RODENT BITING PRESSURE AND CHEWING ACTION AND THEIR EFFECTS ON WIRE AND CABLE SHEATH

by

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Abstract

The biting force of the Gray Squirrel (Sciurus carolinensis), Plains Pocket Gopher (Geomys bursarius) and Norway Rat (Rattus norvegicus) was measured and their biting pressures calculated from the contact area of their incisors. Representative biting pressure of the squirrel was 22,000 psi, the gopher 18,000 psi, and the rat 7,000 psi.

It was found that the rodent gnawing action consisted of very rapid bites up to six per second with an average of 1.5 bites per second. The biting activity among the three species of rodents differed such that in a seven day cage exposure test a specimen could have a total of 90,000, 45,000 and 18,000 bites inflicted by the gopher, squirrel and rat, respectively.

Two modes of wire and cable sheath failure resulting from rodent gnawing action are proposed. In the case of soft materials such as flexible vinyl plastic, polyethylene, aluminum, lead, and annealed copper, the failure is by cutting wear. In the case of relatively hard materials such as steel and copper alloy, ultimate failure is by deformation wear. A toughness index criteria, related to material hardness, breaking strength, and strain, is established as an aid in selecting rodent resistant sheath material.

Introduction

The service life of buried and aerial communication or power distribution wire and cable is often limited by gnawing rodents, particularly pocket gophers, squirrels and sometimes rats. During the past thirty years numerous studies were made of the rodent resistance of a great variety of plastic, ferrous, and non-ferrous wire and cable sheaths.[1,2,3,4] The studies were primarily aimed at determining the susceptibility of materials to rodent damage and the relationship of thickness, size and shape. These studies greatly assisted the selection of improved sheaths. However, none of the past studies focused on the influence of rodent biting pressure and gnawing frequency nor failure mode. A study of rodent biting pressure and chewing action was undertaken in the belief that it would contribute to the understanding of the sheath failure mechanism and lead to more reliable designs. Furthermore, we believed that such a study would lead to a more rapid means of screening candidate sheath materials.

A detailed description of the incisor cutting surface area and hardness, biting force instrumentation, and biting force and pressure of the plains pocket gopher, gray squirrel, and norway rat is presented. Evidence is offered and it is argued that the failure mode of thermoplastic jacket, aluminum, lead and annealed copper sheath is via cutting wear. It is primarily related to incisor/material hardness and frictional force. The failure mode of copper alloys, tin plated steel, and stainless steel is via deformation wear and is primarily related to sheath toughness and gnawing frequency. Mechanical properties of shield/armor necessary to the survival of rodent attack are relative hardness and toughness. A critical toughness index number is proposed.

Materials and Methods

Incisor Surface Area and Hardness

The cutting edge of the rodent incisor is not uniform as in the case of a knife or chisel edge, but irregularly serrated. The irregularity is apparent in the gopher incisors shown in Figure 1. The incisors of squirrels and rats are similar in size and irregularity. In order to obtain a realistic, but conservative estimate of this surface area, all points of the incisors were considered to be contacting a hard surface with the animal's head in the normal position. Various methods of measuring this area were tried, such as ink prints similar to fingerprints; however, none, with the exception of the one described below, were acceptable.

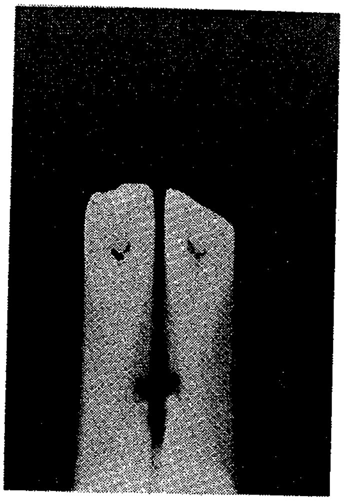


Fig. 1. Lower incisors of the plains pocket gopher (Geomys bursarius) showing irregularity of biting surface area.

