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ABRASION TESTING

OF POLYURETHANE ELASTOMERS

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Abstract: A review of the underlying principles of the frictional and abradability characteristics of elastomers is presented along with a review of the commonly employed ASTM methods for measuring abrasion resistance and coeffiecient of friction (COF). Pico, Taber, NBS, and DIN test results are compared for a broad range of polyurethane elastomers and "conventional" rubber materials. Tensile properties, hardness, tear strength, coefficient of friction, and resilience are also measure to aid in understanding the relativity abrasion results.

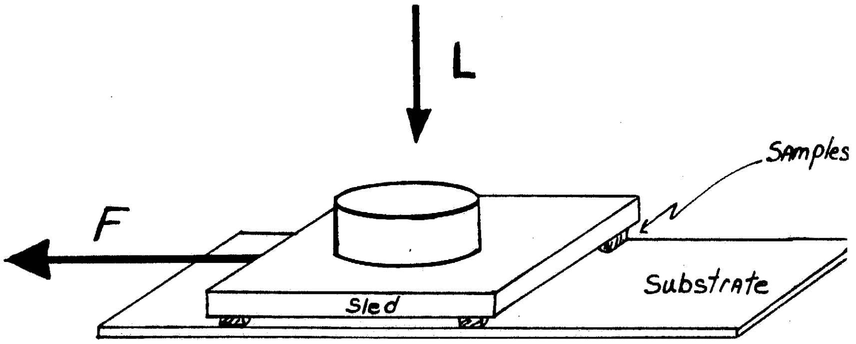
I. Introduction:

The "DIN" method (ASTM D-5963) of measuring the abrasion resistance of elastomers has gained in popularity over the past few years. One of the objectives of this work is to describe this method in the context of the three other test methods commonly utilized. DIN test results on a series of cast polyurethane elastomers and "conventional" rubber materials are put into perspective with Taber, Pico, and NBS abrasion tests..

While standard tests have proven fairly reliable for ranking different materials, many researchers have seen anomalies between the results of one type of abrasion test and another; and between laboratory test results and actual in use performance. Therefore, another objective of this work is to explain the strengths and weaknesses of each test, and then finally to present some of the theory behind the wear and frictional properties of elastomers. It is hoped that recognition of some of the underlying fundamentals will further aid in the understanding of the limitations of the test methods in predicting actual wear life.

II. Frictonal Properties: Coefficient of Friction-ASTM D-1894

While several specialized tests have been devised to overcome limitations, ASTM D-1894 remains the most common test for measuring the coefficient of friction of rubber and plastic materials. The diagram below provides a good description of the test.



ASTM D-1894 Coefficient of Friction Test

III. Frictional Properties: Fundamental Theories

In classical materials there are three laws of friction:

- Friction is proportional to load
- Friction is independent of area of contact
- Friction is independent of sliding speed

Unlike the case in classical materials such as metallics, the measurement of the properties of elastomers is rarely straight-forward due to non-linear elasticity, due to loading time and loading rate dependency, and due to temperature dependency. The measurement of the coefficient of friction of elastomers is no exception.

Coefficient of friction is defined as:

$\mu = F/L$ where F is the force to cause (static) or sustain (kinetic) motion
where L is the total load normal to the friction surface

In commonly accepted theories of friction, frictional forces arise from two interactions between the surfaces; adhesive forces and ploughing (plowing) forces. Adhesive forces arise from "welding" at the points of contact between surface asperities (protrusions) and the ploughing forces arise from interpenetration (intermeshing) of surface asperities. The total frictional force for metallics is then the sum of these forces:

$$F = F_a + F_p$$

where $F_a = (S/P_m) \times L$ where:
S = shear strengths of the adhesion
P_m = plastic yield stress
L = normal load

$$F_p = \text{negligible}$$

so that $F \cong (S/P_m) \times L$

so, it follows that in metallics μ is proportional to shear strength/yield strength. COF values for metallics are typically between 0.6 and 1.2.

