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ELASTOMERS FOR USE IN RADIATION FIELDS

IV. Effect of Gamma Radiation on Heat Resistant Elastomers

An article to be submitted for publication to a technical magazine

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ELASTOMERS FOR USE IN RADIATION FIELDS

IV. Effect of Gamma Radiation on Heat Resistant Elastomers

This is the second in a series of articles concerning the effects of ionizing radiation on elastomers and some rubber-like plastics materials. This article presents data on the gamma radiation effects on heat resistant elastomers. These materials were arbitrarily selected as being representative of elastomers which can operate in air or fluids at temperatures of 125 C and above for prolonged periods without being adversely affected.

The first article in this series provided general background information on the subject of radiation damage to organic polymers, outlined the method of measuring physical property changes, presented two sections concerning some basic considerations (post irradiation effects and effect of dose rate), and presented one section on the stress cracking of elastomers induced by gamma radiation[1]. This article presents data on the effects of gamma radiation on elastomers which have been arbitrarily classed as heat resistant. This designation includes those materials which can be used for service in air or certain fluids at 125 C or higher for prolonged periods without being adversely affected. They were selected both from the manufacturers' technical literature and a series of screening tests[2]. There are other materials which could fall into this category, but for convenience in classifying and grouping, these materials (e.g., some formulations of acrylic and chlorosulfonated polyethylene elastomers) will be treated in future articles.

MATERIALS EVALUATED

The materials used for the gamma irradiation studies reported herein are listed in Table 1. They are grouped in accordance with the general chemical type

of the base polymer used in each material, and where possible, a brief description is given. The materials which are not proprietary items are described more completely in Table 2 which gives recipes and cure schedules. The information given in Table 2 is of prime interest in that it offers an opportunity to asses the role of the various compounding materials on the base polymer. In the case of proprietary materials this information can be obtained, although not nearly as comprehensively, by observing the effects of varying factors such as filler loading, cure system, and post curing schedules on the radiation induced changes occuring in the materials. This is exemplified by the studies carried out with Union Carbide's K-1040 series and to a lesser extent with General Electric's 300 series silicone elastomers. Excellent work in the field of studying the effects of radiation on compounding materials is being carried out currently by Born[3].

EXPERIMENTAL

The studies reported herein were designed to provide information on the room temperature radiation resistance of the elastomers both for screening purposes and for future use when the irradiations will be carried out at elevated temperatures. All materials were exposed to gamma radiation and evaluated by recording changes in physical properties as described previously[1]. For all irradiations up to and including 1×10^8 r a Cobalt-60 isotope source at Hanford was used. For the higher irradiations spent fuel elements of the Materials Testing Reactor (MTR) were used. This latter source was used for the higher doses because the higher dose rates obtainable at the MTR very significantly reduced the amount of irradiation time. The results obtained from the irradiation of the same material to the same dose from both sources agree close enough so that it can be assumed that the experimental results obtained are independent of the two sources[1].

The data obtained from exposing the materials listed in Table 1 to various doses of gamma radiation in air at 25 C at normal atmospheric pressure is presented in Table 3. This Table shows physical property changes induced by exposure to gamma radiation as percent decrease (minus sign) or percent increase (no sign) of the original property values which are given opposite zero irradiation dose. Also shown opposite zero irradiation dose and under the Remarks column is the original color of each material. Significant color changes and other observations needing comment are also noted in this column opposite the particular radiation dose causing the phenomenon.

A portion of the data tabulated in Table 3 has been previously published[4,5].

DISCUSSION

The data presented in Table 3 show how radiation affects the properties of the materials broadly classified as heat resistant elastomers. In most cases short doses, and in some cases intermediate doses do not affect the usefulness of the materials to any great extent, but on continued exposure all of the materials examined are more or less severely damaged depending upon their chemical composition. The data also compare the effects of ionizing radiation on different classes of materials as well as materials within a class. This will be discussed in more detail on the following pages. Additional information of the effects of ionizing radiation on materials and details on the mechanisms of radiation damage can be obtained in a great number of excellent articles in the literature. Typical examples of these articles and general review articles are cited for reference purposes[6,7,8,9,10,11].

A study of the data in Table 3 shows that of the three general classes of materials examined - silicones, fluoroelastomers, and isocyanate-urethanes, the latter materials exhibit a remarkable amount of stability against the damaging effects of ionizing radiation when compared with the other materials under consideration.

The fluoroelastomers in general show the least resistance while the silicones cover a broader range - some being superior to the fluoroelastomers, and some being of the same order of magnitude in radiation resistance.

Graphic representations of how the above classes of materials are affected by gamma radiation are shown in Figures 1 through 6. As space limitations imposed by the large number of materials evaluated preclude a graph of each one, the illustrations are meant to show the changes in a material that is in general typical of its group. Adiprene C-1 is representative of the isocyanate-urethanes; SE-972 (dimethyl silicone), Silastic 80 (methyl vinyl silicone), and Y-1668 (methyl phenyl silicone) are in general typical of the major types of silicone rubbers; and PR 1700-X7 is typical of a new fluoroelastomer (Viton A), and while 1F4 shows still another fluorine containing material. It should be noted that this latter group of materials is not as chemically similar as, for example, are the silicones, and are considered as a class only because they are miscellaneous polymers containing fluorine and afford a convenient means of grouping.

Isocyanate-Urethanes

As was stated above, the isocyanate-urethane polymers are more radiation resistant than the other materials studied and appear capable of giving satisfactory service to the relatively large dose of 1×10^9 r, and in all probability to even higher doses. They are resistant to stress cracking as was discussed previously[1] and retain a great amount of flexibility (passing the 180° bend test at 1×10^9 r) and physical toughness.

All of the isocyanate-urethane materials which were investigated exhibited a decrease in both tensile strength and ultimate elongation with increasing radiation exposure. In general they all became somewhat softer until doses of about 5×10^8 r

were reached at which time they became increasingly harder. This hardness phenomenon (softening followed by hardening) together with a decrease in tensile strength suggests that for doses out to approximately 5×10^8 r chain cleavage is the predominant mechanism causing the physical property changes. However, the leveling off of the tensile curve (in some cases an increase in tensile strength) and an increase in hardness suggest that cross-linking is predominating after doses of 5×10^8 r.

With the exception of Adiprene C-4 which is less resistant to radiation damage than the other Adiprenes studied, the compounding ingredients appear to have little effect on radiation induced changes in these materials. In the case of Adiprene C-4 it appears that the different cure system is responsible for rendering the material less resistant to radiation.

Fluoroelastomers

The materials studied in this group represent three different types of polymers as exemplified by Kel-F Elastomer, 1F4, and Viton A. Kel-F Elastomer shows the least stability to radiation becoming quite soft and tacky at the lower doses which suggests the material undergoes chain cleavage with a corresponding reduction in molecular weight. Previous work[12,13] published gives more details on the radiation induced cross-linking and chain cleavage mechanisms.

The Viton A material and 1F4 both appear about equal in their resistance to radiation and are similar in this respect to many of the silicones studied. Although a decrease in tensile strength occurs in both materials, the increase in hardness which is accompanied by an increase in stiffness suggests that these two materials are cross-linked by exposure to radiation. For dynamic applications requiring a degree of flexibility these two materials probably should not be exposed to doses out to 1×10^8 r. For static applications they, in all probability, could be used

out to higher doses. The remainder of the Viton A materials were quite similar in their radiation resistance showing the same general trend as PR 1700-X7 but becoming quite hard and stiff at a lower exposure and failed the bend test at a dose of 5×10^7 r. All of the fluoroelastomers gave no evidence of radiation induced stress cracking.

Limited supplies of all of the fluoroelastomers precluded a detailed study of their radiation resistance characteristics and further studies will be necessary before the role of the compounding materials can be determined.

Silicones

As can be seen from Table 3 the predominant portion of the studies being reported was concerned with the silicone elastomers. This is in large part due to the large variety of materials commercially available and the fact that they have been tried and proven materials of construction for several years. Because of the various types which were studied, they can best be discussed by further grouping in accordance with their chemical composition.

Dimethyl silicones - These materials appear to be generally less resistant to radiation than the other silicone types. In general, exposure to radiation increases both the hardness and tensile strength of the dimethyl silicones while the elongation decreases. With the exception of Silastic 160 they all failed the bend test at either 5 or 6×10^7 r while Silastic 160 broke after an exposure out to 1×10^8 r.

Methyl vinyl silicones - With the exception of elongation which is reduced with increased exposure to radiation, there appears to be no definite pattern of behavior with the methyl vinyl silicones. The tensile strength in particular exhibits a quite random behavior which is probably due to the amount of vinyl groups in the

polymer and the manner in which they cause cross-linking of the polymer during the cure. The materials all increase in hardness with increased radiation exposure with the exception of a few which initially soften somewhat before becoming harder. All of these materials broke when subjected to the bend test after exposure to doses from 5×10^7 r to 1×10^8 r.