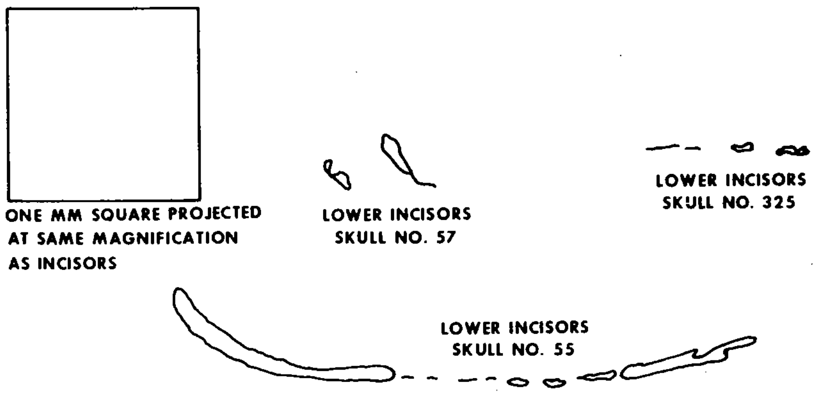
Biting surface area prints were made by pressing the upper and lower gopher incisors into a piece of .005" thick thermoplastic film taped to a standard microscope slide. A similar procedure was used with rats and squirrels. Slides were then projected at 45X and the outline of the impression traced (Figure 2).

Calculation of the surface area was determined using a planimeter and converting the readings to square inches. Incisor hardness was measured with a Shore D Durometer while the incisor lay on its side within a tight fitting cavity cut into a piece of hard wood.[5] The estimated biting surface areas and hardness for each species are listed in Table 1.

Except in a few instances, the biting surface area of the lower incisors of all three species was less than the upper incisors. The greater mobility of the lower jaw resulting from its flexible muscular attachment to the skull probably accounts for the difference in surface area.

Construction of Gnathodynameter

The Gnathodynameter ("biteometer") consists of a variable resistance force transducer, bite-bar, power supply and associated circuitry which converts the changing resistance to a changing voltage that drives a strip chart recorder. A schematic is shown in Figure 3. A description of the components is as follows:



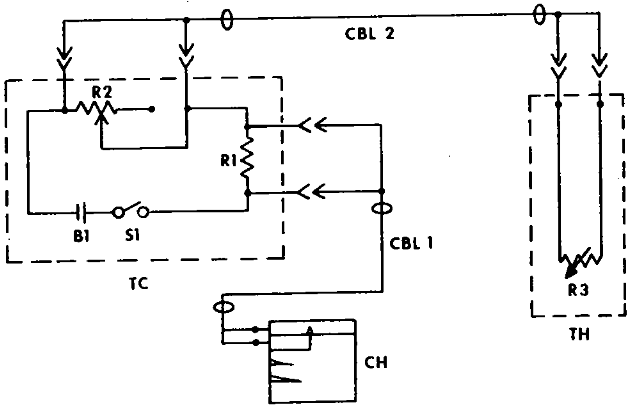
Projected Incisor Impressions-Plains Pocket Gopher

FIGURE 2

TABLE 1

Maximum Biting Surface Areas and Incisor Hardness of Three Species of Rodents

Species	n	Mean Maximum Incisor Surface Area (in^2) Upper	Lower	Shore D Hardness
Plains Pocket Gopher (Geomys Bursarius)	15	0.00015	0.00005	95
Norway Rat (Rattus Norvegicus)	18	0.00041	0.00013	95
Gray Squirrel (Sciurus Carolinensis)	16	0.00019	0.00013	95



Gnathodynameter and Associated Circuitry

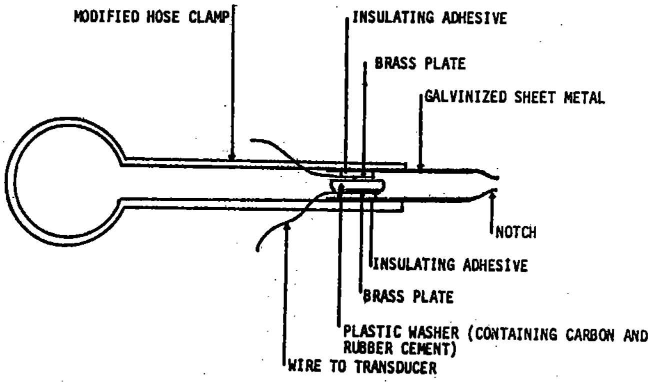
FIGURE 3

R_1 = 0.25 ohm resistor (1% Tol.)
R_2 = 0-500 ohm potentiometer
B_1 = 1.5 volt dry cell
R_3 = Variable resistance force transducer
CBL_1 and CBL_2 = Shielded twisted pair