In elastomers, F_p is replaced by F_H (hysteresis force) so that the total frictional forces are defined by:

$F = F_a + F_H$ **where**

$F_a = K_2 (E''/p^r) \tan \delta$ where
K_2 = constant
E'' = loss modulus
p^r = nominal pressure to exponent r
$\tan \delta$ = loss coefficient (E''/E')

III. Frictional Properties: Fundamental Theories (cont)

$\mathbf{F_H = K_3\ (p/E')\ tan\ \delta}$ where

F_H = hysteretic force
K_3 = constant
E' = storage modulus
p = nominal pressure
$\tan\delta$ = loss tangent (E''/E')

From $\tan\delta = E''/E'$ we can see the very strong dependence of F_a on time and rate and F_H upon strain and modulus. Both terms are dependent upon temperature. All considered, it is not surprising that measured coefficient of friction of elastomers do not adhere the previously stated "laws of friction". Quite the contrary; elastomer friction is:

- dependent on speed of sliding
- dependent on temperature (ambient and generated heat)
- dependent on load.

In the laboratory, one must be very conscious of these factors in measuring coefficient of friction. One must be equally concious of the persistent effects of mold release and internal lubricants on test results. Among the measures to be employed to mitigate these sources of variance are:

- Reducing surface area of elastomers to (4) ½" diameter buttons to increase unit load.
- Molding against mylar or teflon and removing only when ready to test
- Washing elastomer substrate
- Surface grinding elastomer substrate
- (5) runs per specimen
- Washing substrate (test bed) between runs
- Detailed explanation of observed variances in reporting
- Inclusion of force/displacement print-outs with report.

In viewing test results one often observes:

- Static forces equal to or less than the kinetic kinetic force
- Kinetic forces increasing with displacement
- Variable static and kinetic forces among replicate runs.
- Coefficient of friction of elastomers ranges from 0.25 to 2.5 depending upon the type of elastomer, additives present, and stationary substrate..

IV. Abrasion Resistance of Elastomers: Fundamental Theories

Abrasion has been defined several ways:

- From the latin abradere - to gouge,
- The rupture or displacement of small particles of elastomer under the action of frictional forces when sliding occurs between two substrates, or
- The wear of a substrate caused by hard particles or protuberances.

In its most fundamental treatment, abrasion is modelled as the action of an inverted cone. Here the rate of abrasion *dV/dl* (volume loss/unit of length travelled) is written as:

$$dV/dl = K^*(L^* \tan\theta)/(\pi^* p_m)$$

Where,
K = factor
L = Normal Load
θ = Slope of the Cone
p_m = Indentation Hardness

For experiments involving Emery abrasive and rigid materials this relationship is in agreement with observations that abrasion rate increases proportionately with increased load and decreases with increasing hardness. Experiments with wire gauze which has well rounded protuberances shows abrasion increasing with load to the nth power. Here the interaction is not simple cutting but some manner of elastic mode which quite reasonably is proposed to involve fatigue. This mechanism leads to the concept of an abrasion mode where mechanical work applied through friction will remove material if the energy input is equal to the energy under the stress strain curve. This leads to the relationship that:

$$W_l \propto \mu/(H^* s^* \varepsilon)$$

Where;
W_l = Wear Rate
μ = Coefficient of Friction
H = Hardness
$s^*\varepsilon$ = Energy under s/s curve (Stress x Strain)

The net abrasion resistance of a material must be the combination of the ability to get energy or work into a material and the response of that material to that energy or work input. In order to separate these components, Gent separates the two components by defining the abradability of an elastomer in the relationship below. This provides a possible means with which to relate basic material properties like strength or flex cut growth rate to a fundamental propensity to abrade (abradability).

IV. Abrasion Resistance of Elastomers: Fundamental Theories (cont)

Abradability = A/μ where μ = Coefficient of friction
A = V/(d x L)
where V = volume abraded
d = sliding distance
L = normal load