Methyl phenyl silicones - These materials show in general the best resistance to radiation of all the silicone types. Exceptions to this are shown by GE 81504 and Silastic 675 which were quite hard and broke at doses of 5 and 6×10^7 r respectively. The remainder of the materials retained their flexibility up to greater exposures, some out to 3×10^8 r. With the exception of Silastics 675 and S2048 the general trend of the tensile strength of these materials was a decrease with increasing radiation dose. All material got progressively harder while their elongation was decreased.

Methyl phenyl vinyl silicones - Only two materials in this class were evaluated and their behavior (increase in hardness and tensile strength and decrease in elongation) was very similar to the majority of the methyl phenyl types. Both Silastic 916 and GE81716 broke after an exposure of 1×10^8 r.

Silicones-general - In general it appears that the radiation resistance of the silicone elastomers is due in large part to the type and amount of organic groups on the main silicone chain. The phenyl types are superior due to the presence of the aromatic ring which is able to absorb more radiation energy without disruption of the molecular structure. It appears logical to assume that the phenyl materials showing the best radiation resistance had a higher percentage of phenyl groups on the main chain structure. The dimethyl types were the least resistant to radiation while the methyl vinyl compounds were intermediate. For materials which

were compounded from the same silicone gum but showed a difference in radiation resistance only general conclusions can be drawn as the recipes and cure systems are not known for these materials. It is assumed in these cases that the compounding materials and curing ingredients also play a major role in determining the extent of radiation induced changes on the physical properties of the silicone elastomers. For example, the dimethyl Silastic 160 material is presumably based upon the same type of silicone gum as are the other dimethyl Silastic compounds but exhibits better performance in a radiation field. It is therefore assumed that the compounding materials used in Silastic 160 had a significant effect on the radiation induced changes occuring in this material.

In several instances it should be noted that overlapping in the silicone radiation resistance scale occurs. For example, methyl vinyl K-1046R exhibits better resistance than GE 81504 methyl phenyl type. All silicones appear to cross-link during radiation exposure as evidenced by the physical property changes. A few such as Cohrlastic 500 show evidence that chain scission might be taking place at low exposures because they initially become somewhat softer before assuming the general trend of becoming harder. It is of interest to note that many of the silicones, particularly those with light original colors, changed color during exposure to a very marked degree. As far as can be determined to date, these color changes are permanent based upon about eighteen months observation. In all the silicones examined there was no evidence of stress cracking.

Filler loading and post cure - These studies were made primarily to determine the effect of radiation on the properties of silicone elastomers very similar to one another except that their original properties were different because of either a variation in the amount of filler used or a variation in the length of post

heat curing. Table 4 lists the changes occuring in two series of materials with varying filler loading and varying post cures respectively. The materials are compared after receiving a dose of 1×10^8 r. Actual property values are given in this Table to give a better means of comparing with the original values than is afforded by the per cent change method.

The filler loading studies offer a chance to examine the role the fillers play with respect to radiation induced property changes. Although the recipes of the materials (K-1040 series shown in Table and SE-300 series not illustrated) are not known, it is known that the materials in each series essentially differ only in the amount of filler used - the lower the compound number in the series, the less filler was used and the softer the compound.

The data in Table 4 show that in general the ultimate changes in all the properties of these materials is such that given sufficient radiation exposure they will eventually approach the same value for each property although the percentage change will only show this indirectly. For example, the actual values of hardness, tensile strength, and ultimate elongation for K-1046R, K-1047R, and K-1048R are essentially the same at a radiation dose of 1×10^8 r even though there was quite a spread in their original properties. This holds true for the SE-361, SE-371, and SE-381 silicone rubbers.

It should be noted that K-1044R and K-1045R follow the general trend in their series except that the tensile strength is lowered but shows a possible trend of increasing if the radiation dose was increased. This phenomenon is in all probability due to greater unbalance of filler to polymer than is shown in the harder members of the K-1040 series.

Of particular significance in these studies is the fact that a compound

which becomes hard and brittle upon exposure to radiation can not be improved upon simply by compounding to a softer material. This might help for applications requiring a relatively low exposure, but at the higher doses all of the materials tend to approach the same degree of flexibility and hardness.

The post cure data shown in Table 4 (refer to Table 1 for post cure schedules) also show that for similar materials with different post cures (therefore having different original properties) exposure to high doses of radiation will ultimately damage all of these materials such that their final properties will be essentially the same. In addition, these studies indicate that exposure to radiation offers the possibility of producing the desired post cure without the use of heat. The data in Table 5 show that the properties of K-1047R B-4 (no post cure) are very nearly the same as the original properties of the fully post cured K-1047R B-2 when exposed to a radiation dose of 1×10^7 r. The changes in the properties of K-1047R B-4 with increased radiation exposure as shown in Tables 3 and 4 indicate that a slightly higher dose than 1×10^7 r would essentially give this material the same original properties as the conventionally temperature post cured K-1047R B-2.

For conventional applications excluding any radiation environment such a radiation treatment of a cured silicone elastomer would probably be quite satisfactory and would depend to a great extent upon the economics of radiation as opposed to heat treating. With respect to the material being post cured by radiation and then subjected to a radiation environment, it appears that further exposure would affect the material much in the manner as a material which had been heat post cured and then exposed to radiation. Both materials broke and were hardened significantly at a dose of 5×10^7 r. However, if it is assumed that the heat post cured K-1047R B-2 could have broken after a dose of 4×10^7 r, if the measurements had been made after this

dose, and that the radiation post cured K-1047R B-4 would not have broken until a dose of 5×10^7 r was reached, then both materials would have (based mainly upon flexibility) an effective life of 4×10^7 r in a radiation field. It is also assumed that the K-1047R B-4 would have a 25% total longer life in a radiation field by virtue of its being originally softer and would increase in hardness but not surpass K-1047R B-2 at the intermediate doses in question.

The cure system of the K-1047R series and its effect on the radiation induced property changes can be examined by studying the data in Table 3 on the three materials B-1, B-2, and B-3. It should be noted that the B-1 material did not have a full heat post cure. Otherwise, especially on a comparative basis at an exposure of 1×10^8 r, the cure systems apparently do not exert a significant difference on the compounds.

Properties

The elongation of a material appears to be the most sensitive single property measured to provide a good index of the damage induced by radiation. However, the flexibility probably offers, for the longer exposures, a better means of determining the condition of a material. This is illustrated by comparing the silicones K-1025R with GE 81590. At approximately 1×10^8 r the percent property changes occuring in these two materials are essentially the same, yet the former material broke after an exposure of 5×10^7 r while the latter lasted about twice as long in the radiation field before breaking under the bend test. Both hardness and tensile strength measurements appear to be most useful only after a definite trend has been established. However, this is not always the case as illustrated by such materials as Viton A-6 and GE 81598 where the tensile curve shows a fairly definite trend during low and intermediate doses and then abruptly rises or falls.

Actually, to best study the behavior of a material exposed to radiation when physical properties are being employed, it is necessary to take all properties (the more, the better) into account as well as both actual and percent change of these properties. This is particularly true for applications which do not require that all property changes be held to a minimum. For example, a substantial loss in elongation will not affect the operation of some types of seals.

SUMMARY

Physical property changes of a great number of materials classified as heat resistant elastomers have been given. Each material, because of space limitations, could not be discussed completely and the reader is urged to make his own comparisons or examinations on those materials in which he has an interest.

Of the three general classes of materials studies, the isocyanate-urethanes are considered to be the best with respect to radiation resistance, the silicones next, and the fluoroelastomers last. A consideration of other environments could obviously alter the order of this listing. It should be also noted that because of the overlapping of materials in one class with materials in another class, the above order of radiation resistant materials should be considered very general.

From the data presented it is difficult to assign permissible dose limits for classes of materials or even individual materials. This is due in part to the overlapping of radiation resistance between classes and within a class and in part to the fact that the demands of a particular application must be known such as the environmental requirements and the essential properties needed. Each material then, must be considered on its own merits and intended application.

It has been shown that radiation might be utilized as a tool whereby silicone elastomers can be post cured without heat tempering. In this case the econ-

omics of the process would probably determine the practicallity. Also, the color changes occuring in the silicone rubbers suggest the possibility of radiation dosimetry systems based on this color change.

ACKNOWLEDGEMENT

Acknowledgement is made to the various suppliers of materials for their cooperation in submitting test samples and pertinent materials information. It should be noted that many of the materials evaluated might never have been developed or intended by the manufacturers for the conditions to which they have been subjected. Any failure or poor performance of a material is not necessarily indicative of the utility of the material under less stringent conditions or for other applications.