CH = Strip Chart Recorder
TH = Transducer Holder (bite-bar)
TC = Transducer Controller housed in aluminum mini-box
S_1 = Single pole, single throw mini-switch

The heart of the "biteometer" is the variable resistance force transducer (R_3). The transducer's resistance decreases with increasing force and is a component of a simple voltage divider circuit. It is shunted by the variable resistance (R_2) which provides a means of zero-setting the transducer under no-load conditions. The transducer action results in 1 to 16 millivolts across (R_1) for the range of rodent biting forces.

A commercial transducer was tried first, but was abandoned when its variable resistance material prematurely age-hardened. New transducers were constructed by the authors employing a mixture of rubber cement with finely powdered activated charcoal.[7] The ratio of charcoal to rubber cement was varied until a transducer of the desired sensitivity was achieved. When a greater amount of charcoal was added to the cement, the sensitivity to pressure increased. The transducer was mounted within a bite-bar which provided the rodent a means of activating the transducer (Figure 4).



Bite-Bar
FIGURE 4

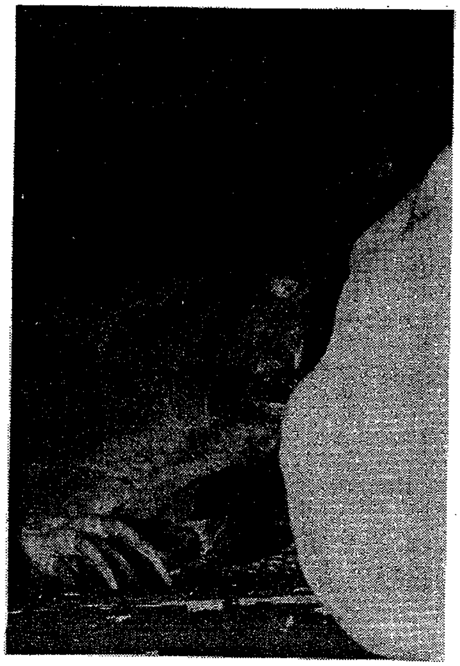
During the course of the experiment, several transducers were calibrated and used in obtaining the data presented. The unit was adjusted to 1 mV output with no pressure on the transducer. Then, 100 gram weights were added to the bite-bar via 1/8" diameter rod. This procedure was repeated ten times for each weight category and the means and range plotted for each category. Transducers were discarded if the ranges for any two weight categories overlapped. Transducers were calibrated on the day of their intended use since their response to pressure changed from day to day due to drying of the rubber cement. It was found that the transducer yielded an immediate response upon application of pressure; however, the response slowly increased if the pressure remained on the transducer. This property did not significantly affect the measured forces since all species exerted force on the bite-bar only momentarily with each bite.

The Gnathodynameter described here is a functional instrument with which biting forces can be determined with a reasonable degree of accuracy. However, it should be noted that several physical variables which influence biting force are inherent in the design of the instrument. First, the thickness of the bite-bar has a direct bearing on the amount of force that can be applied. Biting forces are dependent on the vertical separation of teeth, and when the mouth is open widely, total muscular force cannot be applied. (This is a decided advantage of larger size cables.) The thickness of the bite-bar was approximately 3/16 inch and the total mouth opening of the test animals was approximately one inch. This probably influenced the biting force, but not to a significant degree. In fact, studies have shown that the greatest degree of damage inflicted by rodents have been on wire structures with diameters between 0.20" and 0.50".

