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Flat-Proofed Tire Performance: Thermal Properties and Filling Pressures

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Abstract

Use of elastomeric low-modulus, tire flatproofing media has become standard in many off-road applications posing a hazard to tires. But unanswered questions to date include: [1] how do filled tires perform under extremely cold conditions? [2] What happens to the internal pressures of tires filled with these incompressible elastomers when the tires heat up under severe operating conditions?

This paper describes a series of cold tests run in cooperation with the Arctic Engineering Department of the University of Alaska, as well as results of tire durability tests during which changes in temperature and internal pressure, spring rate, tire deflection, and footprint size were monitored in tires filled with low-modulus elastomers.

SINCE THE ADVENT OF LOW-MODULUS FLATPROOFING media for pneumatic tires nearly ten years ago, with attendant resolution of earlier concerns about heat build-up, durability, and, most recently, ride, the use of elastomeric puncture-proofing tire fill has come common in hostile environments, or in applications where schedule interruptions cannot be tolerated. Examples include: (1)

- Steel Mill Vehicles
- Mining Vehicles
- U. S. Air Force Ground Support Vehicles
- Airport "People Movers"
- Airport Baggage-Transfer Carts
- Land Fill Vehicles
- Metal-Recycling Scrap Yards
- Trash Collectors
- Street Sweepers
- Theme Park Monrails, e.g. Disneyland
- Trams for Visitor Tours
- Industrial Materials-Handling Vehicles
- Parade Floats
- Agricultural Equipment in Thorn Areas

Arnco, a California company (with additional manufacturing facilities in Texas) specializing in the design and production of liquid polyurethane systems, has developed a line of puncture-proofing elastomers with properties tailored to specific applications. Physical properties of two of these urethane flatproofing products, representing polymer systems, and having the commercial names of "RePneu" and "SuperFlex", respectively, are shown in Table 1.

Table 1- Comparison of Physical Properties (2)

Property	RePneu	SuperFlex
Durometer (Shore A)	25	5
Comp. Modulus @ 20%	550 psi	150 psi
Tensile Strength	315 psi	200 psi
Elongation	600%	800%
Rebound	50%	47%
Cold Flexibility to	-50°F (-46°C)	-50°F (-46°C)

When it was first disclosed in 1980, RePneu represented a break-through in the chemistry, physical properties, and the economics of flatproofing elastomers.(3) It had a much lower (softer) modulus, higher physicals, lower cost, as was much more tolerant of moisture in tire casings than state-of-the-art materials. A typical application for RePneu is the U.S. Air Force conveyorized cargo loader shown in Figure 1, which not only sees service in situations where 100% schedule reliability is vital, but is also an

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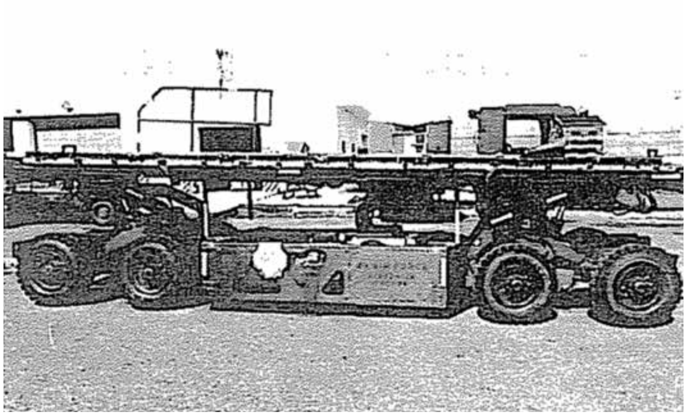

Fig. 1- A U.S. Air force conveyorized cargo loader; tires are flat-proofed with elastomeric fill

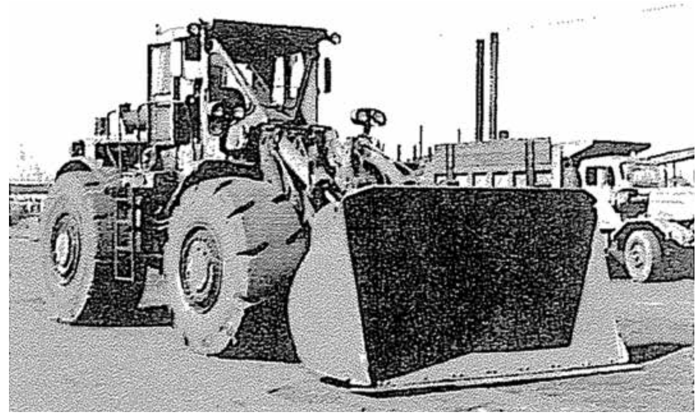

Fig. 2- A front-end loader, typical of unsprung steel mill vehicles.

example which exploits the bulletproofing properties of elastomeric fill.

But for use on unsprung off-road vehicles like the Cleveland steel mill front-end loader shown in Figure 2, or the farm tractor operating in thorn-infested Texas brush, as pictured in Figure 3, SuperFlex, an ultra-low modulus polymer was indicated. (4) Developed, field tested, and released in 1985, and having a Durometer of only 5-8 (Shore A), SuperFlex is believed to be the softest possible elastomeric solid consistent with the requirement that it must not extrude out of the tire in the event of a major puncture. It not only improves driver comfort significantly, but reduces metal fatigue in vehicle chassis components due to operational shock and vibration. A low modulus elastomer such as SuperFlex also improves the operation of agricultural vehicles having low-pressure tires which depend on footprint control for flotation. (5, 6)

Urethane Tire Filling Technology

The tire-filling process for these liquid-urethane elastomeric materials utilizes equipment which is simple and easy to operate, as shown in Figure 4. Two reactive liquid components are mixed together in equal quantities. Pumped from a pair of drums (labeled “A” and “B” in the figure) by a double barreled positive-displacement pump, the components are intimately blended together as they flow through a static mixer on the way to the tire. The tire is filled through the tire valve, which is usually oriented in a “10 o’clock” or “2 o’clock” position on the rim to facilitate a smooth flow of the reactive stream into the tire without turbulence. Air is vented through a needle inserted through a small hole at the top of the tire, which is later sealed after the tire is completely filled.

Figure 5 pictures the actual filling equipment as it appears in the shop.

Before filling, the tire is inflated with air overnight to a pressure corresponding to its maximum rated load to tension the cords and to permit stress relaxation to take place in the tire body. Then, as a final step in the filling process, the tire is accurately pressurized for its rated load. Since it is filled under pressure, the tire is “inflated” by the liquid polymer. That is, in the case of a bias tire, the stretched cords pantograph, assuming the same cord angle they would exhibit if the cords were pressurized with air; in a radial tire the carcass is also stress-loaded. It is these tire-body stresses that store and maintain the pressurization of the tire.

Fig. 3- Thorn-infested mesquite brush debris typical of Texas ranch environment.

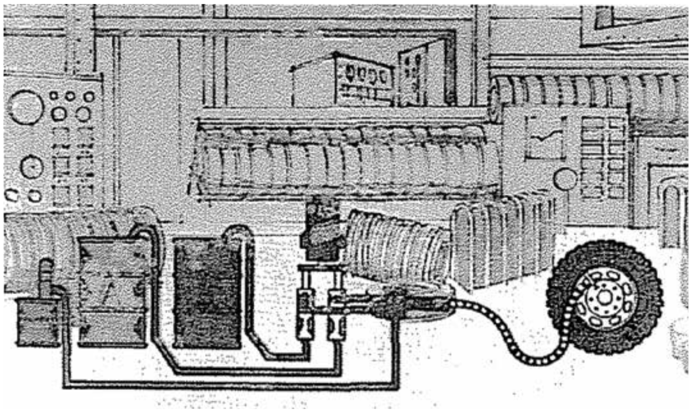

Fig. 4- Two reactive liquid components are blended in a static mixer and pumped into the tire under pressure.