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TABLE 1

HEAT RESISTANT ELASTOMERS USED FOR GAMMA IRRADIATION STUDIES

Material Supplier and Designation	Type or Description and Post Cure (hours/°F)
Silicones	
Dow Corning Corp.	
Silastic 152*	Dimethyl (24/480)
Silastic 181	Dimethyl (4/480)
Silastic 7-170	Dimethyl (24/480)
Silastic 160	Dimethyl (4/480)
Silastic 50	Methyl vinyl (24/480)
Silastic 80	Methyl vinyl (24/480)
Silastic 250	Methyl phenyl (24/480)
Silastic 675	Methyl phenyl (24/480)
Silastic S2048	Methyl phenyl (4/480)
Silastic 916	Methyl phenyl vinyl (24/480)
Silastic LS-53	Fluorocarbon type (16/300)
General Electric Co.	
SE-972	Dimethyl (16/480)
81625	Dimethyl (24/480)
SE-361	Methyl vinyl (24/480)
SE-371	Methyl vinyl (24/480)
SE-381	Methyl vinyl (24/480)
HW-86*	Methyl vinyl (6/450)
SE-751	Methyl vinyl (24/480)
81686	Methyl vinyl (24/480)
SE-550	Methyl phenyl (1/300)
SE-551	Methyl phenyl (4/300)
81590	Methyl phenyl (4/300)
81504	Methyl phenyl (24/300)
81716	Methyl phenyl vinyl
Union Carbide Corp.	
K-1044R	Methyl vinyl, X-1960 cure (24/480)**
K-1045R	Methyl vinyl, X-1960 cure (24/480)
K-1046R	Methyl vinyl, X-1960 cure (24/480)
K-1047R B-1	Methyl vinyl, BP cure (4/450)
K-1047R B-2	Methyl vinyl, DBP cure (24/480)
K-1047R B-3	Methyl vinyl, X-1960 cure (24/480)
K-1047R B-4	Methyl vinyl, DBP cure (no post cure)
K-1047R B-5	Methyl vinyl, DBP cure (6/480)
K-1047R B-6	Methyl vinyl, DBP cure (12/480)
K-1048R	Methyl vinyl, X-1960 cure (24/480)

TABLE 1 - Continued

Material Supplier and Designation	Type or Description and Post Cure (hours/°F)
K-1035	Methyl vinyl (24/480)
K-1025R	Methyl vinyl (24/480)
X-1516	Methyl vinyl (6/480)
K-1014	Methyl vinyl (24/480)
Y-1668	Methyl phenyl (24/480)
Connecticut Hard Rubber Co.	
Cohrlastic 500	Methyl vinyl
Cohrlastic 700	Dimethyl
Cohrlastic HT-665	Methyl phenyl vinyl
Cohrlastic HT-666	Methyl phenyl vinyl
Cohrlastic R-11568	Methyl phenyl vinyl
Arrowhead Rubber Co.	
Arcosil 2184	Methyl vinyl
Parker Appliance Co.	
77-018	Dimethyl
Huntington Rubber Mills	
S-931	Molybdenum disulfide filled
DuPont Fabrics Division	
Fairprene SR-5570	Not known
Fluoroelastomers	
Minnesota Mining and Mfg. Co.	
1F4	Polymer of 1,1-dihydroperfluorobutyl acrylate
Kel-F Elastomer	Copolymer of trifluorochloroethylene and vinylidene fluoride
DuPont Elastomer Chemicals Dept.	
Viton A-1*	Copolymer of vinylidene fluoride and hexafluoropropylene
Viton A-2*	Ditto

TABLE 1 - Continued

Material Supplier and Designation	Type or Description and Post Cure (hours/°F)
Viton A-3*	Copolymer of vinylidene fluoride and hexafluoropropylene
Viton A-4*	Ditto
Viton A-5*	Ditto
Viton A-6*	Ditto
Precision Rubber Products Corp.	
PR 1700-X7	Ditto
Isocyanate-Urethanes	
DuPont Elastomer Chemicals Dept.	
Adiprene C-1*	Not known
Adiprene C-2*	Ditto
Adiprene C-3*	Ditto
Adiprene C-4*	
Goodyear Tire and Rubber Co.	
Chemigum XSL	Ditto
Precision Rubber Products Corp.	
PR 631-70	Ditto
Greer Industries, Inc.	
Disogrin DSA 6865	Ditto
Disogrin DSA 7560	Ditto

* See Table 2 for complete details on recipe used and cure schedule.

** X-1960 cure: curing compound including di-tertiary butyl peroxide catalyst.
BP cure: benzoyl peroxide catalyst.
DBP cure: dichloro benzoyl peroxide catalyst.

TABLE 2

RECIPES OF HEAT RESISTANT ELASTOMERS USED FOR GAMMA IRRADIATION STUDIES

SILICONES

Recipe Materials	Silastic 152	HW-B6
Silastic 401 gum	100.	--
GE 81567 gum	--	100.
Celite Superfloss	10.	60.
Iron Oxide	3.	5.
Dow Corning Silica	35.	--
Luperco ASF	1.5	--
Cadox 56	--	1.

Silastic 152 cured 5'/250 F, post cured 24 hours/480 F.
HW-B6 cured 10'/250 F, post cured 6 hours/450F.

VITONS

Recipe Materials	A-1	A-2	A-3	A-4	A-5	A-6
Viton A	100.	100.	100.	100.	100.	100.
Zinc Oxide	10.	10.	10.	10.	10.	10.
Dyphos	10.	10.	10.	10.	10.	10.
MT Carbon Black	18.	--	--	--	--	--
HiSil LM-3	--	20.	20.	20.	20.	20.
HMDA-Carbamate	1.	2.	--	3.	2.	2.
Benzoyl Peroxide	--	--	2.	--	--	--
Peroxide Regulator (RCD-2110)	--	--	2.	--	--	--
Akroflex CD	--	--	--	--	5.	--
UOP-288	--	--	--	--	--	5.

All compounds cured 30'/275 F and post cured 24 hours/400 F.

TABLE 2 - Continued

ADIPRENES

Recipe Materials	C-1	C-2	C-3	C-4
Adiprene C	100.	100.	100.	100.
HAF Black	30.	50.	25.	30.
Flexol TOF	15.	15.	--	--
Sulfur	1.5	1.5	.75	--
MBTS	3.	3.	4.	--
MBT	1.	1.	1.	--
Sundex 53	--	--	.5	--
RCD-2098	.35	.35	.35	--
Celluflex TPP	--	--	--	10.
Di Cup 40C	--	--	--	2.5

Adiprene C-4 cured 45'/307 F; all others cured 60'/287 F.

TABLE 3

EFFECT OF GAMMA RADIATION ON THE PROPERTIES OF HEAT RESISTANT ELASTOMERS

Materials	Dose ($r \times 10^6$)	Initial Properties and Percent Change			Remarks
		Hardness Shore A; Δ%	Elongation %; Δ%	Tensile psi; Δ%	
Silicones					
Silastic 152	0	50	440	845	Red
	3	4.0	- 3.4	- 1.0	
	5	22.0	-38.6	10.5	
	10	32.0	-52.3	18.2	
	50	62.0	-86.4	11.1	a
	100	74.0	-90.9	- 0.4	a
	150	84.0	-97.7	- 7.7	a
Silastic 181	0	84	110	830	Cream-tan
	5	3.6	-20.0	8.0	b
	10	4.8	-47.3	16.9	c
	50	10.7	-68.2	41.9	a,d
	100	14.3	-72.7	60.6	a,e
Silastic 7-170	0	76	85	670	Cream
	5	5.3	-10.7	14.5	f
	10	6.6	-28.6	29.0	b
	50	15.8	-52.4	42.1	a,c
	100	22.4	-64.3	59.0	a,d
Silastic 160	0	67	245	540	White
	5	7.5	-30.3	- 2.8	
	10	9.0	-46.7	0.0	
	50	26.9	-75.4	25.3	g
	100	38.8	-85.7	97.6	a,g
Silastic 916	0	62	580	1505	Red
	5	1.6	-13.5	- 8.8	
	10	9.7	-24.7	- 9.4	
	50	30.7	-82.7	-38.3	
	100	41.9	-96.0	-63.2	a

TABLE 3 - Continued

Materials	Dose ($r \times 10^6$)	Initial Properties and Percent Change			Remarks
		Hardness Shore A; Δ%	Elongation %; Δ%	Tensile psi; Δ%	
Silastic 50	0	68	255	735	White
	3	- 4.4	-13.0	15.5	
	6	1.5	-26.9	17.0	
	30	10.3	-54.5	36.3	h
	60	20.6	-78.3	5.9	i
	90	25.0	-82.2	- 10.1	a,c
Silastic 80	0	80	205	690	White
	3	2.4	-12.6	13.9	
	6	1.8	-40.1	9.1	
	30	4.8	-56.3	24.2	
	60	9.5	-78.2	47.6	g
	90	11.9	-80.5	62.1	a,g
Silastic 250	0	55	295	885	Rust red
	5	9.1	-21.7	2.9	
	10	9.1	-30.3	0.6	
	50	30.9	-71.1	- 23.8	
	100	50.9	-86.7	- 45.5	a
Silastic 675	0	75	210	700	Red
	3	8.0	-15.1	10.4	
	6	9.3	-22.3	22.1	
	30	10.7	-66.0	32.1	
	60	20.0	-73.0	51.4	a
	90	22.7	-80.6	56.1	a
Silastic S2048	0	64	320	675	White
	3	- 1.6	-22.4	6.8	
	6	3.1	-42.5	10.1	
	30	12.5	-56.5	20.3	
	60	23.4	-73.6	29.4	h
	90	31.3	-76.7	43.1	a,j