Second, the position of the incisors on the bite-bar possibly accounts for some of the variations between animals of the same species. During calibration, it was found that a point 1/16 inch from the tip and along the centerline of the bite-bar was the most responsive area. When biting the bar, some animals may not have bitten this area even though numerous attacks were elicited from each test animal.

Rodent Biting

During biting force measurements, gophers were placed in an open-front cage (Figure 5). One of the front feet of the gopher was grasped lightly with forceps which were in close



Gopher Biting the Bite-Bar
FIGURE 5

proximity to the bite-bar. The gopher striking at the source of irritation readily bit the bite-bar. This procedure was repeated with each of the eighteen gophers. Biting force varied during this time and the highest trace recorded for each gopher was considered its maximum capable force. A similar procedure was used to measure the biting force of eighteen Norway rats and sixteen gray squirrels. However, the rats were placed in a restrainer which covered the entire body except the head, and squirrels were hand-held using a mink handler's glove.

Summary of Maximum Biting Forces and Pressures[7]

TABLE 2

Gray Squirrel Maximum Biting Force

	Body Weight (lbs.)	Biting Force (lbs.)	Biting Pressure (lbs./in^2)*	Ratio Biting Force to Body Weight
$\bar{x}$ =	1.32	2.89	22,245	2.23
σ =	0.17	0.35	2,679	0.40
Max. =	1.61	3.30	25,385	2.94
Min. =	1.02	2.29	17,615	1.46
Range =	.59	1.01	7,770	1.48

*Based on mean maximum biting surface area of 0.00013 in.^{2} for lower incisors.

Plains Pocket Gopher Maximum Biting Force

$\bar{x}$ =	0.42	0.92	18,300	2.23
σ =	0.08	0.13	2,525	0.43
Max. =	0.60	1.20	24,000	2.93
Min. =	0.30	0.71	14,200	1.48
Range =	0.30	.49	9,800	1.45

*Based on mean maximum biting surface area of 0.00005 in.^{2} for lower incisors.

Norway Rat Maximum Biting Force

$\bar{x}$ =	0.66	0.95	7,115	1.54
σ =	0.20	0.26	1,955	0.55
Max. =	1.01	1.56	11,642	3.00
Min. =	0.40	0.67	5,000	0.76
Range =	0.61	0.89	6,642	2.24

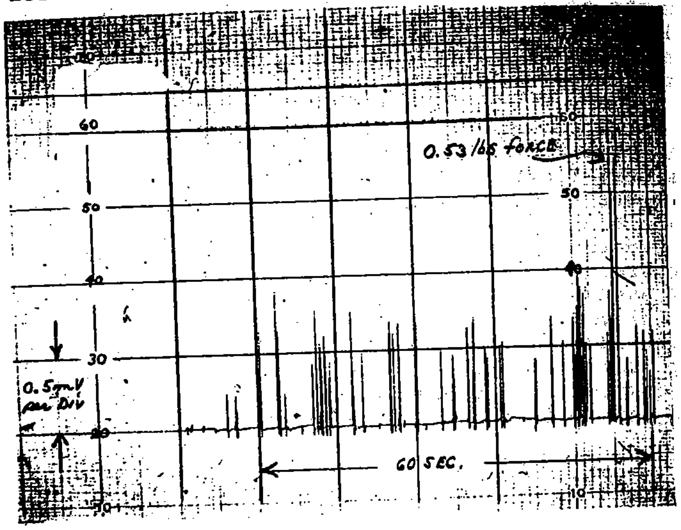
*Based on mean maximum biting surface area of 0.00013 in.^{2} for lower incisors.

The squirrel produced the greatest biting pressure (22,000 lbs./in.^{2}) followed by the gopher (18,000 lbs./in.^{2}) and the rat (7,000 lbs./in.^{2}). Also, the biting force of the squirrel (3 lbs.) was about three times greater than that of the gopher or rat. However, the surface area of the squirrel's lower incisors was almost twice as great as the gopher's and this appreciably decreased their biting pressure. The mean biting force to body weight ratio was identical for the squirrel and gopher and about 50 percent greater than that of the rat.