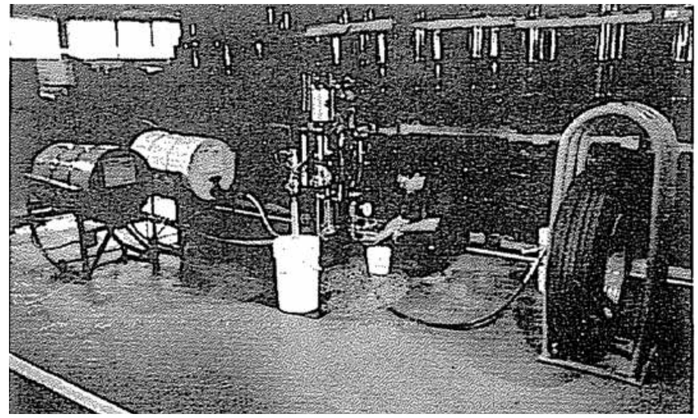

Fig. 5- Filling equipment includes a pair of drums, double-barreled positive-displacement pump, static mixer, and safety cage.

The liquid polymer system begins to "gel" in an hour or so, depending on ambient temperature, and cures overnight at room temperature, to a soft, non-porous, homogeneous solid rubber whose color is usually a translucent reddish brown. Optimum physical properties are attained after a few days.

Laboratory and Vehicle Evaluation

As the above line of new generation tire-fill elastomers was developed, a concurrent testing program has been maintained by ARNCO having both laboratory and field components not only to compare tire performance with prior puncture-proofing media, but to evaluate performance of filled tires in a direct comparison with the same pneumatic tires filled with air.

Earlier papers (2) (7) by the same authors have reported the results of comparative laboratory testing of truck tires to determine the effect of filling on such properties as:

- Ride
- Rolling Resistance
- Durability
- Heat Build-Up
- Effect of Heat Build-Up On Deflection
- Pressure Retention (stress relaxation)
- Footprint Studies

As a measure of ride quality, load-deflection curves were run on identical tires filled to the same pressure with RePneu, SuperFlex, water, and air. These curves are reproduced in Figure 6. The measured slope (or spring rate) of these curves is as follows:

RePneu	2630 lb/in	(471 kg/cm)
SuperFlex	1710 lb/in	(306 kg/cm)
Water	1450 lb/in	(259 kg/cm)
Air	880 lb/in	(157 kg/cm)

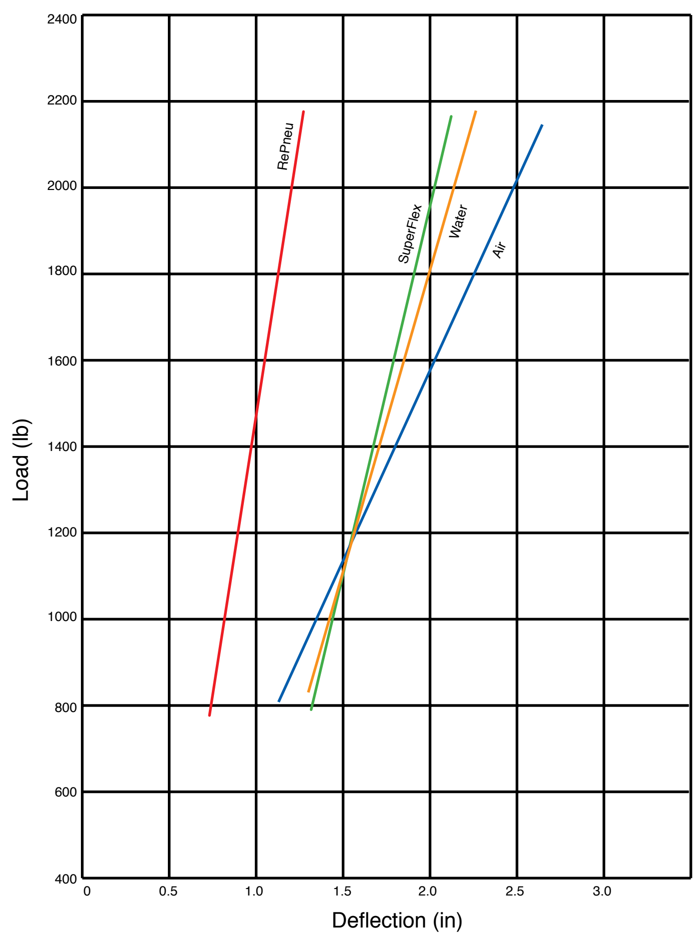

Fig. 6- Comparison of room-temperature load-deflection curves for P215/75/R15 passenger car tires filled with RePneu, SuperFlex, water and air.

Fig. 7- Showing ride test course over which vehicles were driven with various tire fills.

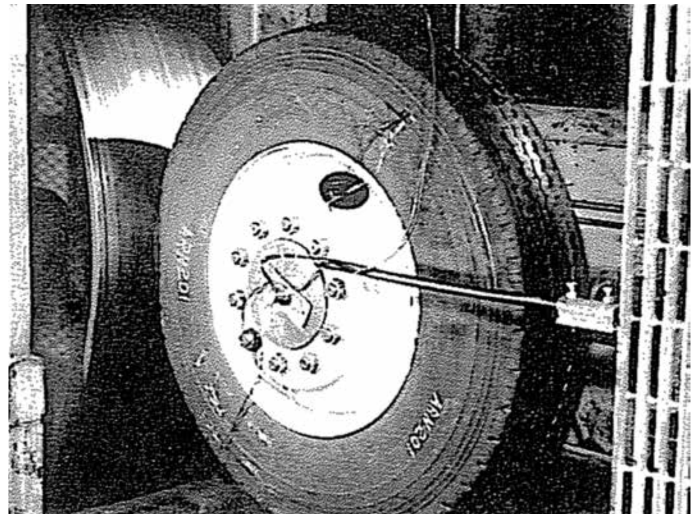

Fig. 8- Road wheel against which durability and load-deflection tests were run.

Thus, it might be concluded that the spring rate of the tires filled with RePneu is approximately three times that of the same tire filled with air; however, SuperFlex is less than twice as stiff as the air-inflated tire. Stated in percentages, compared with RePneu, the SuperFlex-filled tire is 35% softer. The SuperFlex tire is, in fact, only 18% stiffer than the same tire filled with water to the same pressure.

Instrumented vehicle ride tests were also conducted over a course that included the rough railroad tracks shown in Figure 7. G-values measured on the rear axle were consistently less when operating with SuperFlex filled tires than with pneumatically inflated tires, a conclusion subjectively confirmed by both truck's driver and the recording engineer (possibly because relatively small footprint deflections produce less axle movement in the high-mass wheel-tire assembly).

Probably the most significant – and certainly the most surprising – results were those obtained during durability testing in accordance with the 47-hour Federal Motor Vehicle Standard 119 (8) destructive truck tire qualification test. As prescribed, this test is conducted under a variety of loads against a 67.227in (170.76cm) diameter rotating road wheel, or drum, as pictured in Figure 8. Particularly notable in these earlier published results were the following:

1. All tires tested more than survived FMVSS #119 truck tire durability test.
2. RePneu-filled radials actually ran cooler than equivalent tires filled with air in these 40 mph (56 kph) durability tests – which were later extended to 55 mph (88 kph).
3. During these tests, the deflection of the RePneu-filled tires decreased substantially as they heated up (with a corresponding decrease in footprint size), thus reducing energy input to the tire and preventing "thermal runaway."
4. No measurable stress-relaxation (change in load-deflection curve) occurred as a result of extended testing.