TABLE 3 - Continued

Materials	Dose ($r \times 10^6$)	Initial Properties and Percent Change			Remarks
		Hardness Shore A; Δ%	Elongation %; Δ%	Tensile psi; Δ%	
Silastic LS-53	0	59	220	1405	Red
	5	3.4	- 18.7	- 34.9	
	10	3.4	- 36.1	- 51.8	
	50	15.3	- 72.2	- 82.3	
	100	23.7	- 90.9	- 84.5	a
SE-972	0	83	70	955	Brown-tan
	5	1.2	- 14.3	- 5.7	
	10	3.6	- 28.6	5.9	
	50	12.1	- 67.1	20.5	a
	100	15.7	- 85.7	68.9	a
GE 81625	0	60	90	915	Brown-tan
	5	8.3	3.3	6.1	
	10	21.7	- 13.0	5.9	
	50	43.3	- 65.2	19.5	a
	100	55.0	- 78.3	12.4	a
SE-361	0	75	120	945	Red
	5	- 6.7	- 13.9	- 1.6	
	10	- 4.0	- 22.1	- 7.3	
	50	12.0	- 54.9	19.7	
	100	20.0	- 71.3	41.9	a
	150	24.0	- 83.6	50.2	a
SE-371	0	78	90	1020	Red
	3	- 2.6	- 13.0	- 7.4	
	6	- 2.6	- 18.5	- 6.4	
	30	6.4	- 34.8	25.2	a
	60	12.8	- 54.4	22.5	a
	90	16.7	- 67.4	54.9	a

TABLE 3 - Continued

Materials	Dose ($r \times 10^6$)	Initial Properties and Percent Change			Remarks
		Hardness Shore A; Δ%	Elongation %; Δ%	Tensile psi; Δ%	
SE-381	0	86	70	975	Red
	3	- 5.8	- 4.8	- 4.4	
	6	- 4.7	- 11.8	- 2.3	
	30	1.2	- 26.5	33.9	a
	60	3.5	- 41.2	44.3	a
	90	8.1	- 70.6	88.3	a
HW-B6	0	68	140	320	Red
	3	- 14.7	- 9.4	- 5.4	
	6	- 14.7	- 9.4	- 5.7	
	30	- 5.9	- 38.4	20.4	
	50	10.3	- 67.4	38.7	a
	100	19.2	- 78.3	42.8	a
SE-751	0	60	205	670	Light tan
	3	5.0	- 11.8	4.6	
	6	3.3	- 21.6	7.8	
	30	18.3	- 53.4	3.4	
	60	33.3	- 66.2	4.5	a
	90	46.7	- 79.9	- 26.4	a
	100	50.0	- 96.6	- 58.1	a
GE 81686	0	66	240	715	White
	5	- 3.0	- 1.3	11.5	
	10	9.1	- 35.7	19.2	
	50	31.8	- 83.2	25.2	a
	100	42.4	- 91.6	4.6	a
SE-550	0	63	210	660	Light tan
	3	0.0	- 4.3	7.6	
	6	3.2	- 13.9	0.8	
	30	7.9	- 44.9	- 6.1	
	60	19.0	- 66.5	- 13.3	k
	90	30.2	- 79.0	- 6.8	a,l

TABLE 3 - Continued

Materials	Dose ($r \times 10^6$)	Initial Properties and Percent Change			Remarks
		Hardness Shore A; Δ %	Elongation %; Δ %	Tensile psi; Δ %	
SE-551	0	56	350	1215	White
	3	- 3.6	- 10.0	2.6	
	6	5.4	- 15.3	1.0	
	30	16.1	- 52.9	- 9.9	
	60	35.7	- 78.6	- 24.4	g
	100	55.4	- 90.0	- 39.1	a,m
	150	62.5	- 92.1	- 41.2	a,m
GE 81590	0	58	285	1090	Light tan
	3	0.0	- 6.7	- 10.8	n
	6	- 3.5	- 12.0	- 10.7	o
	30	3.4	- 50.7	- 31.2	p
	60	13.9	- 64.1	- 34.9	q
	90	31.0	- 78.9	- 40.7	a,q
GE 81716	0	60	590	1590	Grey
	5	6.7	- 24.1	- 7.1	
	10	16.7	- 36.4	- 8.6	r
	50	35.0	- 86.4	- 41.3	r
	100	45.0	- 91.5	- 51.6	a,r
GE 81504	0	77	350	930	Slate grey
	5	- 1.3	- 7.1	- 16.3	
	10	3.9	- 38.6	- 12.2	
	50	19.5	- 92.9	- 20.2	a,r
	100	23.4	- 95.7	- 8.1	a,r
K-1044R	0	56	360	1080	Red
	5	0.0	- 16.4	- 0.6	
	10	7.1	- 30.4	- 15.7	
	50	33.9	- 81.1	- 46.7	
	100	51.8	- 88.9	- 42.5	a

TABLE 3 - Continued

Materials	Dose ($r \times 10^6$)	Initial Properties and Percent Change			Remarks
		Hardness Shore A; Δ%	Elongation %; Δ%	Tensile psi; Δ%	
K-1045R	0	60	310	930	Red
	5	5.0	- 22.1	- 10.2	
	10	13.3	- 41.9	- 17.8	
	50	36.7	- 83.8	- 20.5	
	100	46.7	- 91.9	- 17.8	a
K-1046R	0	65	290	855	Red
	5	6.2	- 25.0	8.1	
	10	9.2	- 35.8	1.3	
	50	30.8	- 77.4	5.8	
	100	43.1	- 89.6	21.3	a
K-1047R B-1	0	70	310	1010	Red
	5	12.9	- 22.6	- 2.9	
	10	15.7	- 36.7	3.7	
	50	28.6	- 87.1	5.0	a
	100	37.1	- 96.8	37.4	a
K-1047R B-2	0	66	285	820	Red
	5	1.5	- 17.0	- 6.4	
	10	15.2	- 47.0	4.4	
	50	36.4	- 85.9	10.5	a
	100	42.4	- 89.5	19.6	a
K-1047R B-3	0	76	230	885	Red
	5	2.6	- 30.4	2.6	
	10	4.0	- 41.3	8.2	
	50	18.4	- 84.8	13.4	a
	100	26.3	- 89.1	30.7	a

TABLE 3 - Continued

Materials	Dose ($r \times 10^6$)	Initial Properties and Percent Change			
		Hardness Shore A; Δ%	Elongation %; Δ %	Tensile psi; Δ %	Remarks
K-1047R B-4	0	54	620	1020	Red
	5	1.9	- 13.2	4.2	
	10	28.3	- 55.0	- 7.9	
	50	66.7	- 93.6	- 5.8	a
	100	77.8	- 97.3	17.9	a
K-1047R B-5	0	64	400	965	Red
	5	9.4	- 33.9	0.7	
	10	18.8	- 62.6	- 0.5	
	50	42.2	- 92.5	- 0.7	a
	100	51.6	- 96.3	18.8	a
K-1047R B-6	0	67	375	940	Red
	5	3.0	- 24.9	0.9	
	10	13.4	- 57.1	4.4	
	50	35.8	- 92.5	8.4	a
	100	44.8	- 97.3	24.3	a
K-1048R	0	79	215	875	Red
	5	7.6	- 30.2	2.7	
	10	10.3	- 39.5	- 1.3	
	50	17.7	- 84.7	12.8	a
	100	22.8	- 89.3	31.1	a
K-1035	0	55	240	740	Light tan
	3	0.0	- 17.4	- 4.9	
	6	7.1	- 29.8	- 6.8	
	30	16.1	- 48.3	- 1.1	
	60	25.3	- 71.1	- 1.0	a
	90	48.2	- 77.3	- 12.0	a

TABLE 3 - Continued

Materials	Dose ($r \times 10^6$)	Initial Properties and Percent Change			Remarks
		Hardness Shore A; △ %	Elongation %; △ %	Tensile psi; △ %	
K-1025R	0	62	180	775	Red
	5	1.6	- 14.4	- 0.6	
	10	9.7	- 28.2	- 7.1	
	50	29.0	- 80.7	- 38.8	a
	100	40.3	- 84.5	- 43.4	a
X-1516	0	70	180	620	Black
	5	5.7	- 17.6	9.4	
	10	10.0	- 35.2	4.0	
	50	24.3	- 75.3	13.3	a
	100	31.4	- 90.4	20.2	a
K-1014	0	48	590	430	White
	5	- 2.1	- 38.1	- 13.5	
	10	10.4	- 57.5	- 13.0	
	50	54.2	- 86.0	- 24.0	a
	100	72.9	- 95.3	- 15.6	a
Y-1668	0	52	330	800	Grey
	5	- 3.9	- 6.6	- 0.8	
	10	13.5	- 36.7	- 10.3	
	50	42.3	- 75.9	- 13.3	a
	100	59.6	- 84.9	- 31.6	a
Cohrlastic 500	0	80	170	300	Red
	3	- 16.3	- 3.8	- 5.3	
	6	- 15.0	- 16.7	0.0	
	30	- 10.0	- 49.4	30.2	
	60	- 1.3	- 73.2	33.2	a
	90	6.3	- 75.0	100.0	a