The pressure exerted by any of the three species on wire and cable sheaths (metal shield/armor and plastic jacket) under field conditions could be several times greater than that reported here. It would depend upon the angle of the animal's head as it relates to the amount of incisor surface area contacting the sheath. For example, the area of five contact points of lower incisors total .00005 in.^{2}; however, the gopher could exert 0.93 pounds force using only one of the points. Therefore, the biting pressures reported herein are considered to be conservative values.

Gnawing Action

During the course of this experiment, it was observed that the gnawing action of the rodents seldom approached the maximum forces reported here. Usually the gnawing action consisted of very rapid bites, up to six per second, the magnitude of which was one-half or less of the maximum force (Figure 6).



Gopher Biting Frequency and Force
FIGURE 6

It appeared highly probable that this gnawing action was more frequently used to penetrate sheaths than a series of strong singular bites. Therefore, the biting rate (bites per second) resulting in a wear action and the persistence of attack may be equally important as the maximum force exerted, especially in damaging materials that are as hard or harder than the incisors. Gnawing action and incisor hardness were examined against sheath penetration evidence to establish the principle mode of mechanical failure.

Discussion

As described in the preceeding paragraph, the gnawing action of the rodents consisted of very rapid bites at a maximum rate of six per second and an average rate of 1.5 per second. If each rodent did nothing but gnaw continuously at the average rate, then 900,000 bites could be inflicted on any wire or cable specimen during the "standard" seven day cage test. (During this test, ten specimens are exposed for seven consecutive days to each of ten individually caged rodents. The rodent has access to the horizontally mounted specimen through a 2 inch x 2 inch opening in the front of the cage. Wire or cable designs are judged rodent resistant if at least 80 percent of the test specimens are not penetrated through the armor/shield.)

Our laboratory observations and measurements indicate that the gopher is actively gnawing approximately 10 percent of the time (90,000 bites), the squirrel 5 percent of the time (45,000 bites) and the rat 2 percent of the time (18,000 bites). Based on the above duty cycles and past experience, the seven day criterion is a reasonable one for gopher tests. However, it should be extended to 14 days for squirrel tests and 35 days for rat tests for comparable biting activity.

An examination of rodent sheath damage was made in order to associate the damage or failure mode with biting pressure, biting frequency and incisor hardness. Those sheath materials that were completely penetrated and rendered discontinuous yielded small chips of sheath, plastic and metal, which were dislodged by the rodent. These materials were rated as failures by cutting wear. The ratio of incisor/material hardness and frictional force are associated with this type wear.

Those sheath materials that either resisted penetration or exhibited penetration without the evidence of residue chips were rated damaged or failures by deformation wear. Gnawing frequency and material toughness, the latter characterized as the product of ultimate tensile strength of the material by the strain at fracture, are associated with this type wear.

In the following paragraphs, whenever rodent damage is mentioned, it refers to either gopher or squirrel damage to small size (0.2 inch to 0.4 inch diameter) buried wire structures. The degree of damage caused by gophers and squirrels is similar. Since rats are not a major cause of damage to communication wire and cable, no specimens were exposed to them. We would expect similar types of damage from the rat. The rat biting data may be of use to those concerned with protecting foodstuffs.

Proposed Sheath Failure Modes

Failure by Cutting Wear

During cutting wear, a hard particle or rough edge cuts a chip from the wearing surface. The rough edge in our case is the rodent's incisors. If a chip is cut, then very high rates of wear will result. For this type wear to occur, the cutting agent must have a hardness greater than 1.2 times the material being cut and must have a cutting angle with the wearing surface which is greater than θ_C.[8] The angle θ_C is defined as follows:[9,10]

$$\tan\left(\theta_C-90^\circ\right) \approx \frac{1-\mu^2}{2\mu}$$

where θ_C = critical angle for cutting
μ = friction coefficient.

A tabulation of these conditions for aluminum, annealed copper, lead, polyethylene and poly (vinyl chloride) sheath materials is contained in Table 3.

