WADC TECHNICAL REPORT 55-58
PART III
ASTIA DOCUMENT No. AD 130803

A STUDY OF THE EFFECTS OF NUCLEAR RADIATIONS ON ELASTOMERIC COMPOUNDS AND COMPOUNDING MATERIALS

JOHN W. BORN
DWAIN E. DILLER
EUGENE H. ROWE

THE B. F. GOODRICH COMPANY
RESEARCH CENTER

JUNE 1957

Materials Laboratory
Contract No. AF 33(616)-2308
Supplemental Agreement No. S2(56-994)
Project No. 1252

WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Carpenter Litho & Prtg. Co., Springfield, O.
400 — Sept. 1957

FOREWORD

This report was prepared by the B. F. Goodrich Company under Supplemental Agreement S2(56-994) to USAF Contract No. AF33(616)-2308. The contract was initiated under Project No. 1252, "ANPP Development Support Project", Task No. 73023, "Radiation Effects". The work was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Lt. Warren R. Griffin acting as project engineer.

This report covers work conducted from 1 January 1956 to 31 December 1956.

The authors wish to acknowledge the important contributions of other research personnel to the work which is reported here. Mr. A. Hawthorne made the infrared analyses and evaluated the results. Dr. R.G. Bauman provided valuable critical examination of the research and the reports. Mr. J.R. Beatty was of considerable assistance in the interpretation of the dynamic test data of the eight irradiated rubber compounds. The preparation and testing of samples and the preparation of papers and reports involved the capable services of the Department of Technical Services and of the assistants. Their contributions are all highly appreciated.

The authors again wish to thank Mr. O.A. Kuhl of the Fission Products Utilization Project at Brookhaven National Laboratory for his cooperation in the gamma irradiation of samples.

ABSTRACT

The effort to define, understand, and prevent radiation damage to rubber continued during 1956. Research followed four main lines: the development of Anti-Rads to prevent radiation damage; infrared and mass spectral analyses to relate radiation stability to molecular structures of elastomers; stress relaxation studies to define the mechanisms of radiation damage; and measurements of dynamic mechanical properties of representative rubber compounds after irradiation. Emphasis upon applied testing of end-item materials increased.

The best Anti-Rad extended the retention of tensile strength and ultimate elongation by natural rubber tread stock more than tenfold. The screening study is providing criteria for the selection of superior Anti-Rads. A new technique of mass spectral analysis promises to aid greatly in determining what molecular structural features impart radiation stability. Stress relaxation measurements detail the important role of oxygen in radiation damage. Dynamic test data are given for eight representative rubber compounds.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

R. T. Schwartz

R. T. SCHWARTZ, Chief
Organic Materials Branch
Materials Laboratory
Directorate of Research

TABLE OF CONTENTS

Page

I INTRODUCTION 1

II EXPERIMENTATION 2

2.1 The Evaluation of 90 Potential Anti-Rads 2
2.2 Stress Relaxation during Irradiation in Nitrogen 3
2.3 Infrared Analysis of Radiation Damage in Vacuum 4
2.4 Mass Spectral Analysis of Volatile Irradiation Products 4
2.5 Dynamic Testing of Irradiated ASTM Rubber Compounds 5

III DISCUSSION OF RESULTS 6

3.1 The Selection of the 20 Best Anti-Rads 6
3.2 A Comparison of Radiation Damage in Air and in Nitrogen . . . 7
3.3 Results of Infrared Analysis of Radiation Damage in Vacuum . . 9
3.4 Results of the Mass Spectral Analysis of Irradiation Products . 10
3.5 Dynamic Test Results for Irradiated Rubber Compounds 11

IV SUMMARY AND CONCLUSIONS 13

4.1 Summary 13
4.2 Conclusions 14

Bibliography 16

LIST OF TABLES

Table		Page
I	Rubber Compounds for Screening Potential Anti-Rads	17
II	The Effect of Gamma Irradiation on the Physical Properties of the Anti-Rad Screening Compounds	20
III	Efficiency Rating of Anti-Rads Based on Tensile Strength and Ultimate Elongation	30
IV	Efficiency Rating of Anti-Rads Based on 100% Modulus	31
V	The Recipes of the A.S.T.M. Rubber Compounds	32
VI	Comparison of Gaseous Product Yield with Polymer Structure	33
VII	The Change in Yerzley Resilience (Per Cent) with Gamma Irradiation	34
VIII	The Change in Pico Abrasion Index with Gamma Irradiation	35
IX	The Change in Permanent Set with Gamma Irradiation	36
X	The Change in Gehman Freeze Point (°C.) with Gamma Irradiation	37