TABLE 3 - Continued

Materials	Dose ($r \times 10^6$)	Initial Properties and Percent Change			
		Hardness	Elongation	Tensile	Remarks
		Shore A; Δ%	%; Δ%	psi; Δ%	
Cohrlastic 700	0	65	210	440	Grey
	3	- 16.4	- 10.4	20.6	
	6	- 12.3	- 31.6	16.3	
	30	0.0	- 55.2	25.1	
	60	15.4	- 71.7	26.5	
	90	26.2	--	--	a, c
Cohrlastic HT-665	0	55	725	1525	Grey
	3	6.2	- 17.1	- 19.8	
	6	12.7	- 27.5	- 27.6	
	10	20.0	- 44.8	- 40.9	
	40	41.8	- 84.1	- 49.3	
	50	49.1	- 89.0	- 50.0	
	67	50.9	- 93.1	- 55.6	
	100	60.0	- 95.2	- 40.9	a
Cohrlastic HT-666	0	63	560	1465	Grey
	3	1.6	- 8.6	- 16.6	
	6	1.6	- 17.6	- 21.7	
	10	7.9	- 29.2	- 31.0	
	40	27.0	- 81.2	- 46.2	
	50	34.9	- 86.6	- 51.2	
	67	34.9	- 90.1	- 54.1	
	100	41.3	- 92.8	- 57.9	
	300	57.1	-100.	- 59.6	a
Cohrlastic R-11568	0	24	370	310	Grey
	5	8.3	- 2.4	28.9	
	10	33.3	- 28.2	1.9	
	50	102.	- 72.9	- 14.1	
	100	175.	- 82.4	- 21.9	
	300	267.	- 98.4	- 34.1	a, t
	500	304.	-100.	-100.	a, t

TABLE 3 - Continued

Materials	Dose ($r \times 10^6$)	Initial Properties and Percent Change Hardness Shore A;Δ%	Elongation %;Δ%	Tensile psi;Δ%	Remarks
Arcosil 2184	0	54	375	360	Red
	3	7.4	- 11.1	41.8	
	6	11.1	- 50.4	42.0	
	30	31.5	- 66.5	88.3	
	60	44.4	- 83.9	79.3	
	90	57.4	- 89.3	126.	a
Parker 77-018	0	78	375	985	Green
	3	- 5.0	0.0	- 16.6	
	6	- 2.6	- 7.8	- 10.5	
	30	2.0	- 29.8	- 10.0	
	60	11.5	- 80.5	- 13.5	a
	90	17.9	- 87.6	- 13.7	a
Huntington S-931	0	55	295	590	Dark grey
	10	23.6	- 52.5	- 12.9	
	50	49.1	- 86.4	- 5.8	a
	100	60.0	- 89.8	- 8.3	a
Fairprene SR-5570	0	62	420	1025	Grey
	3	6.5	- 31.0	5.5	
	6	9.7	- 33.3	6.1	
	30	25.8	- 65.5	- 0.4	
	60	40.3	- 90.5	- 29.1	a
	90	55.2	- 94.7	- 36.8	a
Fluoroelastomers	0	71	150	1200	Black
3M 1F4	5	5.6	- 6.7	9.7	
	10	15.5	- 33.3	2.1	
	59	23.9	- 76.7	- 44.9	
	100	28.2	- 86.7	- 33.8	a

TABLE 3 - Continued

Materials	Dose ($r \times 10^6$)	Initial Properties and Percent Change			Remarks
		Hardness Shore A; Δ%	Elongation %; Δ%	Tensile psi; Δ%	
Kel-F Elastomer	0	75	640	1100	White
	3	- 12.0	4.4	13.6	u
	6	- 6.7	- 10.4	27.4	v
	60	- 10.8	- 14.8	- 36.4	w
Viton A-1	0	55	350	2070	Black
	50	49.1	- 84.4	- 23.4	a
	100	60.0	- 84.3	- 24.3	a
Viton A-2	0	77	275	1980	Brown
	5	14.5	- 32.6	- 12.9	
	10				
	50	25.0	- 87.0	- 11.6	a
	100	29.0	- 87.0	22.2	a
Viton A-3	0	66	575	1800	Grey-tan
	50	34.9	- 91.3	4.5	a
	100	40.9	- 92.2	8.9	a
Viton A-4	0	88	180	2625	Brown
	5	11.4	- 55.6	- 22.2	
	10				
	50	12.5	- 90.0	- 12.6	a
	100	13.6	- 94.4	8.2	a
Viton A-5	0	77	160	1875	Brown
	5	18.2	- 21.9	1.7	
	10				
	50	24.7	- 84.4	9.9	a
	100	29.9	- 84.4	25.4	a

TABLE 3 - Continued

Materials	Dose ($r \times 10^6$)	Initial Properties and Percent Change Hardness Shore A;Δ%	Elongation %;Δ%	Tensile psi;Δ%	Remarks
iton A-6	0	80	130	2125	Brown
	5	13.8	- 28.5	- 2.2	
	10				
	50	22.5	- 80.8	- 5.5	a
	100	25.0	- 84.6	49.2	a
R 1700-X7	0	75	250	1865	Black
	5	4.0	- 33.2	- 4.6	
	50	18.7	- 79.8	- 14.5	
	100	25.3	- 85.8	12.5	a
socyanate-Urethanes					
diprene C-1	0	62	530	4300	Black
	5	- 1.5	- 10.4	*	
	10	- 2.9	- 13.2	*	
	50	- 1.5	- 40.6	- 30.4	
	100	- 2.9	- 57.6	- 53.3	
	300	- 1.5	- 74.5	- 75.7	
	500	7.3	- 83.4	- 80.1	
	1000	15.9	- 87.7	- 80.4	
diprene C-2	0	75	360	3800	Black
	5	- 2.5	- 6.9	*	
	10	- 2.5	- 4.2	*	
	50	- 1.3	- 1.5	- 15.1	
	100	- 3.8	- 30.5	- 39.3	
	150	0.0	- 55.5	- 46.9	
	300	0.0	- 74.2	- 62.3	
	500	5.1	- 81.1	- 72.2	
	1000	11.4	- 84.7	- 67.9	a

TABLE 3 - Continued

Materials	Dose ($r \times 10^6$)	Initial Properties and Percent Change Hardness Shore A; Δ%	Elongation %; Δ%	Tensile psi; Δ%	Remarks
dipreme C-3	0	69	595	4400	Black
	5	1.4	3.2	*	
	10	1.4	- 6.0	*	
	50	- 6.0	- 17.8	- 37.5	
	100	- 7.2	- 30.4	- 50.4	
	150	- 6.0	- 48.0	- 58.4	
	300	- 1.5	- 67.3	- 66.4	
	500	1.5	- 81.5	- 75.9	
	1000	14.5	- 87.0	- 80.9	
hemigum XSL	0	69	690	4000	Black
	6	- 2.9	0.0	- 5.9	
	10	- 9.0	- 12.1	- 25.2	
	50	- 17.4	- 31.9	- 68.0	
	100	- 20.3	- 58.0	- 79.5	u
	300	- 14.5	- 22.8	- 86.7	x
R 631-70	0	77	540	3170	Black
	5	- 1.3	- 2.2	- 4.1	
	10	1.3	- 2.2	- 1.1	
	50	0.0	- 20.7	- 22.1	
	100	- 2.6	- 30.2	- 33.9	
	300	- 5.2	- 56.6	- 58.5	
	500	- 2.6	- 69.6	- 65.1	
	1000				
dipreme C-4	0	68	445	3445	Black
	100	27.9	- 83.2	- 59.1	u
isogrin DSA 6865	0	77	700	6500	Tan
	5	1.3	2.6	*	
	10	- 1.3	5.0	*	
	50	0.0	- 44.3	- 52.5	z
	100	5.2	- 68.1	- 76.4	
	300	9.1	- 95.0	- 86.7	
	500	10.4	- 96.4	- 90.3	
	1000	20.8	- 95.7	- 89.9	

TABLE 3 - Continued

Materials	Dose ($r \times 10^6$)	Initial Properties and Percent Change			
		Hardness Shore A; Δ%	Elongation %; Δ%	Tensile psi; Δ%	Remarks
Disogrin DSA 7560	0	80	650	6000	Brown
	5	- 5.5	- 13.1	*	
	10	- 5.0	- 19.2	*	
	50	- 5.0	- 48.2	- 46.8	
	67	- 3.8	- 49.5	- 68.7	
	100	- 2.5	- 60.7	- 81.2	
	150	- 2.5	- 83.8	- 87.1	z
	300	2.5	- 92.3	- 91.6	z

Notes:

a. Broke when bent 180°
b. Medium grey
c. Grey
d. Darker grey
e. Dark grey
f. Light grey
g. Slightly yellow-cream
h. Slightly grey
i. Light blue-grey
j. Yellow-grey
k. Slightly yellow
l. Dark amber
m. Yellow-cream
n. Pale green
o. Slightly darker green
p. Darker green
q. Dark green
r. Grey-green
s. Too brittle for testing
t. Grey-tan
u. Slightly tacky
v. Tackiness increased
w. Flow-like marks on surface
x. Soft and tacky
y. Turning darker brown-orange
z. Darker brown

* Exceeded capacity of tensile tester. Tensile strength greater than 4000 psi.