Chemistry: The "Champagne Bubble" Effect

The chemistry of for both RePneu and SuperFlex polyurethane systems represents a radical departure from prior art. Unlike conventional urethane compositions which demand anhydrous conditions to avoid deleterious water-isocyanate side reactions, RePneu actually incorporates water in its composition to achieve final polymerization. The resulting reaction, unlike conventional urethanes, is non-stoichiometric; i.e., it allows some tolerance in the mix ratios of its components. Moreover, the end polymer is a substituted urea with improved tolerance to high temperatures, and decomposition products that will not liquefy. Furthermore, because of its special catalysis, the elastomers can tolerate the water condensates which are frequently found in tires to be filled.

The unique chemistry of these polymer systems is related to their relatively cool-running characteristics.

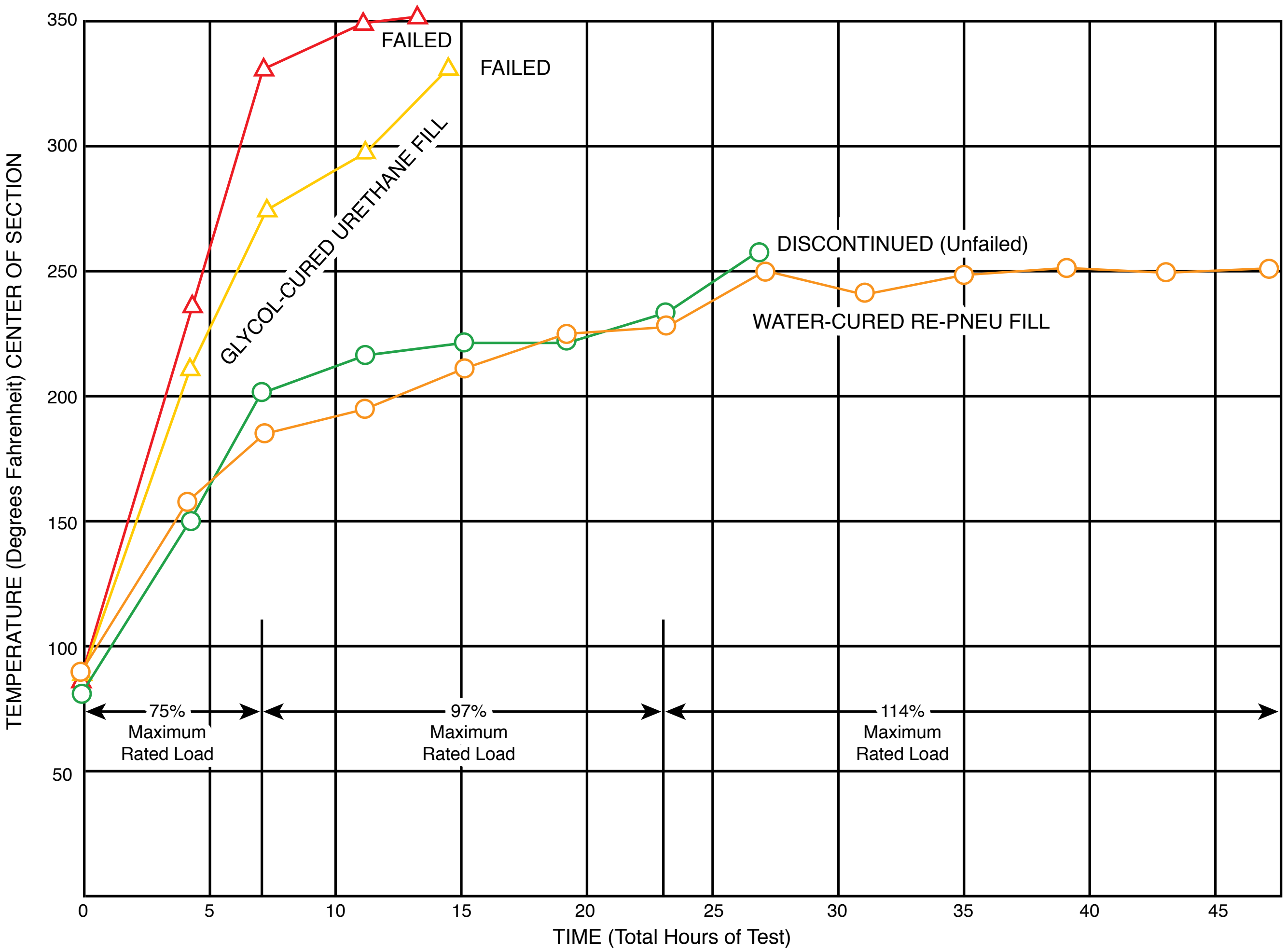

Fig. 9- Showing temperature performance of tires filled with water-cured RepPneu during durability test, contrasted with tires filled with glycol-cured urethane, noting temperature plateau as "champagne bubble effect" (incipient CO_2 nucleation) creates temperature equilibrium.

Figure 9 demonstrates the point. Unlike some other tire-filling systems, notably those having a glycol cure (as contrasted with ARNCO's water cure), the temperature of the working tires levels off and tends to establish a plateau for any given load during the 47-hour FMVSS durability tests.

The physical explanation for this temperature plateau phenomenon is illustrated in Figure 10. As the tire heats up, the slope of its load-deflection curve increases slightly, and the entire curve shifts to the left. In short, there is a substantial decrease in tire deflection (as much as an inch (2.5cm) under some conditions). This reduction in deflection varies directly with the temperature; as a result, an equilibrium is established as less energy is dissipated in the rolling tire (i.e., its rolling resistance decreases), and its temperature levels off, as noted earlier in Figure 9.

There are two reasons for this deflection decrease. The first, also true of other urethane systems, is that polyurethanes have a large coefficient of thermal expansion (linearly of the order of 0.0001 per degree Fahrenheit [0.0002 per degree Celsius]); (8) in addition, the urethane fill is incompressible. That the amount of deflection decrease due to expansion of the fill is not sufficient to prevent "thermal runaway," however, is demonstrated by the failure of the glycol-cured tires in Figure 9, above. Clearly, something else is happening with the ARNCO products. Now generally accepted as a result of work reported in an earlier paper (2), the physical mechanism for the phenomenon has been dubbed the "champagne bubble effect":

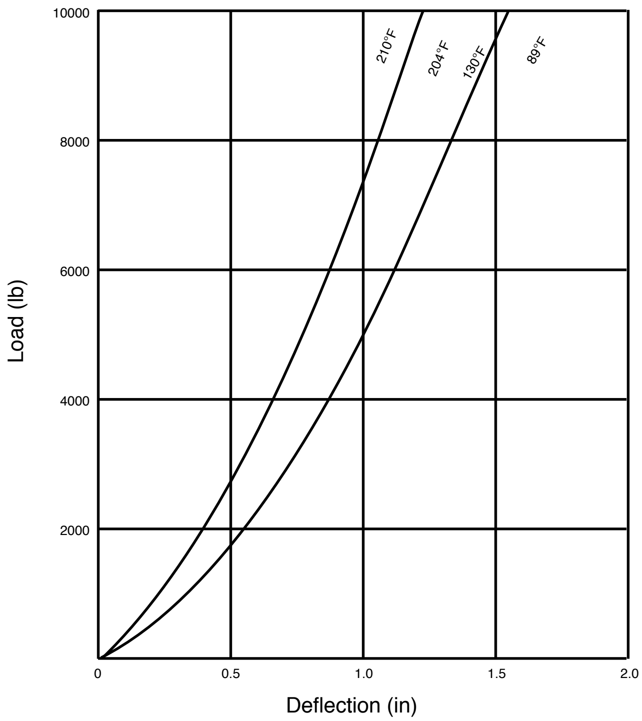

Fig. 10- Showing reduction in deflection and shift of load-deflection curve on radial truck tire as temperature increases.