LIST OF ILLUSTRATIONS

Figure		Page
1	The Effect of Gamma Irradiation on the Continuous Stress Relaxation of Compound 1GFA2	38
2	The Effect of Gamma Irradiation on the Continuous Stress Relaxation of Compound 1GFA3	39
3	The Effect of Gamma Irradiation on the Continuous Stress Relaxation of Compound 1GFA4	40
4	The Effect of Gamma Irradiation on the Continuous Stress Relaxation of Compound 1GFA5	41
5	The Effect of Gamma Irradiation on the Continuous Stress Relaxation of Compound 1GFA6	42
6	The Effect of Gamma Irradiation on the Continuous Stress Relaxation of Compound 1GFA7	43
7	The Effect of Gamma Irradiation on the Continuous Stress Relaxation of Compound 1GFA8	44
8	The Effect of Gamma Irradiation on the Continuous Stress Relaxation of Compound 1GFA9	45
9	The Effect of Gamma Irradiation on the Continuous Stress Relaxation of Compound 1GFA10	46
10	The Effect of Gamma Irradiation on the Continuous Stress Relaxation of Compound 1GFA11	47

I. INTRODUCTION

The basic purpose of this research is to learn what constitutes radiation damage to rubber in a structural sense and to inhibit or prevent such damage. The former problem is a part of the general problem in rubber research of correlating physical properties with molecular structure. The latter problem has two approaches to solutions: namely, the development of radiation-resistant elastomers and the discovery and development of rubber chemicals to inhibit radiation damage.

It is apparent that a fundamental understanding of the molecular changes produced by nuclear irradiation should precede an attempt to synthesize a radiation-resistant polymer. The studies involving the infrared spectrophotometer and the mass spectrometer were designed to reveal radiation-induced structural changes. Past studies showed the need for irradiating simpler sample systems. This year pure polymers with particular structures were used. Mass spectral analysis of volatile irradiation products was expected to give information about chain scission, removal of short branches or side groups, and crosslinking induced by irradiation. It also provided a means of revealing whether the mode of radiation damage is the same for different kinds of radiation such as ultraviolet rays, Cobalt 60 gamma rays, and accelerated electron radiation. Infrared analysis of the solid residue from these pure polymers after irradiation can complement the mass spectral analyses by detailing the degree of unsaturation and the ratio of methyl groups to methylene groups, providing additional information about changes in structure.

Previous studies have shown that oxidation or ozonization or both, accelerated by irradiation, contribute significantly to the radiation damage of rubber samples. Measurements of changes in equilibrium modulus during irradiation in air and in the absence of air were designed to observe the effects of oxygen and ozone.

The screening of 90 potential Anti-Rads (radiation damage inhibitors for rubber) according to effectiveness to provide criteria for the synthesis of specific new Anti-Rads was completed during this period. The physical testing and evaluation of data completed the screening study, which was begun during 1955 and carried through the compounding and irradiation stages as described in WADC Technical Report 55-58, Part II (1). The Anti-Rad development represents our most important approach so far to inhibiting radiation damage in rubber compounds.

During the initial phase of the study of radiation damage to rubber the emphasis was on the measurement of tensile strength, ultimate elongation, and 100 per cent modulus as a function of increasing radiation exposure (2). These measurements permitted a survey of the effects of radiation on a wide variety and large

"Manuscript released by author 10 December 1956 for publication as a WADC Technical Report."

number of rubber compounds. A need then arose for information about how radiation affects the dynamic mechanical properties of rubber. The selection of the standard ASTM rubber compounds (3), their optimum cure, and their gamma irradiation with the exposures ranging from 0.1 through 100 megareps were described in the 1955 Technical Report WADC TR 55-58 Part II (1). The physical testing of the resulting irradiated samples took place during 1956. Most of the tabulation of the results has been completed, and the evaluation of four physical properties is reported.

