formulations to make a design decision. Superior uses the much published equation:

$$R.R. = 2 \tan \delta \, [W^4(b-a)/E_c S b^2]^{1/3}$$

Where Tan δ = Energy Loss and the other variables are as above. Recognizing that Tan δ varies with temperature, and not having a handy DMTA, we have measured rebound versus temperature for a range of elastomers - **Figure 4**. Tan δ can then be calculated from the rebound % at a given temperature using **Figure 5** which is based upon the relationship: Fractional Loss = $\pi\tan\delta/(1+(\pi/2)\tan\delta)$. PMA Design Manual paper XXVII explains the relationship between Tan δ and rebound in detail. **Figure 6** shows a typical temperature profile due to continuous operation on Superior's dynamometer. As you can see, the rebound profile varies greatly for various elastomers. Knowing the vehicle application - typical loads, speeds, length of runs, the engineer may estimate the typical internal tire temperature and consequently, a reasonable relative rolling resistance for the various elastomer choices. This is usually enough to weigh against other parameters for design trade-offs.

Finite Element Analysis

Another relatively easy to use tool is finite element analysis. FEA's strength is to give the relative performance of various options, particularily in non-linear analysis. We find FEA most useful in modeling complete tire and wheel assemblies as opposed to use in polyurethane material selection. Often in specialty applications, an engineer is using polyurethane due to extremely high loads. In such situation the engineer may be concerned about the deflection or maximum carrying capacity of the complete tire and wheel assembly. To model such situations, we use a package called Cosmos/M. The cost of the linear, nonlinear, and thermal packages was approximately $8,000. As with most software today, Cosmos has extensive on-line help and examples. It is a very powerful PC based package that allows up to 5,000 elements and 60,000 nodes. In order to effectively use FEA, it is necessary first to model the nonlinear behavior of the elastomer in both tensile and compressive modes.

Mooney-Rivlin Tensile Model

Paper XXIII details how the ASTM-412 can be applied to the calculate the Mooney-Rivlin constants. **Figures** 7 and **8** show the plot of the ASTM test that we used at Superior to calculate the constants and the resulting finite element model of the ASTM-412 dumbbell. Figure 7 shows that this elastomer is not a "good" Mooney-Rivlin material (not linear at small extension ratios). The original calculation of the M-R coefficients were $C_1 = -49$ and $C_2 = 312$. Best fit was $C_1 = 20$ and $C_2 = 140$ for 100% extension. For this elastomer, the effective range for a given set of Mooney - Rivlin coefficients is much narrower than the published 20% to 150% extension ratios. Nevertheless, for industrial tire models the extension range need can be easily estimated and the M-R coefficients set accordingly.

Compression Button Model

Similarly, we have used ASTM compression data to plot Young's modulus as a function of load, **Figure** 9. Calculating Young's Modulus and using previously defined Mooney-Rivlin coefficients, the ASTM button can be modeled. **Figure 10** shows the actual compression data and the model for an 85A MDI. This best fit was acheived by lowering the FEA Young's modulus from an

estimated 2100 to 1700 and changing the M-R coefficients to $C_1 = 10$ and $C_2 = 235$. As in the tensile test, it is difficult to get a perfect curve fit for the full range from 100 psi to 400 psi. This particular match is sufficient for the 100 psi to 150 psi compressive stress in which we were interested.

Once these basic evaluations for each material in your material portfolio have been completed at the appropriate stress levels, design trade-offs are easily simulated.

Sources referred to in the text found in the Polyurethane Manufacturer's Association's Reference Guide to the Engineering Design of Cast Elastomeric Polyurethane Components

IX. Jairus C. Lawrence, Simplified Tire Design, 1977 Fall PMA meeting.

X. R.L. Palinkas, Successful Design of Castable Urethane Parts for Dynamic Applications, 1987 Spring PMA Meeting.

XVIII. C. Demarest, R. Moore, Chemistry and Applications of High Resilience Urethane Elastomers.

XXVII. C. Demarest, R. Moore, Prediction of End Use Performance From Dynamic Measurements (Abrasion Resistance), based on Paper from Utech '88.