When water is used as a curing agent for urethane, as in RePneu and SuperFlex, carbon dioxide is a reaction product of the resulting polymer. The CO_2 remains dissolved and/or complexed in the tire fill, especially since the tire is filled under pressure, thus increasing the solubility of the gas in elastomer.

Then, when the tire begins to heat up while running at high speeds under load, the CO_2, being less soluble in the hot elastomer, begins to come out of solution. The resulting "nucleation," or incipient formation of sub-microscopic bubbles in the non-compressible elastomer (in combination with the effect of the thermal coefficient of expansion of the polymer), in effect increases its pressure, thus further reducing tire deflection.

As stated above, flexing the tire carcass through a lesser deflection reduces the amount of work done on the fill, and the tire stops heating up; its temperature thus levels off, establishes an equilibrium, and "thermal runaway" is prevented. As the tire cools, this carbon dioxide redissolves, and disappears.

Another result of this "champagne bubble effect" is illustrated in Figure 11, which shows the reduction of the footprint of a radial truck tire (11R 22.5) filled with RePneu as its temperature increases from 90°F (32°C) to 152°F (67°C). The decrease in footprint area is 18.4%.

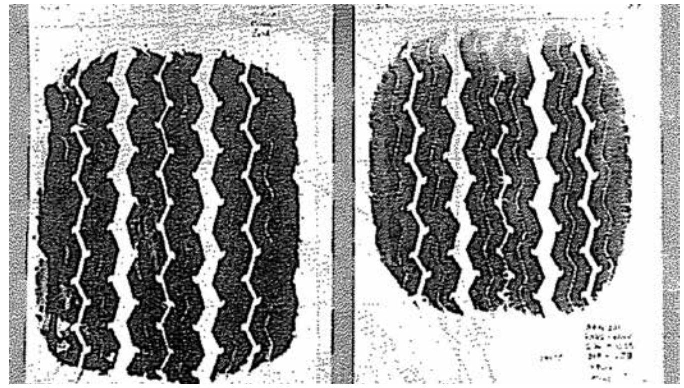

Fig. 11- Showing 18.4% decrease in footprint area of RePneu-filled radial truck tire as its temperature increases from 90°F (32°C), left, to 152°F (67°C), right.

Further Work Needed: Tire Pressure Studies

Since it had been established that volume of the elastomer and effective tire pressure consistently increase as tires heat up while working under load, and since radial tires have less capacity or volume change than bias tires, it seemed important to the authors to determine the magnitude of the resultant pressures in radial tires filled with both RePneu and SuperFlex. Moreover, results of monitoring pressures under severe operating conditions could influence the current recommendation that tires be filled to a pressure corresponding to the maximum rated load of tire.

A series of tests was planned in cooperation with Standards Testing Laboratories (abbreviated below as STL) of Massillon, Ohio, where all of the testing described above has taken place. During durability testing in such a professional facility, it is relatively easy to monitor tire pressure during testing of pneumatic tires: and, indeed, the pressure can be altered as desired. Obviously, the pressure of a filled tire can be adjusted only once, as a final step at the end of the filling process; and, as noted, current practice calls for pressurizing the fill to the maximum rated load of the tire – the wisdom of which was one of the items to be investigated.

To provide for continuous measurement of the pressure in the filled tire during durability testing, ARNCO had three pressure transducers made by Sensotec, having a pressure range of 0-500 psi, compensated for accuracy to 250°F (121°C). The transducers have a configuration that permits their being screwed into the side of the wheel rim on which the tire to be filled is mounted, presenting a calibrated diaphragm about the size of a dime to the tire interior. During the filling process the pressurized elastomer, thus, comes directly into contact with the diaphragm of the transducer. Tires were also instrumented with a thermocouple emplaced in the center of the filled cross section.

Since a number of elastomer formulations were to be evaluated, a passenger car tire size was selected for both economy and repeatability: General P226/70R14/98T, mounted on 6-hole chrome rims. For each elastomer tested, tires were filled to three different pressures:

5 psi
26 psi
35 psi

The rationale behind the pressures selected was as follows: 35 psi represents the maximum rated load of the tire. But when testing pneumatic tires filled with air, STL has a standard procedure that involves inflating "cold" to approximately 75% of the stipulated gage pressure prior to testing; or 26 psi for the tire selected, since laboratory experience has shown that the air pressure will build up to the requisite 35 psi after the tire warms up; this procedure usually makes it unnecessary to read just pressure during a durability test. Perhaps a similar value, it was considered, would be optimum for inflation with an incompressible elastomer.

The 5 psi inflation was a concession to a school of thought that has suggested that tires should be filled only until "full", and not further stressed; but to make sure the tire was, indeed, completely filled, it was deemed desirable to actually see a reading on the pressure gauge at the end of the process.

Pressure and Rate Characteristics

Flat-plate load-deflection tests were run on each of the above tires by STL while also recording pressure. As expected, both static deflection and footprint area at rated load varied inversely with pressure (see Figure 13, below).

In Figure 12, pressure is plotted against load for SuperFlex filled tires. It will be noted that the curves for the 26 psi and 35 psi tires converge near the rated load for the tires and have almost parallel slope, while the 5 psi tire has almost zero slope.

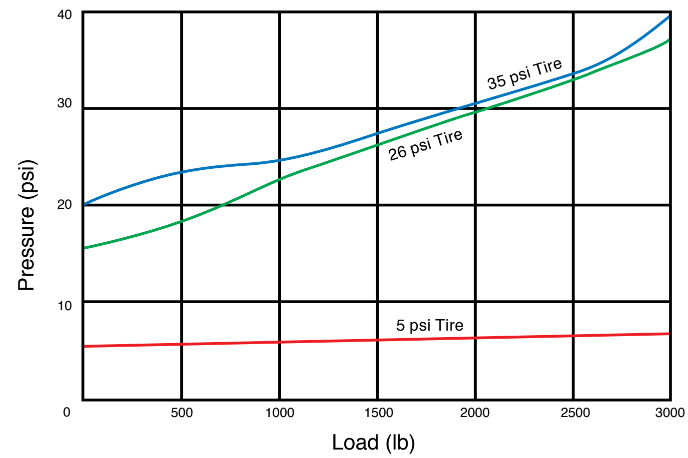

Fig. 12- SuperFlex filled tire pressure plotted as a function of load.

These considerable variations do not appear in the corresponding load deflection curves, however. Table 2 compares their respective slopes, and it will be noted that the rate differences are small.

Table 2 - Rates of SuperFlex-Filled Tires

Tire Pressure	Spring Rate	
5 psi	3330 lb/in	(596 kg/cm)
26 psi	3530 lb/in	(632 kg/cm)
35 psi	3635 lb/in	(651 kg/cm)

Table 3 makes an interesting comparison, both in relative magnitude and in rate change with pressure increase, with an air-filled tire of a similar size: FR 78-14 (P195).

Table 3 - Rates of Air-Filled Tires (10)

Tire Pressure	Spring Rate	
12 psi	750 lb/in	(134 kg/cm)
16 psi	800 lb/in	(143 kg/cm)
20 psi	980 lb/in	(176 kg/cm)
28 psi	1250 lb/in	(224 kg/cm)
36 psi	1560 lb/in	(279 kg/cm)
48 psi	1950 lb/in	(349 kg/cm)

Pressure-Monitored Durability Tests

Endurance testing was carried out as prescribed in Federal Motor Vehicle Safety Standard No. 109, a test used to "establish performance and marking requirements for tires for use on multi-purpose passenger vehicles, trucks, buses, trailers, and motorcycles…" (9) As with FMVSS 119, above, this test is run in contact with a road wheel of 6.227 in (170.76 cm), or 1/300 of a mile, as illustrated in Figure 8. These FMVSS tests are regarded as destructive tests, since the circumference of the road wheel imposes a "reverse curve" into the tread – a condition never continuously encountered in service.