But since; **μ = L/F where L = normal load**
F = frictional force

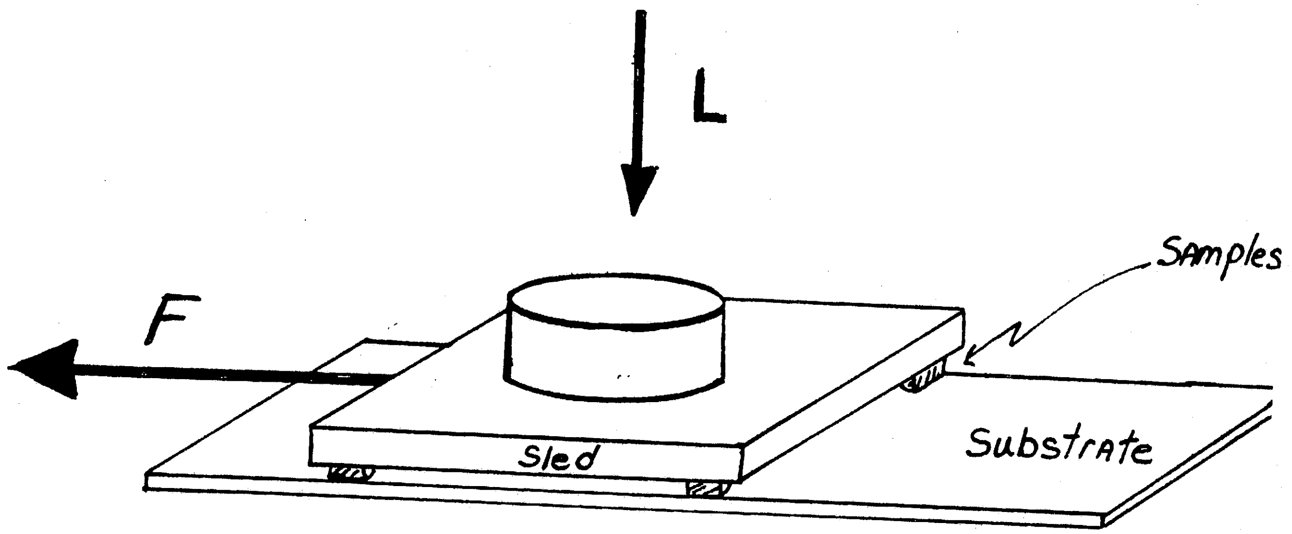
So; **Abradability = V/(d x F)** or volume of material abraded per unit of energy expended.

It has been shown that abradability decreases with increased speed through a minimum then again increases. This same rate relationship has been observed with respect to breaking energy. The minimum observed is associated with the transition to the glassy state. It has also been observed that abradability may be dependent on load, temperature, surface speed, size of abrasive asperities (particles/protuberances), and atmosphere (N2 vs. air).

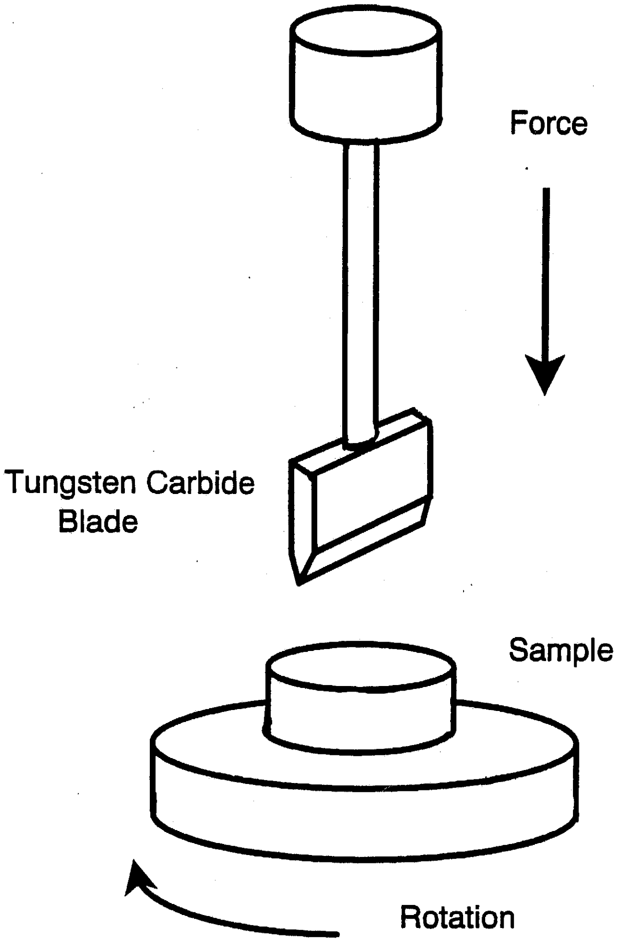
The conclusion is reached that the best accounting for the variety of experimental observations made with regard to the abrasion rates of a range of elastomers under a variety of conditions will result from resolving the abrasion process into (3) components:

1. Cutting **$dV/dl = K^*(L^* \tan\theta)/(\pi^* p_m)$**
2. Fatigue/Flex Cut Growth **$W_l \propto \mu/(H^* s^* \varepsilon)$**
3. Thermo Oxidation **$W = K^* \exp(-(E-k/RT)$**