TABLE 3

Incisor/Substrate Interface	μ_k	θ_c	Shore D Hardness (Substrate)	Ratio Incisor/Substrate Hardness
Gopher/ flexible PVC	0.77	104.8°	32	2.97
Gopher/ L.D. polyethylene	0.64	114.8	45	2.11
Gopher/lead	0.68	111.6	70	1.35
Gopher/annealed copper	0.34	142.4	79	1.20
Gopher/aluminum(soft)	0.48	128.7	80	1.19

The hardness ratios of annealed copper and aluminum are borderline with respect to the critical value of 1.2, but experimental error can account for the required margin. Figure 7 shows the gopher incisors are capable of assuming the position of a cutting tool with the required range of critical angles.

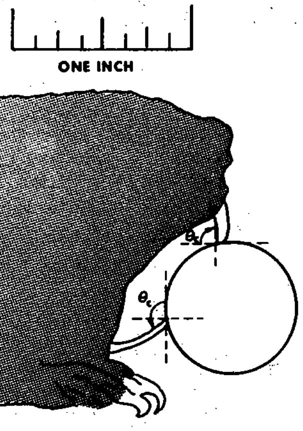


FIGURE 7

Kinetic coefficient of friction (μ_k) between the incisors and substrates was measured in accordance with ASTM D 1894-63 Standard Method of Test for Coefficient of Friction of Plastic Film except for the following change. Three rodent incisors were mounted in tripod fashion on a separate rubber pad and placed beneath the sled. The weight of the rectangular sled was 200.5 grams and the weight of gopher incisors plus rubber pad was 12.7 grams.

The Shore D Durometer Hardness Tester per ASTM Standard D 2240 was selected because its 30° spherocone indentor with 0.004 inch radius simulated the sharp rodent incisors better than other type hardness testers.

It has been well known that the relatively soft metals and plastics listed in Table 3 are susceptible to rodent penetration, but a failure mode was not previously assigned. A cutting wear mode is now proposed.

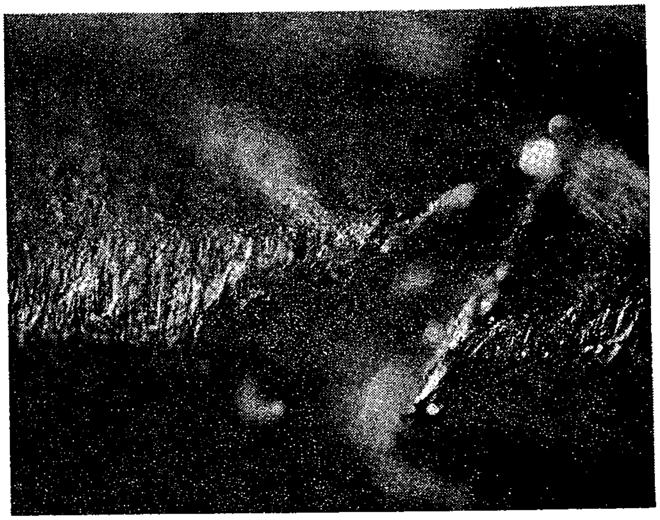
Failure by Deformation Wear

The relatively hard metal sheaths, such as tin plated steel, austenitic and ferritic steels, and certain copper alloys, have Shore D hardness values ranging from 90 to 95 and incisor/metal hardness ratios ranging from 1.00 to 1.05. These ratios are well below the 1.2 level required for cutting wear.

Examination of these metal surfaces after seven day gopher exposure tests revealed the presence of wear tracks. Examples of wear tracks of varying degrees on several of the above metals are shown in Figures 8-11.