The 34-hour durability test was run at a road wheel velocity of 50 mph (80 kph) for RePneu-filled tires, and at both 50 mph and 35 mph (56 kph) with SuperFlex tires. 35 mph is the maximum operational speed recommended by ARNCO for tires filled with the softer elastomer. Because of the above reverse curvature imposed on the tire tread by the road wheel, test speeds are equivalent to a highway velocity approximately 5 mph faster.

The prescribed schedule for the durability test is:

- 4 hours at 85% of rated load
- 6 hours at 90% of rated load
- 24 hours at 100% rated load

During the test, internal temperature, tire deflection under the test load at the time, and internal pressure were recorded, taking readings hourly for the first eight hours, then every four hours until termination of the test, or tire failure.

In addition, both load-deflection curves and pressure deflection curves were run on the tires before the tests began; these were repeated with the tires hot after 30 hours of testing. Then, 24 hours after completion of the test, and after the tire had returned to room temperature, another set of load-deflection tests was run to measure any stress relaxation in the tire. Hot and cold footprint studies were also conducted.

Test Results

In the case of RePneu, as in all previous durability tests with this elastomer, the tires readily survived the durability test. Even at 50 mph, pressure increases were moderate, as shown in Table 4.

Table 4- RePneu Temperature/Pressure: 50mph

	5 psi Tire	26 psi Tire	35 psi Tire
Max Temp	NA	230°F	NA
Max Pressure	7 psi	35 psi	44 psi

During two of the above RePneu tests, the thermocouples were extruded out of the section by the working, pressurized elastomer – a problem which was solved by hot-patching them in place for the balance of testing.

To provide a direct comparison, and since 50 mph is the FMVSS test speed specified for a passenger tire of this size, the durability test was initially repeated on SuperFlex filled tires at the same velocity. At 50 mph, SuperFlex filled tires developed both excessive temperatures and pressures, as shown in Table 5 (the starred 56 psi value shown may represent an instrumentation error). Moreover, the 35 psi tire experienced tread separation after 20.7 hours, at which point the test was discontinued.

Table 5- SuperFlex Temp/Pressure: 50 mph

	5 psi Tire	26 psi Tire	35 psi Tire
Max Temp	288°F	298°F	289°F
Max Pressure	114 psi	56* psi	130 psi

But when the SuperFlex tires were run at 35 mph, the maximum operational speed specified by Arnco for this polymer, the temperatures and pressures were reduced to the levels shown in Table 6. All tires survived the durability test at 35 mph.

Table 6- SuperFlex Temp/Pressure: 35 mph

	5 psi Tire	26 psi Tire	35 psi Tire
Max Temp	275°F	269°F	271°F
Max Pressure	70 psi	60 psi	70 psi

Footprint Studies

As might be expected, footprint size decreased with higher filling pressures. Figure 13 compares the relative footprint size of tires filled to 35 psi and 5 psi, respectively.

Because of the very high temperatures generated at 50 mph during durability testing, with substantial pressure increases due to both thermal expansion and the champagne bubble effect, footprint size decreased much more dramatically with SuperFlex, as seen in Figure 14, than was the case with the cooler temperatures produced with RePneu filled tires at the same test speed. Compare Figure 14 with Figure 11, above.

Table 7 summarizes and quantifies this footprint date. Since changes in footprint width are minimal, the length of the footprint provides a direct measurement of its area.

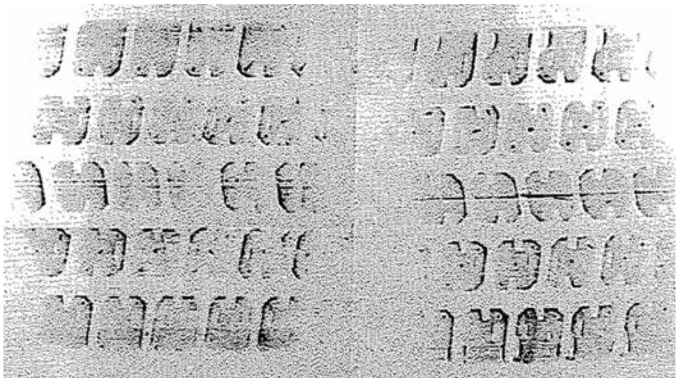

Fig. 13 – Footprint at rated load of tire filled with SuperFlex to only 5 psi, at left, is 15% larger than that of same tire filled to rated pressure of 35 psi, right.

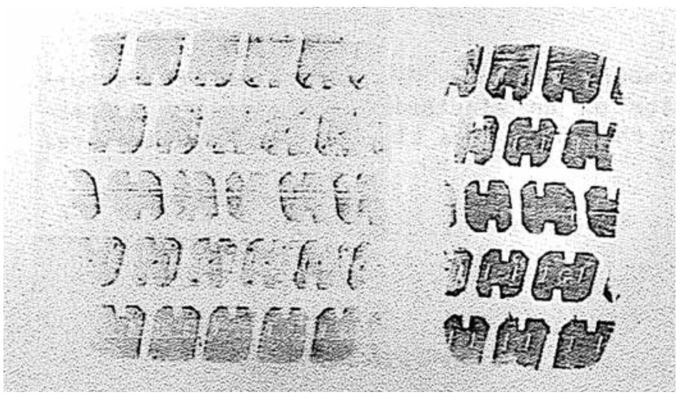

Fig. 14 – Footprint of above 5 psi SuperFlex tire at 98° F, left has decreased 42% at 280° F, right after 30 hours of testing

Table 7 – SuperFlex Tire Footprint Length

Tire Pressure	Cold 0 Hrs	Hot 30 Hrs	Reduction
5 psi	6.06 in	3.50 in	42%
26 psi	5.38 in	3.25 in	35%
35 psi	5.13 in	N/A	-

The data in Table 7 were taken during the 50 mph durability test; a footprint made on the 35 psi tire at 20.7 hours (when the test was discontinued due to tread separation) is not reported since the tire's pressure had decayed to 40 psi and its deflection had increased by more than 0.2 in.

From Tables 6 and 7 it might be concluded that while there may be an advantage to filling a tire to 75 percent of its rated pressure, it appears disadvantageous to fill SuperFlex tires to only 5 psi, since the greater work done on a softer tire creates higher temperatures and pressures.

Cold Tests

To evaluate the performance of filled tires under extremely cold conditions - - the other major question to be resolved - - the number of laboratory and field tests were carried out in cooperation with the Arctic Engineering Department of the University of Alaska, Anchorage, utilizing the facilities of the School of Engineering. The exterior of the University's suite of walk-in cold rooms is pictured in Figure 15. Covering a wide variety of ARNCO products, including RePneu and SuperFlex, at temperatures as low as -100° F (-73°C), these tests (11) included:

- GROSS FLEXIBILITY
- HAMMER IMPACT FRACTURE TEST
- LOW TEMPERATURE DUROMETER INCREASE
- COEFFICIENT OF THERMAL EXPANSION
- ASTM BRITTLENESS TESTS
- LOAD-DEFLECTION DATA
- FLAT-SPOT RECOVERY ON A VEHICLE

The first four listed properties were evaluated on sample bars of polymer cut from cast slab; these samples measured approximately 12 in long and 2 in wide by 0.75 in thick (30.5 X 5 X 2 cm). Marks were inscribed on the surface of these bars for the purpose of evaluating thermal expansion and contraction. Other samples included round "pucks" cast in biscuit tins approximately 2 inches in diameter by half an inch thick (5 cm dia. X 1.3 in thick).

Durometer (Shore A) of each sample was measured in the laboratory at 77°F (25°C). Each sample was also struck a heavy blow with a 16-ounce claw hammer while warm. The impacts produced no damage to the samples. It was also observed that each of the bar samples could readily be bent or twisted.