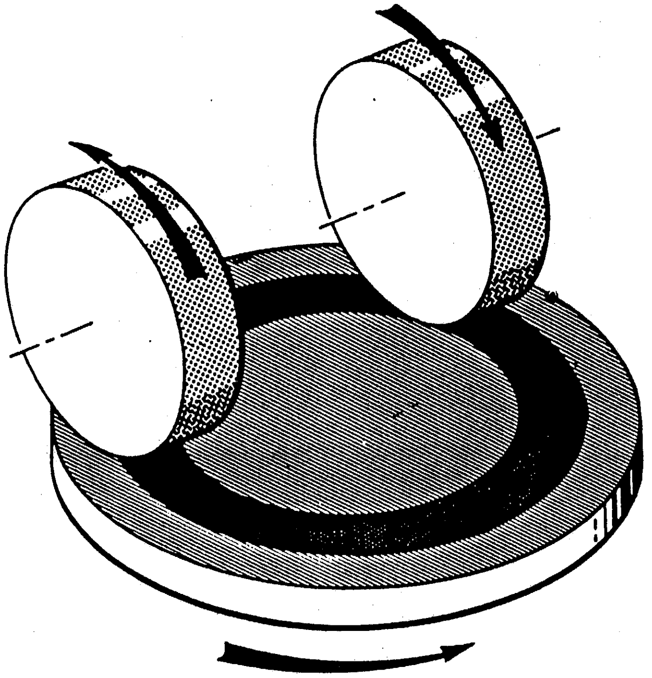
COF (Mod. for Elastomers)
ASTM D-1894



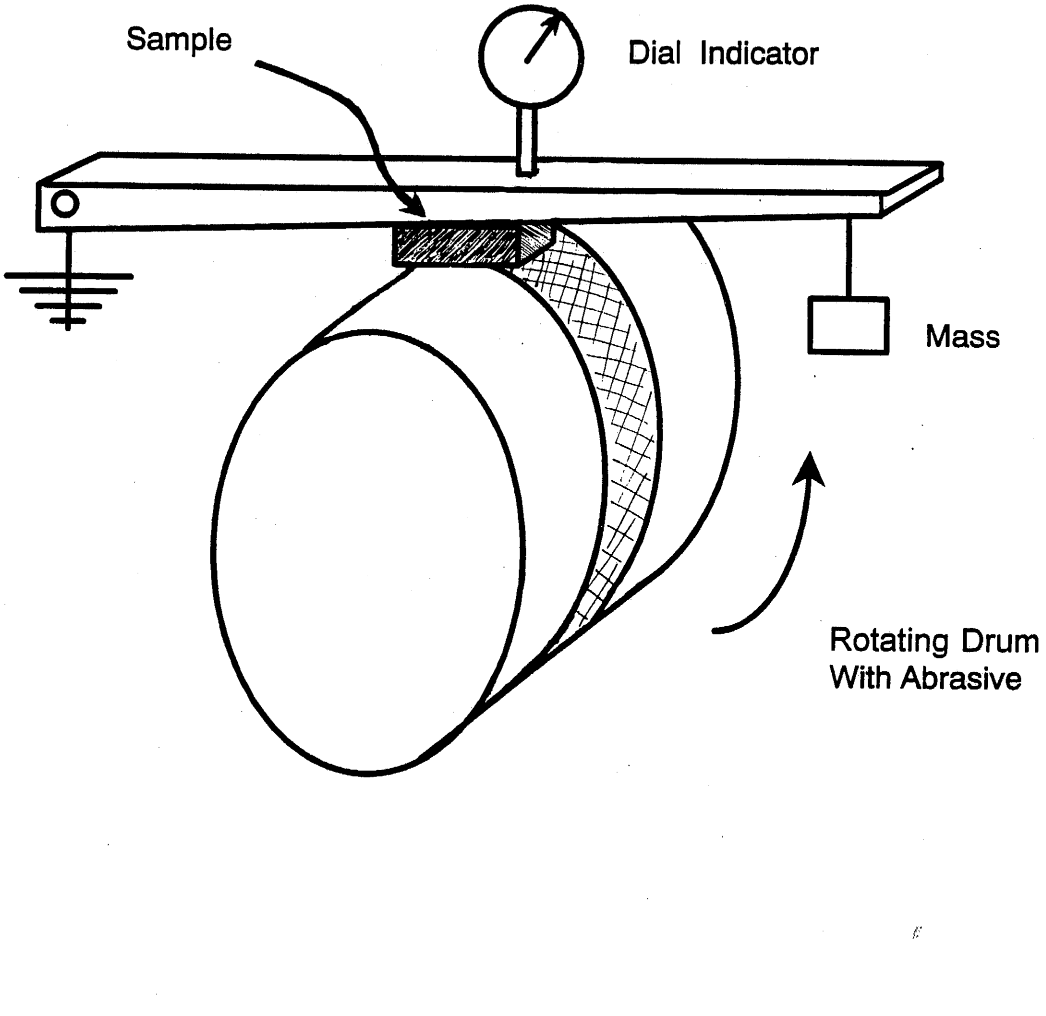
PICO ABRASION TEST
ASTM D-2228



TABER ABRASION TEST
ASTM D-3389



NBS ABRASION
ASTM D-1630



DIN ABRASION TEST
ASTM D-5963

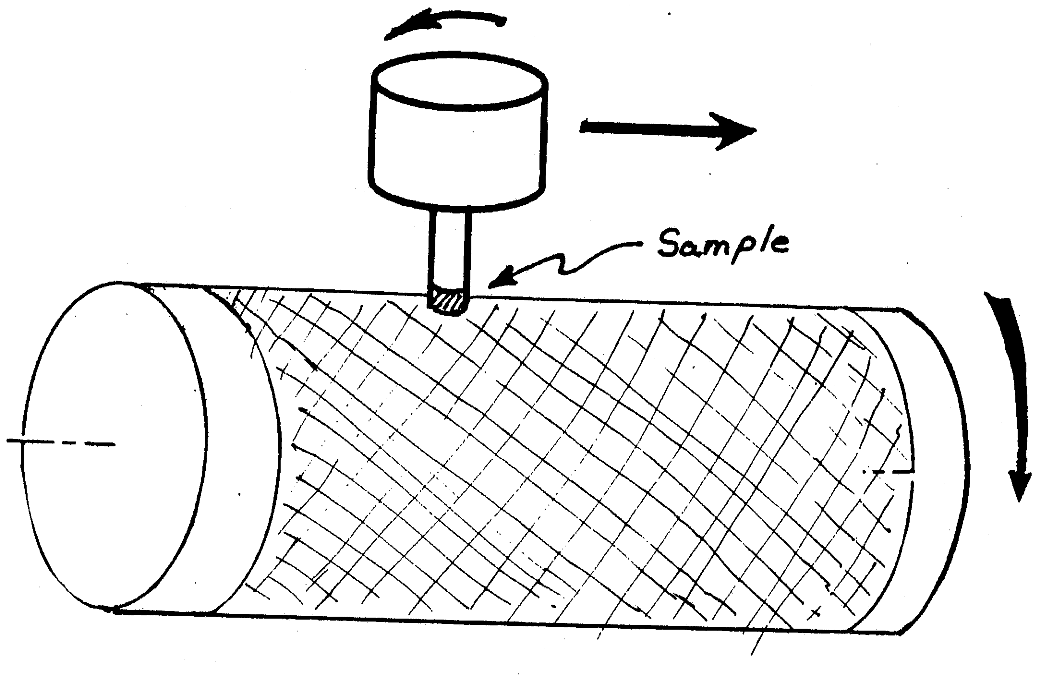


Table 1: Data Summary

Sample ID	Description			Shore A	Shore D	Tensile St. (psi)	%UE	Die C Tear (pli)	Die T Tear (pli)	Density (gm/cc)	Bashore (% Rebound)
	Polyol	Iso	Stoch.								
PU- A	Ester	MDI		92	39	9536	490	454	260	1.24	35
PU- B	Ester	LF TDI	90	81	31	9441	520	377	150	1.26	32
PU- C	Ester	LF TDI	95	83	32	9653	560	417	200	1.25	34
PU- D	Ester	LF TDI	100	84	34	8512	600	430	275	1.25	35
PU- E	Ester	LF TDI	105	84	33	7733	640	413	255	1.25	36
PU- F	Ester	MDI	90	83	32	9492	590	379	190	1.25	31
PU- G	Ester	MDI	95	84	32	9139	625	376	210	1.25	31
PU- H	Ester	MDI	100	84	33	7769	610	380	258	1.25	32
PU- I	Ester	MDI	105	84	31	6418	700	353	240	1.25	32
PU- J	PCL	MDI	95	81	33	4190	590	385	335	1.21	49
PU- K	Ether	PPDI	95	97	49	8299	620	529	435	1.10	61
PU- L	Ester	PPDI	95	95	48	8621	635	679	570	1.19	66