CDA 220 Bronze Armor (.005" thick, 1/4 hard) On 1-Pair 19 AWG Rural Distribution Wire

FIGURE 8



CDA 220 Bronze Armor (.005" thick, 1/4 hard) On 1-Pair 19 AWG Rural Distribution Wire

FIGURE 9

Type 304 Stainless Steel Armor (.003" thick, annealed) On 1-Pair AWG Rural Distribution Wire

FIGURE 10

Type 430 Stainless Steel Armor (.0025" thick, annealed) on 1-Pair 19 AWG Rural Distribution Wire

FIGURE 11

This physical evidence suggests damage by deformation wear. "Deformation wear consists of the continual plastic working of a surface until cracks form, grow, coalesce, and a wear particle is produced."[8] Under conditions where stresses are high, wear tracks are produced and particles are dislodged from the edge of the wear track. Although no direct correlation has been established for metals, specialists in the field of wear agree that high toughness is necessary to resist deformation wear. It will be shown that such is the case for rodent gnawing action on certain metals.

A metal sheath material that has consistently resisted gopher and squirrel penetration in the laboratory and in service (in the absence of corrosion damage) is .006" thick Terneplate (tin plated steel). Its hardness, tensile strength, elongation, and toughness index number are compared to other armor/shield materials in Table 4.

TABLE 4

Shield Material	Shore D Hardness	Tensile Strength (P.S.I.)	ε (in/in)	Toughness Index (T)
CDA 220 Bronze - 1/2 hard	---	52,000	0.11	5,720
- 1/4 hard	94	45,000	0.25	11,250
CDA 195 Precipitation Temper Copper Alloy	---	80,000	0.15	12,000
Terneplate	94-95	54,000	0.26	14,040
CDA 220 Bronze - "1/4 hard"	93-94	48,600	0.34	16,525
Stainless Steel Type 430	95	80,000	0.26	20,800
Stainless Steel Type 304	95	112,000	0.29	32,480

One of several methods of evaluating toughness is to calculate the toughness index number (T).[11] It is obtained by multiplying ultimate tensile strength of the material by the strain at fracture (T = U.T.S. x ε). Toughness is expressed as the amount of energy absorbed per unit volume of material, normally in pound-force-inches per cubic inch.

It can be seen from Table 4 that, in general, the various steel materials have superior toughness as compared to the copper alloys. However, one lot of copper alloy yielded a toughness index somewhat greater than that of tin plated steel. The data was taken on shield materials after processing into completed wire to allow for work hardening effects, particularly in the case of Type 304 Stainless Steel.

If the toughness index is a reliable indicator of the resistance to deformation wear caused by rodents, then there must be a correlation between increasing toughness and improving performance in the cage tests. A comparison of relative performance is shown in Table 5. In order to emphasize the effects of shield thickness and minimize the effects of width, the toughness index was modified as follows:

$$T_1 = T(w \times t)$$
$$T_1 = U.T.S. \times \varepsilon\ (w \times t)$$
$$T_1 = B.S. \times \varepsilon$$

where

w = 0.200", an arbitrarily small width equal to that of two gopher incisors.
t = metal sheath thickness, inches.
U.T.S. = Ultimate tensile strength (psi)
B.S. = Breaking strength, (lbs.)
ε = strain, (in./in.)
T_1 = Modified toughness index

Shield width per se, short of enclosing the underlying core, does not contribute to rodent resistance, but is a necessary component of toughness - hence, the selection of a constant arbitrarily small width.

TABLE 5

One or Two Pair Buried Distribution or Service Wire With Helically Applied Shield

Shield Material	Thickness (inch)	Breaking Strength (lbs)	ε (in/in)	T_1	Cage Test Percent Surviving[12]
CDA 220 Bronze					
1/2 hard	.005	52	.11	5.7	10
1/4 hard	.005	45	.25	11.2	37
CDA 195 Precipitation Temper Copper Alloy	.005	80	.15	12.0	20
Stainless Steel Type 430 Annealed	.003	48	.26	12.5	30
CDA 220 Bronze "1/4 hard"	.005	48.6	.34	16.5	80
Stainless Steel Type 430 Annealed	.004	64	.26	16.6	90
Terneplate, Annealed	.006	64.8	.26	16.8	100
Stainless Steel Type 304 Annealed	.003	67.2	.29	19.5	100
Stainless Steel Type 304 Annealed	.005	112	.29	32.5	100

The relationship between T_1 and percent surviving specimens is more easily determined from Figure 12. A correlation of improving performance with increasing toughness is apparent. The cut-off point of minimum acceptable performance is quite sharp at T_1 = 16.5.