Fig. 15 – Technicians prepare cinematography equipment for operation at -40° in University of Alaska School of Engineering cold chambers

Fig. 16 – An array of ARNCO polymer test strips, bars, and pucks, in -40° cold chamber; bar at left is wrapped around mandrel.

Fig. 17 – Bars of RePneu and SuperFlex elastomers are very flexible at -40°

All of the samples were then placed in one of the University of Alaska cold chambers adjusted to -40°F (also -40°C) over night - - for a minimum of 16 hours. Prior to this soaking period, one each of the bar samples had been bent around a 1.5 in diameter (3.8 cm) pipe mandrel and clamped in place. An array of these samples in the cold room, as well as those prepared for ASTM brittleness tests, is pictured in Figure 16.

Gross Flexibility; Hammer Impact

After soaking overnight in the cold room, each of the bars, although detectably stiffer, could easily be bent, twisted, and otherwise distorted, as seen in Figure 17. The bars of elastomer which had been clamped around the pipe mandrels unbent readily, but retained a slight "stirrup" set at -40°. When permitted to warm up to the exterior laboratory temperature of 77°F (25°C) over night, this set completely disappeared.

Both bars and pucks were struck a heavy blow with the above 16-ounce claw hammer, swung through an arc of 30 to 36 inches (75 to 90 cm) as hard as the operator could muster, without any evidence of cracking. The impacts did produce slight dimples in the sample having the shape of the hammer head - - evidence of energy-absorbing flow rather than fracture under these high transient stresses. Upon rewarming to room temperature, these dimples completely disappeared.

Durometer Increase

Increase in Durometer (Shore A) at -40°F (-40°C) is shown in Table 8. After soaking over night at this temperature the maximum durometer readings shown represent characteristics of an elastomer substantially softer than that of a tire tread at room temperature.

Table 8 – Durometer (Shore A) [12]

Elastomer Sample	77°F Peak	(25°C) Decay	-40°F Peak	(-40°C) Decay
RePneu Bar	27	25	50	40
RePneu Puck	29	27	52	45
SuperFlex Bar	8	7	30	20
SuperFlex Puck	9	8	28	20

Thermal Expansion Coefficient

Average values obtained for coefficient of linear expansion for both RePneu and SuperFlex, measured over a temperature range of -45°F to +75°F (-43°C to + 24°C) was 0.00012 per degree Fahrenheit (0.00022 per degree Celsius) - - at least an order of magnitude greater than that for most metals, and three times greater than the expansion coefficient for natural rubber. (11)

These figures are not only significant in the studies of pressure increase due to heat build-up and consequent reduction in tire deflection as discussed above in association with the "champagne bubble effect," but a curious reverse effect was also noted when chilling tires to -40° for the load deflection tests in the Anchorage laboratories. Under their own weight (86 to 88 lb.), filled tires developed local flat spots and sidewall depressions where their shoulders contacted the bottom of the cold cabinet. The effect

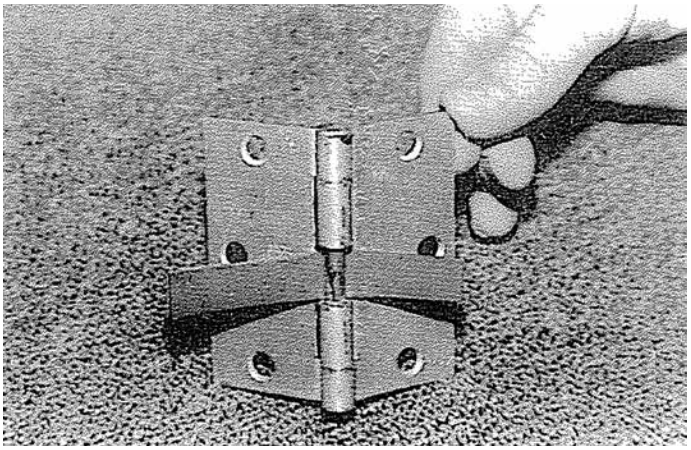

Fig. 18 – Modified door hinge fixture for ASTM D2136 bend test

was noted with both SuperFlex and with substantially stiffer RePneu. Stated more simply, the tires appeared to "suck in." Upon rewarming, these anomalies disappeared. The fact that the thermal coefficient for urethane is substantially greater than that of rubber as well as those of reinforcing synthetic fibers used in tire construction explains this temporary shrinkage phenomenon. It also contributes to flat-spotting when the tire is chilled under load, as described below.

ASTM Brittleness Tests

Both ASTM D2136 and ASTM D2137 standard brittleness tests were run on strips of RePneu and SuperFlex. The first of these, ASTM D2136, simply wraps a strip of elastomer half an inch wide and several inches long around a small-diameter mandrel. (13) To facilitate handling the metal test fixtures with heavily gloved hands, a modified door hinge, Figure 18, was fabricated to produce a tight 180° bend in a sample of approximately 1/8-inch thickness by ½ in wide (.3 cm thick by 1.3 cm wide) around a 1/4–inch (0.6 cm) mandrel.(12)

All of the samples of RePneu and SuperFlex could be easily wrapped around the 1/4–inch pin at 40 below zero without any evidence of cracking.

Additional samples, together with the ASTM D2136 hinge fixture, were then chilled in a smaller chamber having greater cooling capacity to a temperature of -100°F (-73°C), and the test was repeated. Both the RePneu and SuperFlex samples passed without evidence of fracture. (11)

ASTM D2137 is primarily designed for coated fabrics, and is more severe. This test uses samples nom-

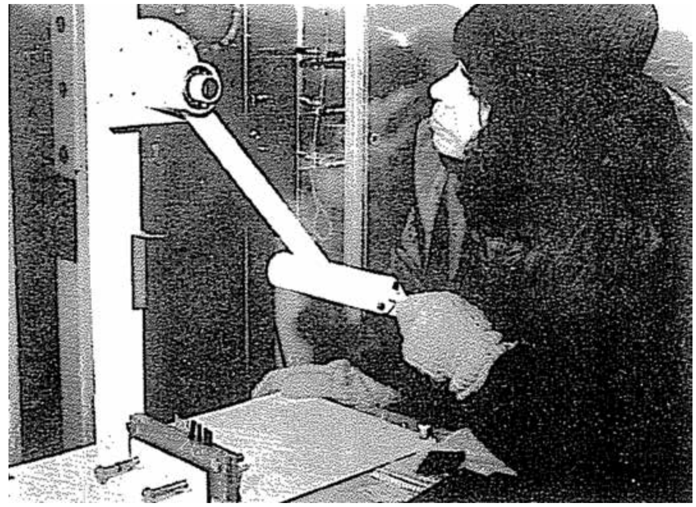

Fig. 19 – Pendulum apparatus which produced 7 to 8 fps impact on strips at -40° and -100° F

inally 1/16-inch thick, a quarter of an inch wide and an inch and a half long (0.2 cm thick, 0.7 cm wide, by 3.8 cm long); these were placed in the pendulum impact apparatus shown in Figure 19, which apparatus is also chilled. Samples are clamped at one end between metal plates and impacted essentially in shear by a weighted plate 0.125 in (0.318 cm) thick having a radiused edge traveling at 7 to 8 feet per second (213 to 244 cm per second).(14)

Both RePneu and SuperFlex tire-flatproofing materials repeatedly passed this ASTM D2137 test at -40° with no evidence of cracking.