PU- M	Ester	TDI	85	80	30	NT	NT	NT	NT	1.24	34
PU- N	Ester	TDI	90	81	31	NT	NT	NT	NT	1.23	35
PU- O	Ester	TDI	95	82	32	NT	NT	NT	NT	1.24	36
PU- P	Ester	TDI	100	83	34	NT	NT	NT	NT	1.23	37
PU- Q	Ester	TDI	105	83	33	NT	NT	NT	NT	1.23	37
NR- A	N/A	N/A	N/A	47	10	3624	625	305	46	1.06	51
NR- B	N/A	N/A	N/A	61	18	3782	545	331	128	1.11	39
NR- C	N/A	N/A	N/A	40	9	3844	705	132	35	0.99	63
CR- A	N/A	N/A	N/A	63	20	2066	150	92	11.5	1.44	41
NBR- A	N/A	N/A	N/A	70	20	2471	435	172	57	1.25	27
NBR- B	N/A	N/A	N/A	59	18	3259	515	156	30	1.15	25
NBR- C	N/A	N/A	N/A	66	22	3207	440	185	46	1.20	21
LINATEX	N/A	N/A	N/A	39	7	>3328	>775	175	47	0.96	72
LINATRILE	N/A	N/A	N/A	56	15	869	475	130	42	1.09	22
ARMABOND	N/A	N/A	N/A	38	7	>2132	>705	179	48	0.96	65

Table 2: Data Summary

Sample ID	Description			Shore A	COF static	COF kinetic	Pico Index	NBS Index	Taber (mg/1000Rev	DIN (mg)
	Polyol	Iso	Stoch.							
PU- A	Ester	MDI		92	0.70	0.59	114	126	47.4	77
PU- B	Ester	LF TDI	90	81	1.23	1.24	75	117	64	100
PU- C	Ester	LF TDI	95	83	1.45	1.59	83	171	28.7	92
PU- D	Ester	LF TDI	100	84	0.87	0.94	111	213	34.1	82
PU- E	Ester	LF TDI	105	84	1.16	1.12	103	260	31.9	86