XXIII. R.H. Finney, A Kumar, Development of Material Constants for Nonlinear Finite-Element Analysis

Polyurethane Tire Polymer Characteristics

Polymer	Cost	Ease of Processability	Cut & Tear	Dynamics	Rolling Resistance
TDI Ether - PPG	Low	High	Low	Low	Moderate
TDI Ether - PTMEG	Mod. to High	High	Moderate	Moderate	Moderate
MDI Ester	Moderate	Low	Mod. to High	Mod. to High	High
NDI Ester	High	Very Low	High	High	Mod. to High

Figure 1

Polyurethane Tire Performance Attributes

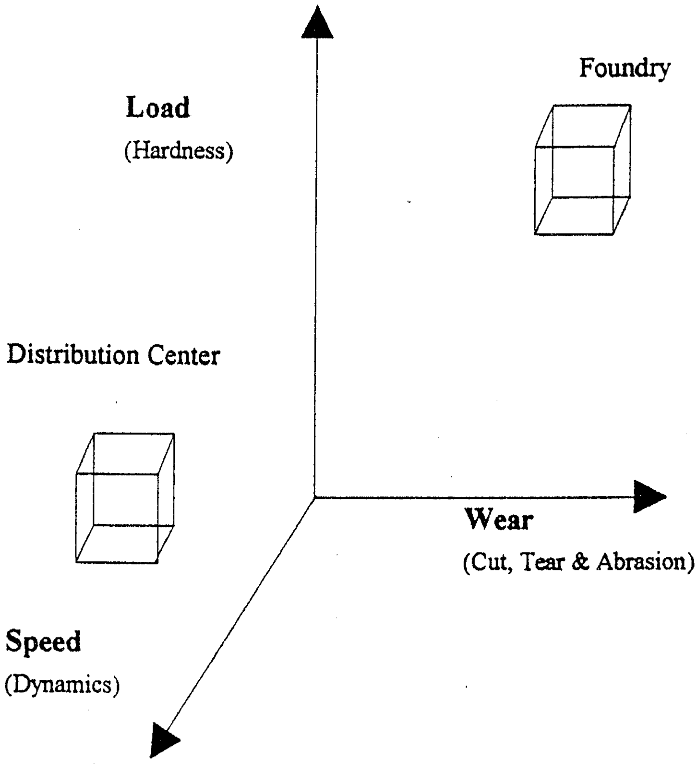

Figure 2

Superior Tire & Rubber Corporation
Static Parameter Calculations
Deflection
Rolling Resistence
Footprint

Formulas:

Rolling Resistence
R=2tand(W^4(b-a)/ESb^2)^.333

Deflection
U=(.75W(b-a)/(EcS(8b)^.5))^.666

Footprint
P=2S(b^2-(b-U)^2)^.5

Load
L=W/P

Ec=Compressive Modulus for Tire Form Factor
Eo= Compressive Modulus Young's
tand= Tan Delta
F.L. = Foot Length 1st Order Approx.
F.F. = Form Factor - Calculated from Tire Dimensions
F.I.=Foot Length Input from 1st Order to Avoid Circular
Wm= Maximum Load at X% Deflection (% of Radius)
Dp=Deflection Percentage of Outer Radius for Max Load

P=Footprint
L=Load
U=Deflection
W=Weight
b=Outside Radius
a=Inside Radius
S=Tire Wdth @Trd

10 x 5 x 6-1/2 MDI 85A

Calculation:

	Input:		Eo @ 100	Eo @ 200	Eo @ 300	Eo @ 400	
Inp	W=	lbs	2,040	2,040	2,040	2,040	
Cal	Ec=	psi	2,558	2,821	2,993	3,084	
Inp	b=	in	5.00	5.00	5.00	5.00	
Inp	S=	in	5.00	5.00	5.00	5.00	
Inp	a=	in	3.25	3.25	3.25	3.25	
Inp	Tand=		0.0300	0.0300	0.0300	0.0300	
Cal	F.L.=	in	2.02	2.02	2.02	2.02	
Cal	F.F.=		0.411	0.411	0.411	0.411	
Inp	F.L. Inp.	in	2.02	2.02	2.02	2.02	
Inp	Eo=	psi	1,912	2,108	2,237	2,305	
Inp	Dp=	%	1.93%	1.93%	1.93%	1.93%	
	U	Deflection (in.)	0.103	0.097	0.093	0.091	in
	R	Rolling R. (lbs.)	27.19	26.32	25.81	25.55	lbs
	P	Footprint (in^2)	10.10	9.78	9.59	9.50	in^2
	L	Gnd Press. (psi)	201.95	208.56	212.67	214.79	psi
	Wm	Load @ Dp (lbs)	1,851	2,041	2,165	2,231	lbs