Placing the apparatus in the test chamber with additional capacity, the ASTM D2137 pendulum impact test was repeated at lower temperatures with the following results: (15)

Both RePneu samples passed at -55°F (-48°C)

Both RePneu samples passed at -70°F (-57°C)

One SuperFlex sample passed; one failed at -55°F (-48°C)

Both SuperFlex samples failed at -70°F (-57°C)

Load-Deflection Data

Increase in tire stiffness at cold temperatures, as indicated by changes in load-deflection curve, was measured on four Goodyear Ariva P 185/70/14 tires which had been filled to 35 psi – two each with RePneu and two with SuperFlex – to 35 psi at ARNCO's South Gate facility before shipment to Anchorage. A pneumatic tire inflated with air to 35 psi was also tested.

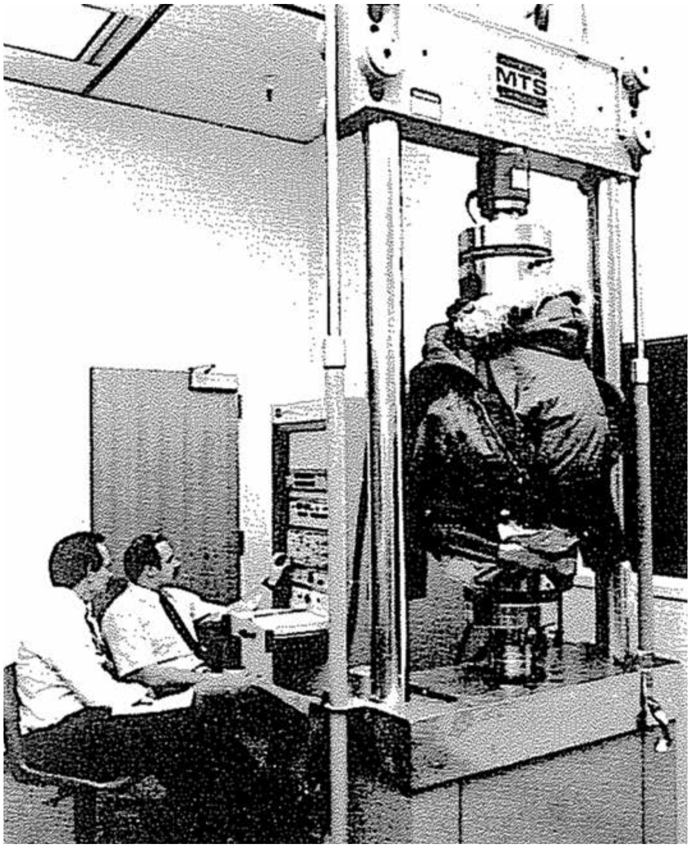

Fig. 20 – Thermally insulated tire in MTS equipment on which load deflection curves were run after chilling to -40°F

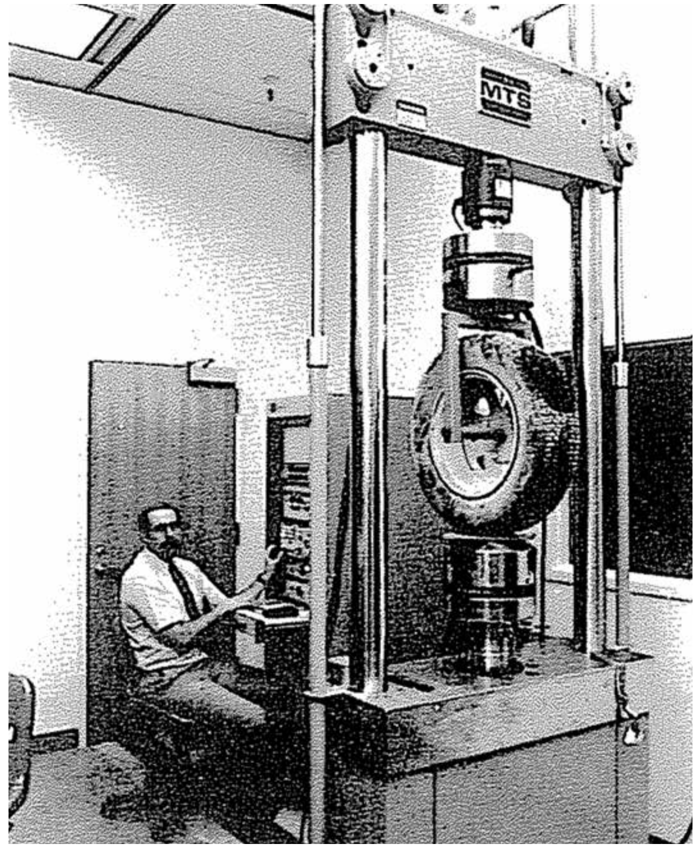

Fig. 21- Unwrapped tire on MTS test equipment; oval dark spot in frost on tread was produced by previous test, tire rotated 120°

At the University facilities, each tire was drilled and instrumented with a thermocouple in the center of the filled tire cross section. The tires were chilled in a Thermatron cold chamber for a minimum of 12 hours at a temperature of -40°F (-40°C), insulated by wrapping in two heavy parkas, and immediately tested in the MTS equipment shown in Figure 20 at a rate of two inches (5 cm) per minute while recording fill temperature. The tests were repeated at 120-degree intervals on the tire circumference. The tire and test fixtures are pictured in Figure 21 after insulating wraps were removed.

A typical set of curves for a RePneu filled tire at a variety of temperatures is shown in Figure 22. It will be noted that although the deflection of the tire decreases with chilling, its rate does not increase substantially, Table 9 summarizes the average spring rates obtained for the five tires tested as their temperature dropped from +68° (16°C) to -45° or -46°F (-43°C). The reduction in spring rate of the air filled tire is, of course, due to its pressure decrease upon chilling to the subzero temperature.

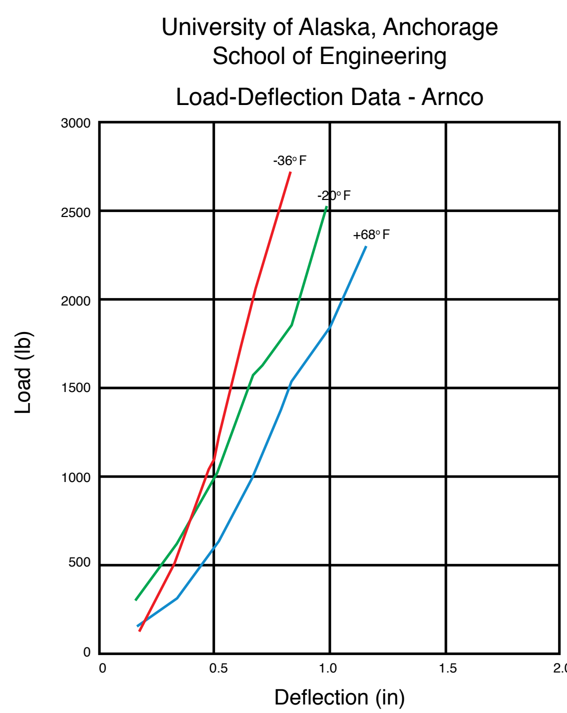

Fig. 22- Load-deflection curves of RePneu filled tire at several temperatures produced on above MTS equipment

Table 9 – Tire spring rate vs. temperature (11)

(+68°F vs -46°F)

Sample	Rate Warm lb/in	Rate Cold lb/in	Percent Change
RePneu #1	3125	3665	+17.3%
RePneu #2	3295	3994	+19.7%
SuperFlex #1	2489	2566	+3.1%
SuperFlex #2	2536	2797	+10.3%
Air	1079	993	-8.0%

Flat-Spot Recovery

Since the outside temperature in Anchorage at the time the subject tests were run varied from 18°F (-8°C) to 40°F (4°C), flat-spotting was accomplished under controlled conditions in the laboratory at the University's School of Engineering. Each of the Goodyear Ariva P185/70/14 tires (which had been filled to 35 psi) was flat-spotted at by imposing a 760 lb. (345kg) radial load, the curb weight on each front tire of the 1982 4-door Subaru on which vehicle tests were later run, using the yoke and automotive spring arrangement shown in Figure 23.