PU- F	Ester	MDI	90	83	1.08	1.04	94	162	65.3	104
PU- G	Ester	MDI	95	84	1.33	1.36	97	194	74.6	95
PU- H	Ester	MDI	100	84	1.44	1.19	101	184	56.5	90
PU- I	Ester	MDI	105	84	1.36	1.22	91	166	49.5	101
PU- J	PCL	MDI	95	81	0.39	0.41	145	176	31.4	95
PU- K	Ether	PPDI	95	97	0.25	0.26	378	804	95.6	52
PU- L	Ester	PPDI	95	95	0.26	0.24	530	574	81.3	33
PU- M	Ester	TDI	85	80	1.48	1.39	77	99	55.5	134
PU- N	Ester	TDI	90	81	1.64	1.70	69	118	47.6	116
PU- O	Ester	TDI	95	82	1.43	1.33	83	169	41.7	105
PU- P	Ester	TDI	100	83	1.32	1.38	96	165	NT	101
PU- Q	Ester	TDI	105	83	1.27	1.28	94	194	45.8	102
NR- A	N/A	N/A	N/A	47	3.70	2.02	77	88	NT	CHAT
NR- B	N/A	N/A	N/A	61	3.98	2.42	98	123	NT	191
NR- C	N/A	N/A	N/A	40	1.23	1.31	44	85	NT	CHAT
CR- A	N/A	N/A	N/A	63	2.24	2.06	83	96	165.8	255
NBR- A	N/A	N/A	N/A	70	1.52	1.50	55	64	1375.3	206
NBR- B	N/A	N/A	N/A	59	2.93	2.60	67	155	184.9	212
NBR- C	N/A	N/A	N/A	66	2.90	1.50	80	145	178.4	366
LINATEX	N/A	N/A	N/A	39	1.04	1.31	43	72	NT	CHAT
LINATRILE	N/A	N/A	N/A	56	0.50	0.62	68	152	142.6	214
ARMABOND	N/A	N/A	N/A	38	0.73	0.83	39	79	NT	CHAT

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