Figure 3

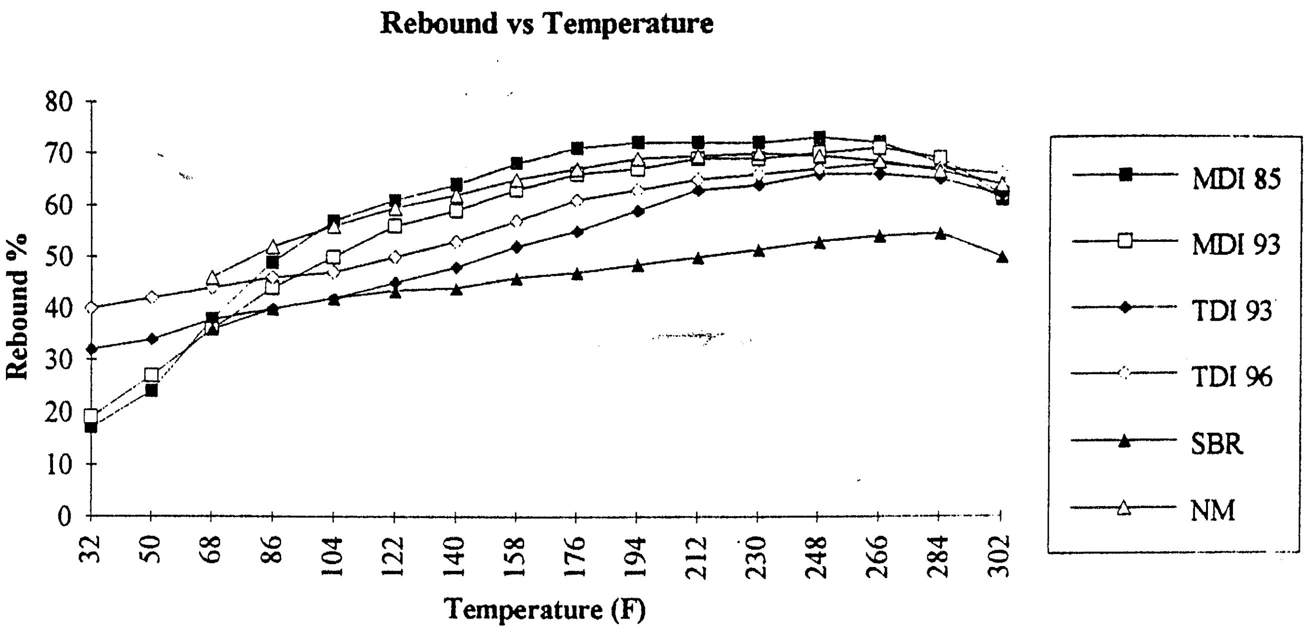

Figure 4

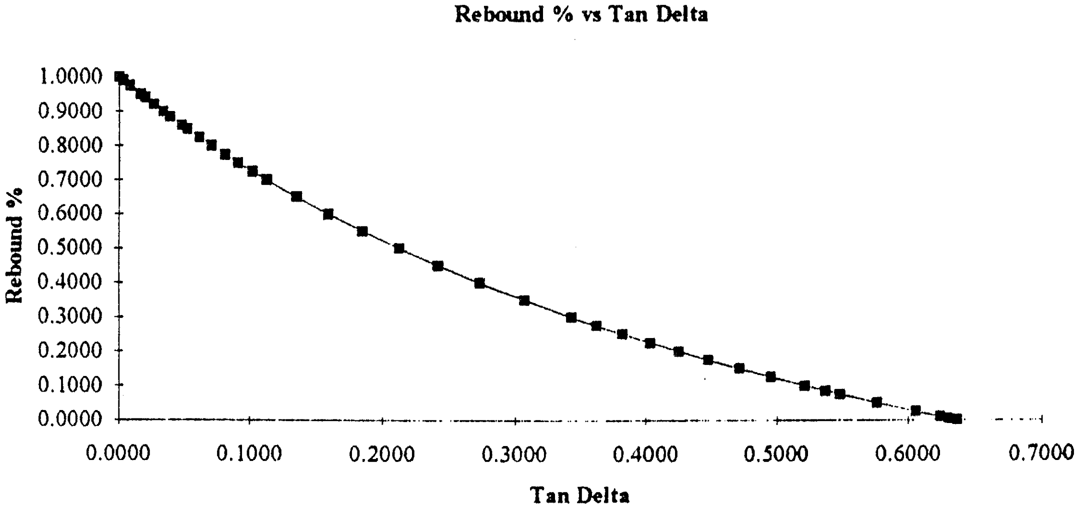

Figure 5