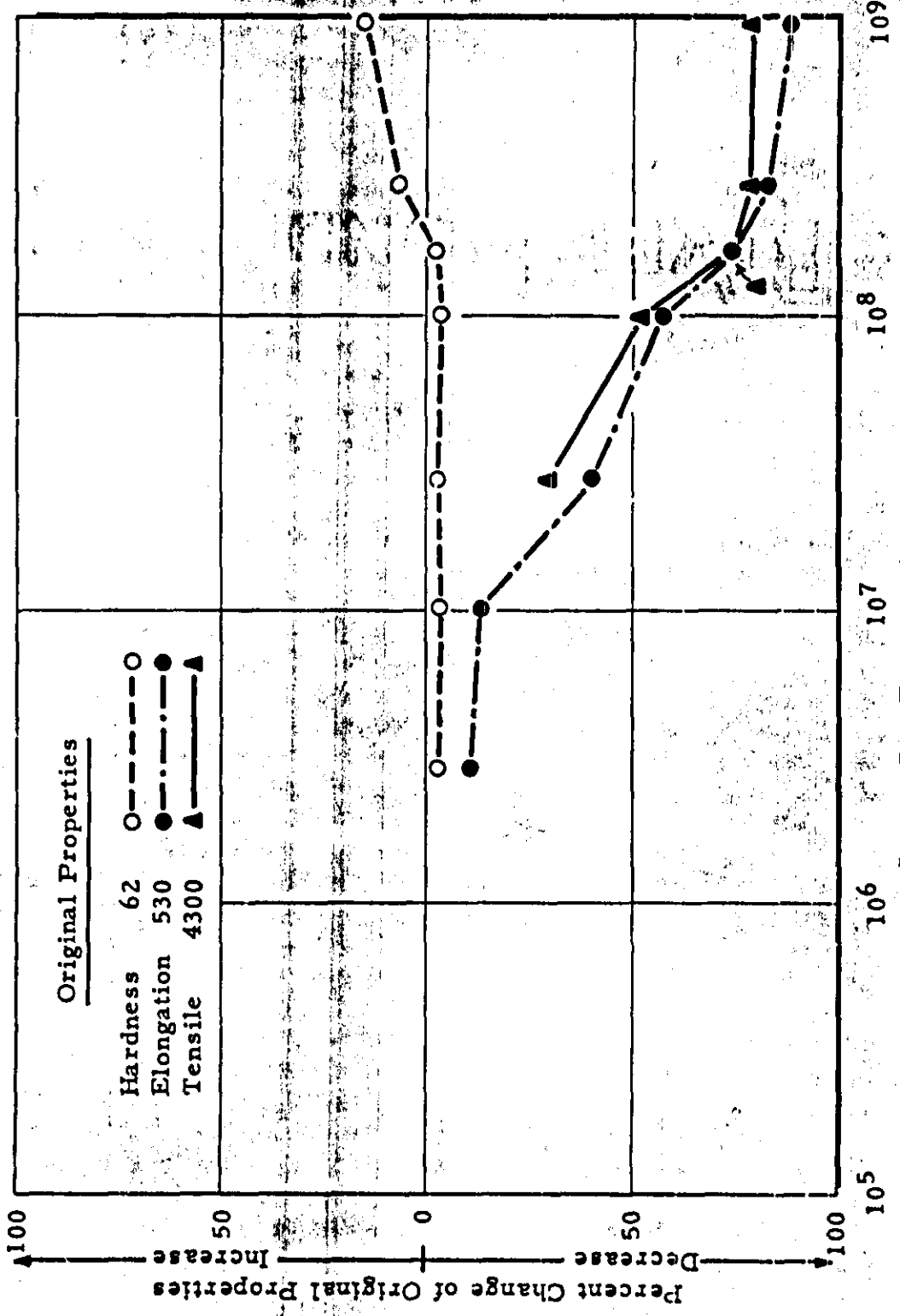

FIGURE 1
CHANGE IN PROPERTIES OF ADIPRENE C-1 ISOCYANATE-URETHANE ELASTOMER INDUCED BY GAMMA RADIATION IN AIR AT 25 C AT NORMAL PRESSURE

AEC-GE RICHLAND, WASH.

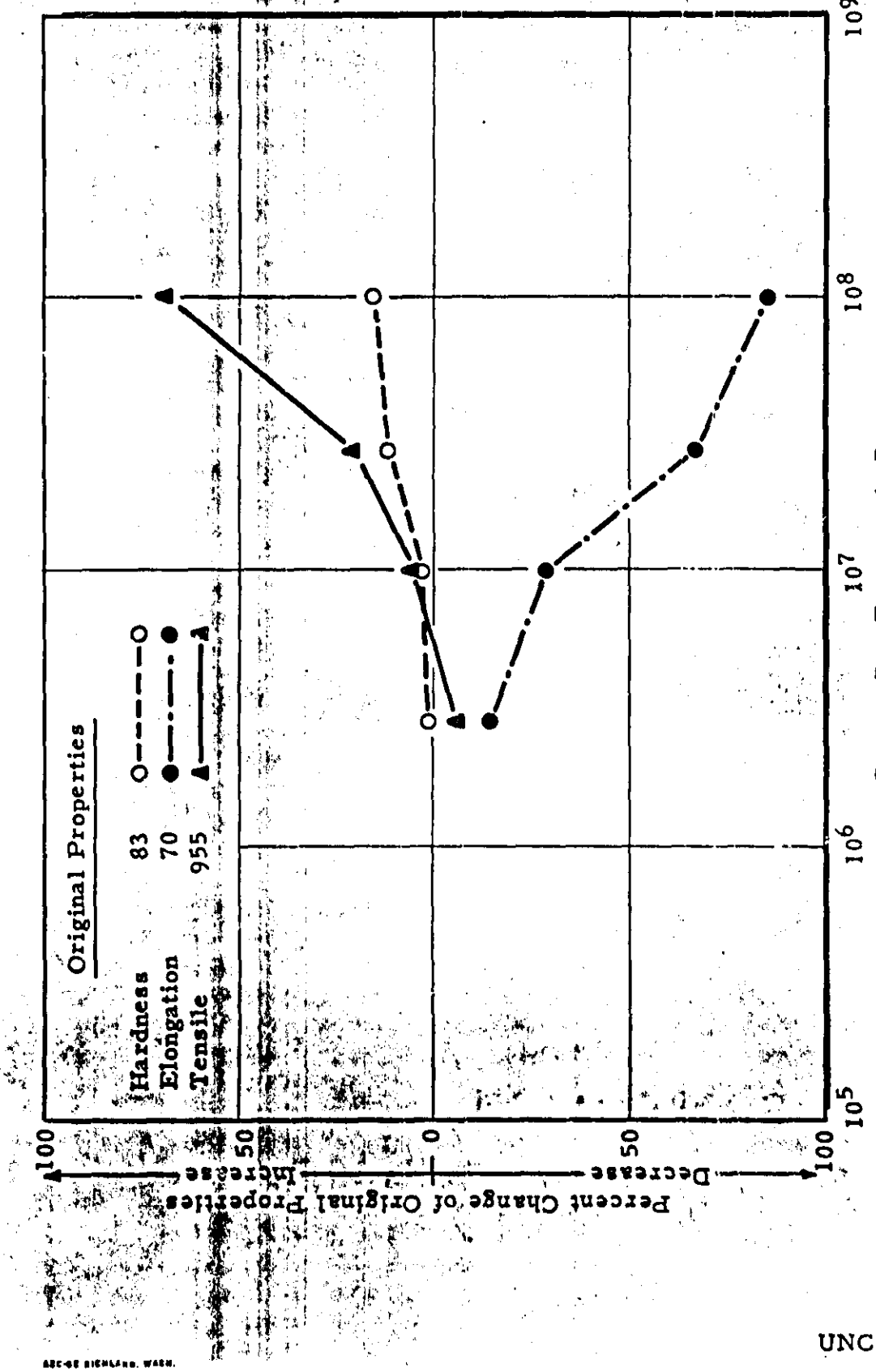

FIGURE 2
CHANGE IN PROPERTIES OF SE-972 DIMETHYL SILICONE ELASTOMER INDUCED BY GAMMA RADIATION IN AIR AT 25 C AT NORMAL PRESSURE