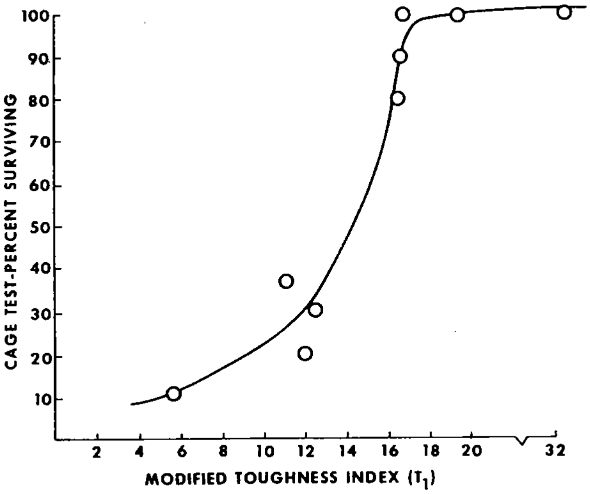


FIGURE 12

Conclusions and Recommendations

Two modes of sheath failure resulting from rodent gnawing action have been proposed. First, relatively soft materials such as flexible vinyl plastic, polyethylene, aluminum, lead and annealed copper fail by cutting wear. Small chips of these materials are dislodged by the rodent's incisors. The key factors are an incisor/substrate hardness ratio greater than 1.2 and an incisor cutting angle with the wearing surface which is greater than θ_C. The angle θ_C is a function of the coefficient of friction between the interacting surfaces. Presently, there is no practical economical way to impart rodent resistance to these soft materials short of physical isolation.

Second, the relatively hard materials such as stainless steel, tin plated steel, and certain copper alloys ultimately fail by deformation wear. It involves the continual plastic working of a surface until cracks form, grow, and a wear particle is produced. The key factor is material toughness which is expressed as the product of ultimate tensile strength and strain at fracture. A modified toughness index, the product of breaking strength and strain at fracture, is used to further evaluate material thickness effects.

The following guidelines are recommended for selecting rodent resistant armor/shield material for wire or cable. Select a material which will yield a Shore D Hardness of ≈94 and a toughness index equal to or greater than

14,000, preferably after processing into completed product. Adjust the thickness (keeping width constant at 0.200 inch) such that the modified toughness index will be equal to or greater than 16.5.

While these guidelines will provide acceptable rodent resistance with reference to the seven day cage tests, a higher index and the greater margin of safety may be desirable for special situations. Depending upon the metal selected, adjustments to thickness may be required to compensate for corrosion wear and the need for low d.c. resistance to minimize the effects of inductive interference and lightning surge currents.

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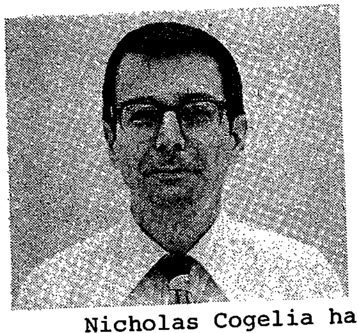

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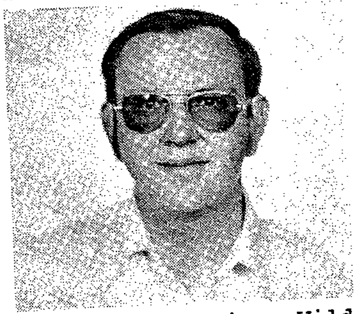

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Jim Glahn is a Wildlife Biologist with the U. S. Fish and Wildlife Service, Denver Wildlife Research Center. Jim was born in Blue Island, Illinois October 29, 1945. Undergraduate studies were completed at Cornell University and graduate studies at Colorado State University. He served with the U.S. Army in Munich, Germany for two years as a medical laboratory specialist. He began his professional career with the Service in September 1972. He is currently the Project Leader at the Fresno Field Station dealing with rodent problems in agriculture. Jim is married and has two children.