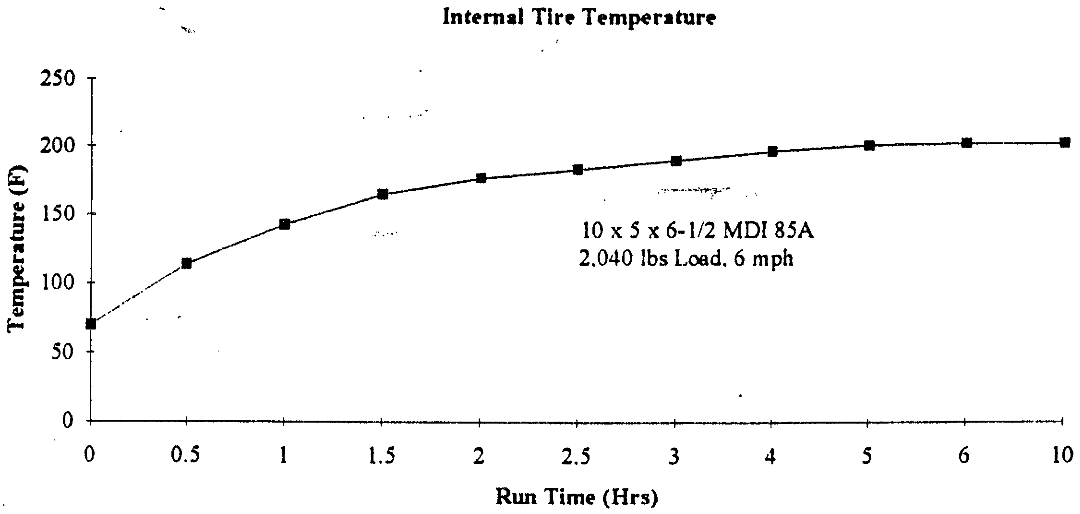

Figure 6

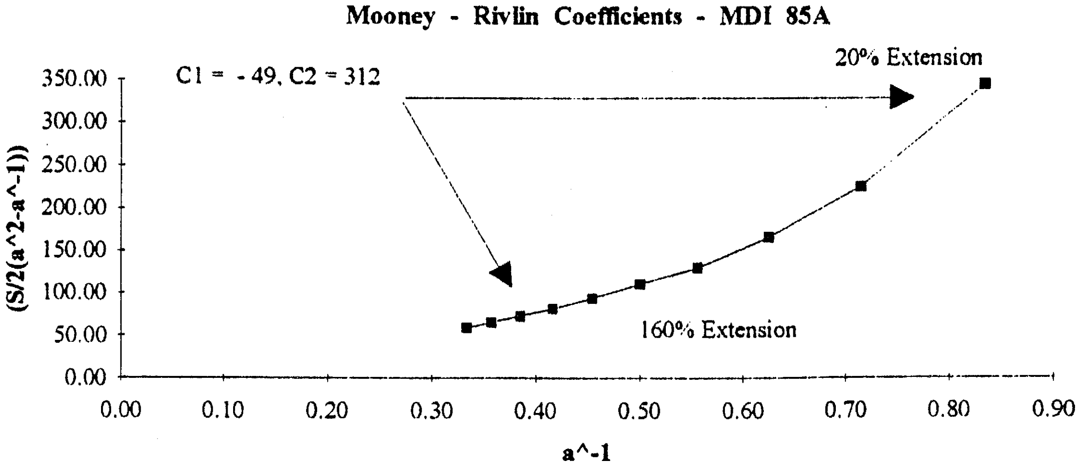

Figure 7

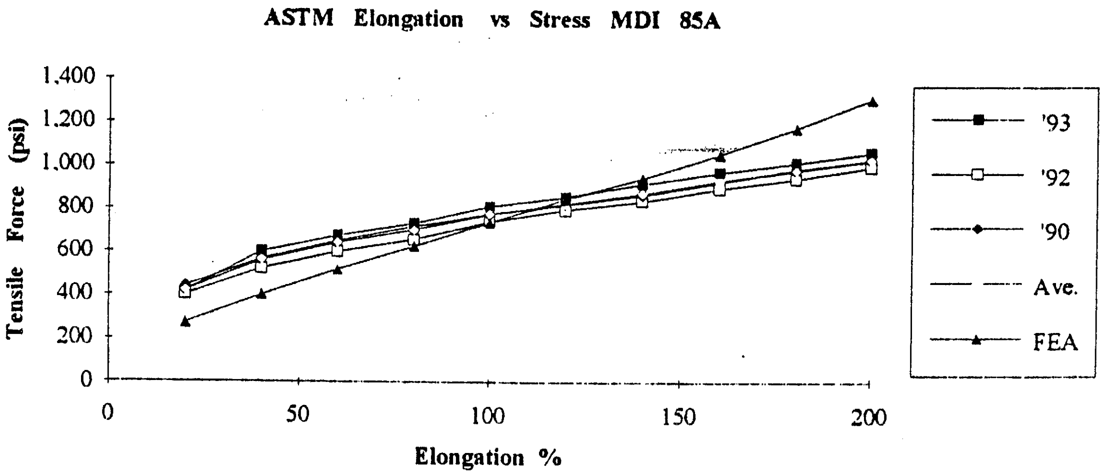

Figure 8