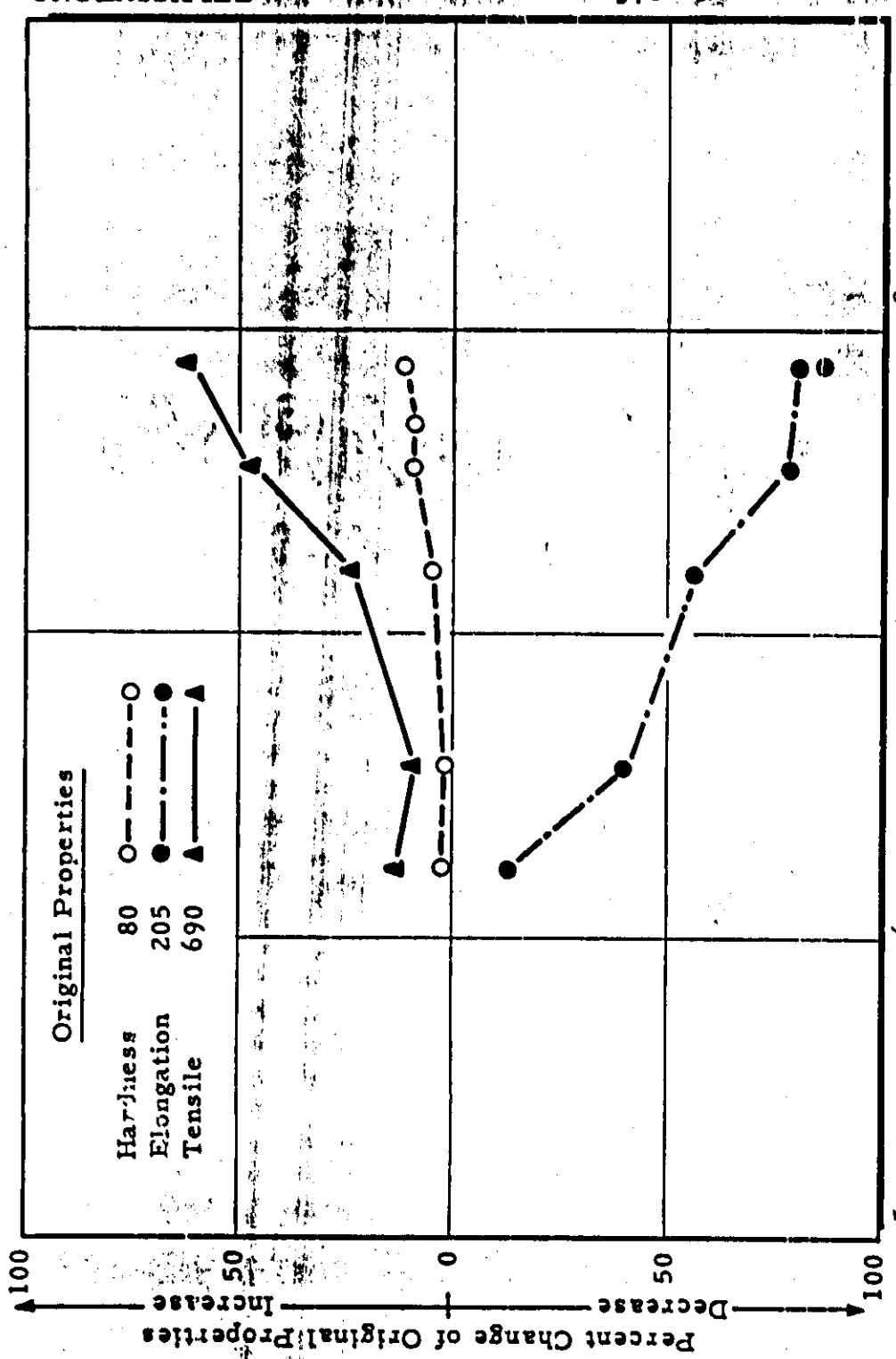

FIGURE 3
CHANGE IN PROPERTIES OF SILASTIC 80 METHYL VINYL SILICONE ELASTOMER INDUCED BY GAMMA RADIATION IN AIR AT 25 C AT NORMAL PRESSURE

AEC-GE RICHLAND, WASH.

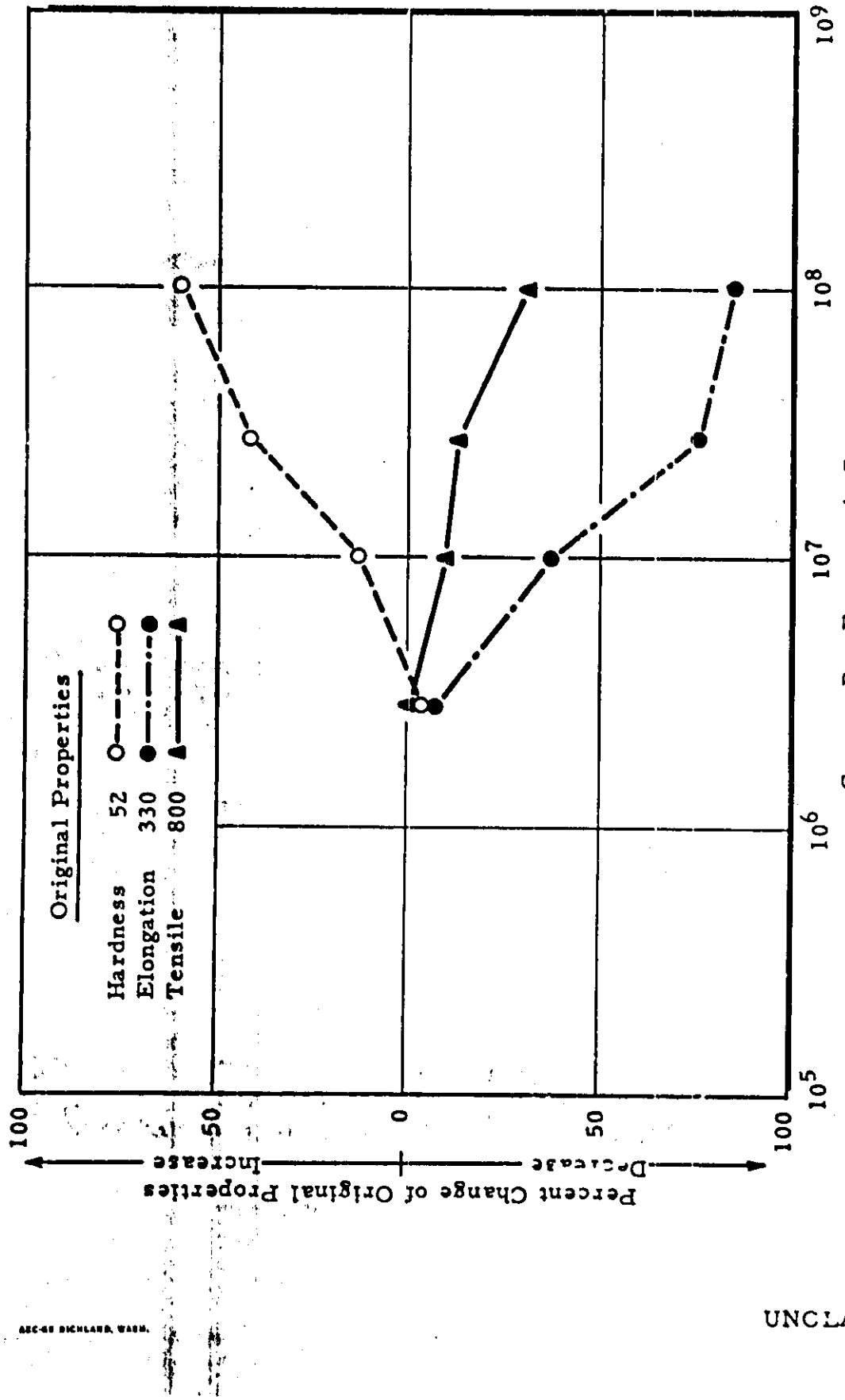

FIGURE 4
CHANGE IN PROPERTIES OF Y-1668 METHYL PHENYL SILICONE ELASTOMER INDUCED BY GAMMA RADIATION IN AIR AT 25 C AT NORMAL PRESSURE