Flat-spotting began thus at 77°F (25°C), after which the assembly was placed in the cold room for 24 hours at -40°F/C. This procedure produced a substantial flat spot on the softer SuperFlex tires - - exaggerated by fill shrinkage due to its large coefficient of thermal expansion, as may be seen in the picture made in the cold room, Figure 24. During the cold soak, the calibrated spring was periodically retightened to maintain the requisite 760 lb. load. Actual flat-spot deflections are shown in Table 10. (11)

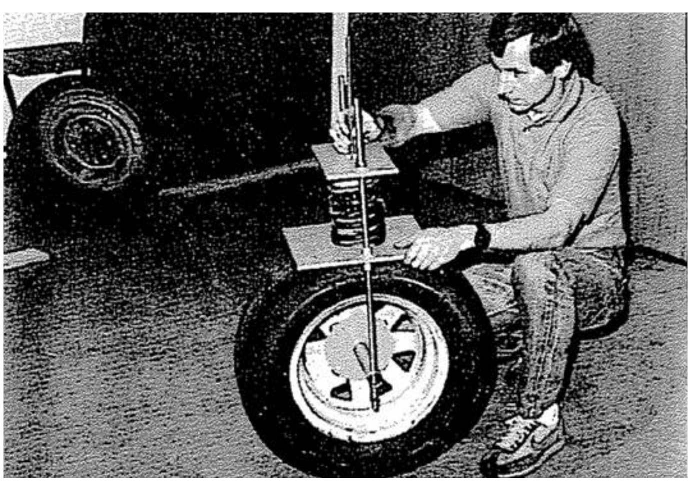

Fig. 23 – Yoke and automotive spring fixture is tightened to impose curb weight of vehicle on which it will be road tested

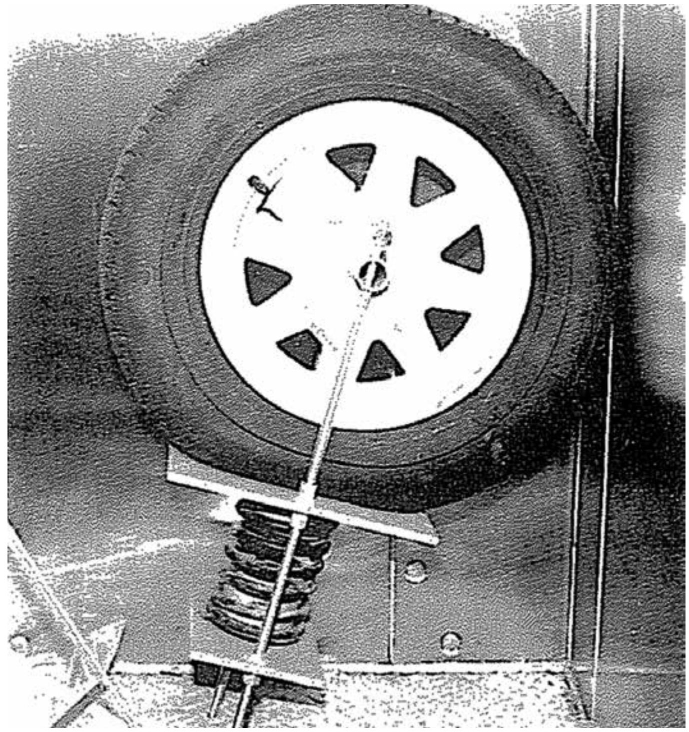

Fig. 24 – Filled tire developing flat spot under curb weight radial load in cold chamber

Table 10 – Tire Flat-Spot Deflections at -40°

Tire Fill	Time=0 Hrs	Time=24 Hrs
RePneu	0.3 in	0.6 in
SuperFlex	0.6 in	0.8 in
Air	0.7 in	0.9 in

Each of the flat-spotted tires was evaluated on the above Subaru passenger vehicle. The flat-spotting apparatus was disassembled in the cold room; the tires were conveyed to the car wrapped in insulating parkas and immediately mounted on the left front of the vehicle, as seen in Figure 25. Although the car was equipped with both vertical- and horizontal- mode accelerometers to supplement subjective evaluation of the resulting thump as (a) heard, and (b) felt in the steering wheel, accelerometer data proved inconclusive because of variations in the pavement along the driving course.

Each test began at the UAA Engineering building, traversed 1.5 miles (2.4 km) to a limited-access highway, where a 55 mph speed could be maintained while driving a total of 15.6 freeway miles (25 km), including turn-around. The vehicle was periodically slowed to 30 mph and 10 mph (48 kph and 16 kph) to observe the effect of the tire flat spot on ride. The total test circuit was approximately 19 miles (30 km).

Fig. 25 – Chilled tire with flat spot is mounted on left front of Subaru test vehicle

Driving time and mileage required to eliminate any perceptible evidence of flat-spotting in either steering wheel feel or car vibration is reported in Table 11 together with ambient temperature and the temperature measured in the center of the elastomeric fill upon return to the Engineering Building. (11)

Table 11 – Time/Mileage to Eliminate Flat Spots

Tire Fill Medium	Amb Temp °F	Time Min	Total Miles	Tire Temp °F Final
RePneu	40	9	4.5	60
RePneu	18	20	13.5	68
SuperFlex	40	14	8.3	82
SuperFlex	18	11	6.8	71
Air	18	1	0.3	-

Analysis

In all cases, it took less than 14 miles (22 km) and less than 20 minutes for flat-spotting to become undetectable, even though the tires had large visible flat spots when assembled on the car at approximately -40°. These results seem to be a demonstration of a common phenomenon observed with many elastomeric materials:

1. Hysteresis of an elastomer increases as temperature decreases.
2. Modulus increase is not sufficient to limit flexibility significantly.
3. Working the hysteretic elastomer converts mechanical energy to heat at a rate sufficient to rapidly warm the material into its normal performance range.

Even though the softer SuperFlex had a greater flat spot, its lower modulus (Durometer) permitted it to flex more than the RePneu – which, on the second (colder) day of flexing actually warmed it up faster than the RePneu-filled tire. This piece of data suggests that results might not be significantly different if the tests had been conducted at much lower ambient temperatures – as does the fact that thermal conductivity of these urethanes is so poor that it takes 12 to 24 hours for the tire interior to come to equilibrium with ambient temperatures; i.e., the authors doubt that exterior air temperature played a significant role in warming the tires – although future vehicle testing in mid-winter (after parking a vehicle overnight at -40°) is planned.

Conclusions

1. **Filling tires with incompressible (25 Durometer) RePneu elastomer to the pressure corresponding to the maximum rated load for the tire does not generate excessive pressure in the tire even at highway speeds.**
2. **To avoid excessive tire temperatures and pressures, tires filled with very soft (5 Durometer) elastomers, e.g. SuperFlex, should be limited to operating speeds of 35 mph (56kph). There appears to be some merit to pressurizing such tires to 75% of rated load during the filling process.**
3. **Both RePneu and SuperFlex remain flexible at temperatures as low as -55°F (-46°C). There is no danger of fracturing the tires due to shock impact when operating under the most severe winter conditions encountered in the United States.**
4. **The ride of tires filled with ARNCO elastomers is not significantly compromised when operating at extremely cold temperatures.**
5. **Flat spots may be expected to develop when parking a vehicle with filled tires overnight in extremely cold weather. But these flat-spots self-dissipate in a few miles of driving due to accelerated heat build-up as a result of increased hysteresis when the elastomer is cold.**
6. **Both RePneu and SuperFlex-filled puncture-proofed tires perform very satisfactorily at both hot and cold temperature extremes.**

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