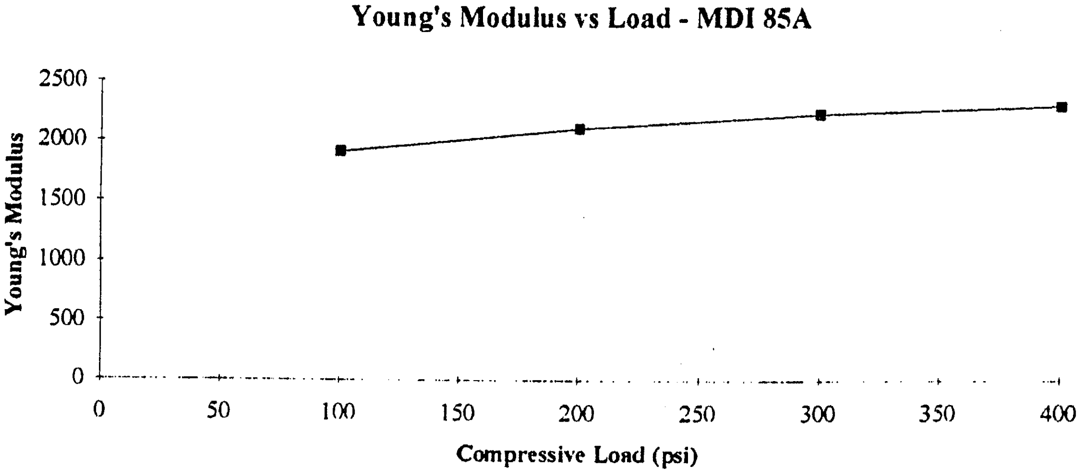

Figure 9

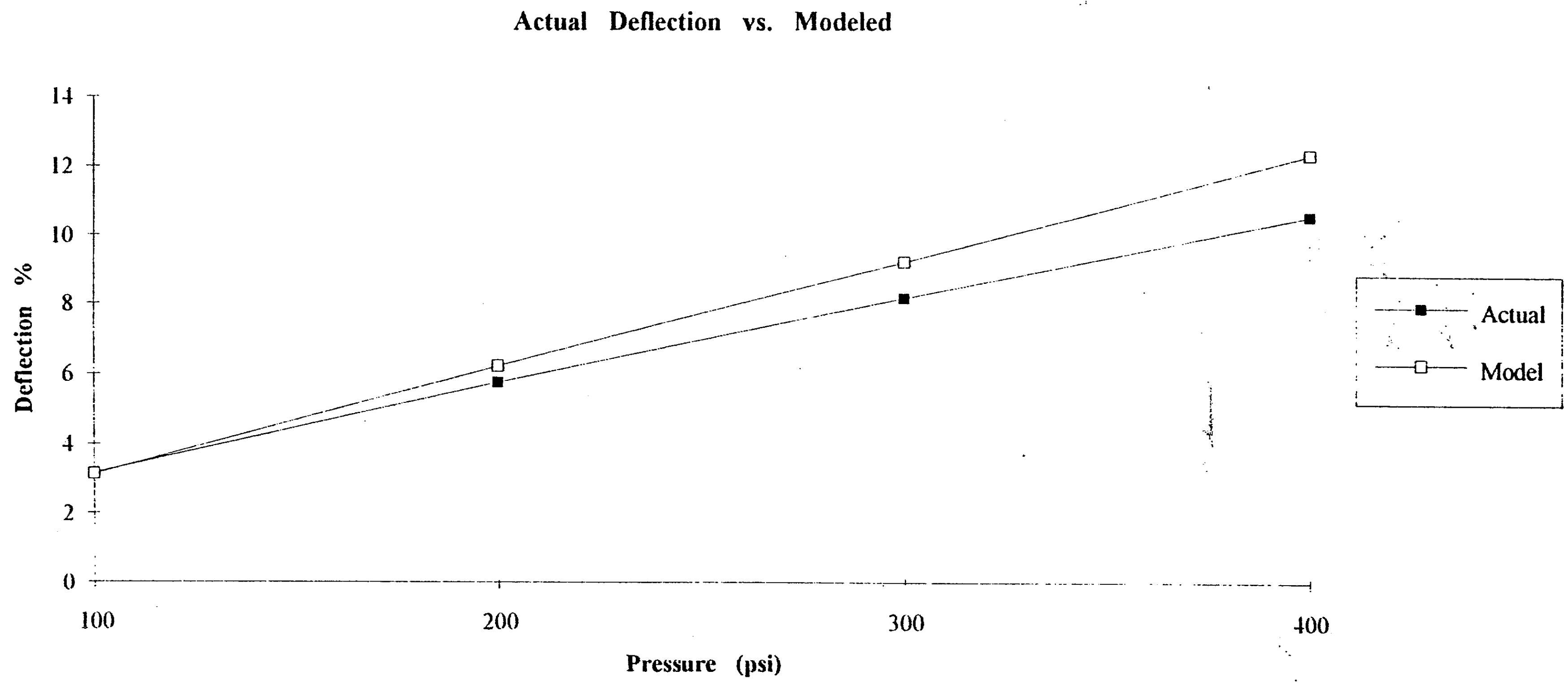
Actual Deflection vs. Modeled

Figure 10