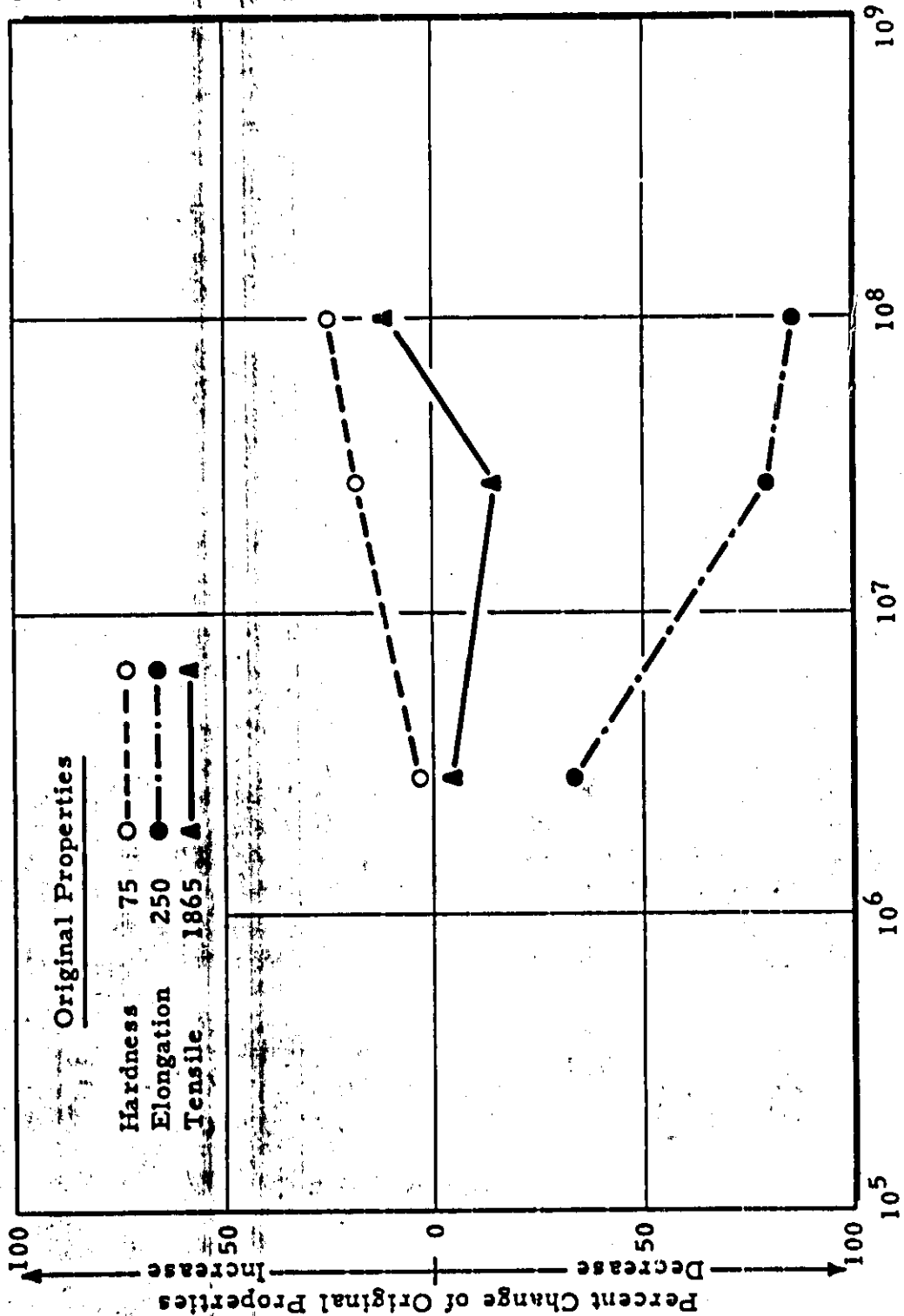

FIGURE 5
CHANGE IN PROPERTIES OF PR 1700-X7 FLUOROELASTOMER
INDUCED BY GAMMA RADIATION IN AIR AT 25 C AT NORMAL PRESSURE

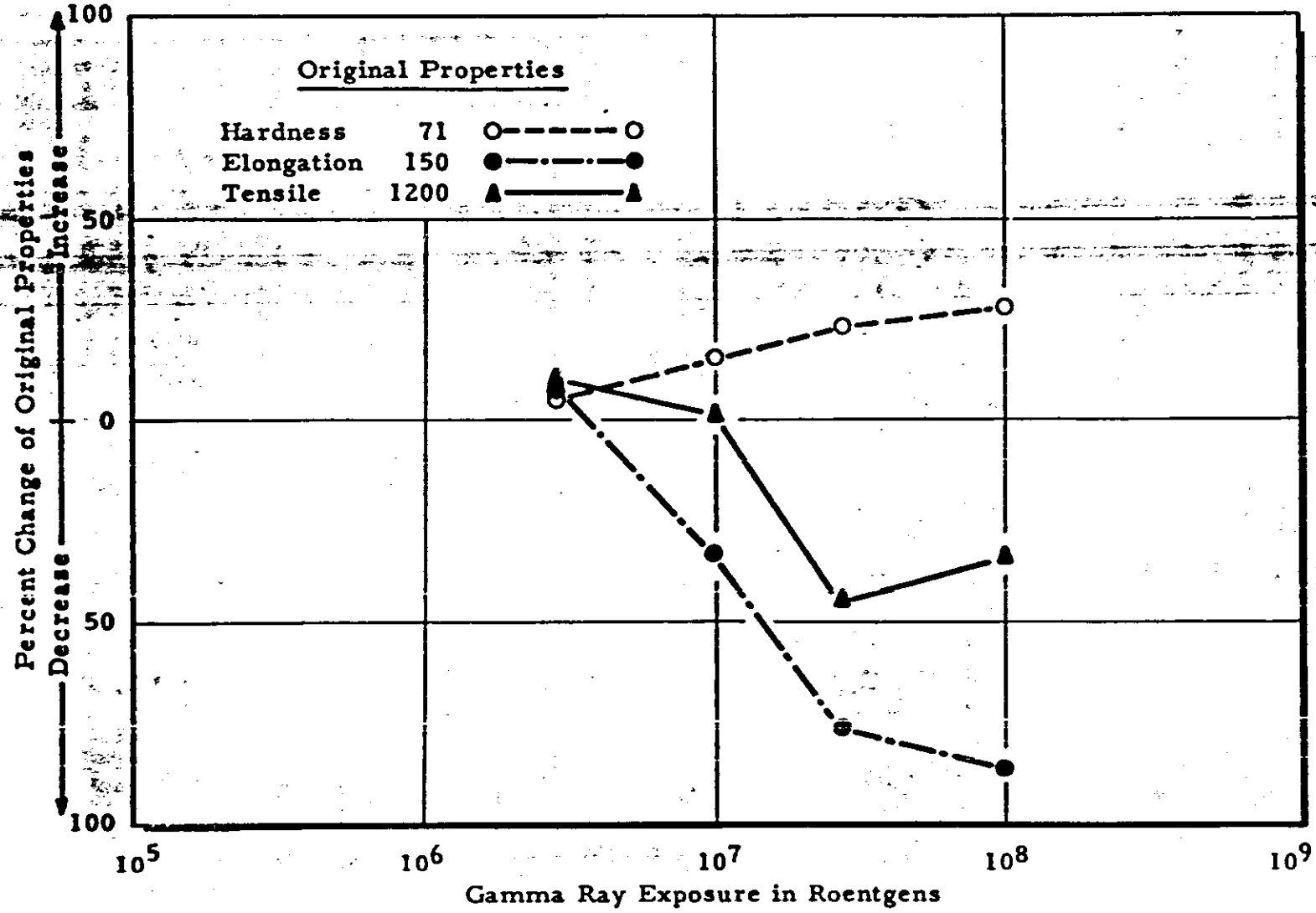

FIGURE 6
CHANGE IN PROPERTIES OF 1F4 FLUOROELASTOMER INDUCED BY GAMMA RADIATION IN AIR AT 25 C AT NORMAL PRESSURE

TABLE 4

GAMMA RADIATION INDUCED PROPERTY CHANGES IN A SERIES OF SILICONE ELASTOMERS WITH VARYING FILLER LOADING AND POST CURES

Materials	Original Properties			Properties After Exposure to 1×10^8 r		
	Hardness Shore A	Tensile psi	Elongation %	Hardness Shore A	Tensile psi	Elongation %
Filler Loading Series						
K-1046R	65	855	290	93	1035	30
K-1047R B-3	76	880	230	96	1155	25
K-1048R	79	875	215	97	1150	25
Post Cure Series						
K-1047R B-4	54	1020	620	94	1085	40
K-1047R B-5	64	965	400	94	980	40
K-1047R B-6	67	940	375	94	1185	40
K-1047R B-2	66	820	285	94	985	55

TABLE 5

GAMMA RADIATION POST CURING OF A SILICONE ELASTOMER

Material	Properties		
	Hardness Shore A	Tensile psi	Elongation %
Original Properties of K-1047R B-2	66	820	285
Properties of K-1047R B-4 After 1×10^7 r	61	1010	390