II. EXPERIMENTATION

2.1 The Evaluation of 90 Potential Anti-Rads

The selection of the 90 potential Anti-Rads, their compounding into a standard natural rubber tire tread stock recipe, and their gamma irradiation took place during 1955 (1). The Anti-Rads were selected to include the molecular main structures and reactive side groups considered most effective in inhibiting radiation damage. The resulting 91 natural rubber compounds, including the control compound, received optimum cures. Since each Anti-Rad was incorporated in the same amount into the same master rubber recipe, any difference in resistance would be due to a difference in the original state of cure or to the protective ability of the Anti-Rad in question.

A rating of the Anti-Rads according to their effectiveness was expected to reveal what main chemical structures, what reactive side groups, and what combinations of the two give the most protection during irradiation. Tensile strength, ultimate elongation, and 100 per cent modulus were the measurements which were used in the evaluation. The samples were 0.25 of an inch wide, 2.75 inches long, and nominally 0.020 of an inch thick. The first group of Cobalt 60 gamma radiation exposures ranged from 0.1 through 100 megaroentgens-equivalent-physical (megareps), and exposures of 500 and 1000 megareps have recently been completed. The tests which are reported here were made after the former series of irradiations. All samples were wrapped in aluminum foil during irradiation to prevent cross-contamination.

The following master recipe, which is an ASTM standard natural rubber tire tread stock (3), was used throughout the screening study:

Pigment	Parts by Weight
Natural Rubber (Hevea)	100
Stearic Acid	3
Zinc Oxide	5
Sulfur	3
Benzothiazyl Disulfide	1
Phenyl-Beta-Naphthylamine	1
EPC Black	50
Potential Anti-Rad	5

The Anti-Rads which were included are given in Table I. They consist of three groups: general rubber chemicals (in Compounds 1GFA 13-47, inclusive), chemicals prepared at the B. F. Goodrich Company Research Center for other earlier studies (in Compounds 1GFA 50-75, inclusive), and commercial chemicals not generally considered to be rubber chemicals (in Compounds 1GFA 77-113, inclusive). The various chemicals, principally aromatic, represent eight classes: amines; diamines; quinolines; dihydroquinolines; quinones; hydroquinones; homocyclic and heterocyclic resonant compounds; and monohydroxy -, polyhydroxy -, and bis-phenols. The chief reactive side groups are mercapto (SH), hydroxy (OH), methoxy (OCH_3), sulfonyl (SO_2), and amino (NH_2) groups.

The complete data appear in Table II, which lists the 91 rubber compounds and details the effect of Cobalt 60 gamma irradiation in air on tensile strength (psi), ultimate elongation (per cent), and 100 per cent modulus (psi). Table III rates the 20 best Anti-Rads on the basis of retention of the original tensile strength and elongation during irradiation. Table IV rates the 20 best on the basis of retention of original modulus.

2.2 Stress Relaxation during Irradiation in Nitrogen

Measurements of stress relaxation of the ten rubber compounds described in Table V, Compounds 1GFA 2-11, inclusive, were made during irradiation in lamp-grade nitrogen. The purpose was to gain a better understanding of the role which oxygen and the ozone formed from it by irradiation play in causing rubber deterioration. Ozone causes greater deterioration in rubber under stress than in rubber which is in the relaxed state. Therefore, the stress relaxation studies would detail ozonization effects in rubber which would not be revealed by stress-strain measurements of rubber samples after irradiation in a relaxed state. Earlier measurements had been made during irradiation in air, permitting a comparison of effects. The same technique and equipment were used in both cases. A description of the procedure and the equipment appears in WADC Technical Report 55-58 Part II (1). Briefly, small rectangular thin strips of the rubber compounds are held at an elongation of 80 per cent and irradiated in Cobalt 60 Source Number Co-17. Either the atmosphere surrounding the samples or the temperature or both can be varied. The present study was made at room temperature. Concurrent measurements were made of duplicate sets of samples at 80% elongation. One set underwent irradiation in nitrogen. The control set was stored in nitrogen for equivalent periods of time. Each set of measurements required less than an hour for the 48 samples involved. The samples were in air during this time. After they were returned to the sample canister each time, the canister was flushed with nitrogen for one hour before irradiation resumed. This procedure removed the oxygen and ozone from the canister and the samples. The total stress relaxation time for both sets of samples was 768 hours, or 32.0 days. The total radiation exposure for the one set of samples was 1.18×10^8 reps, although many samples broke before the exposure reached this value.

Figures 1 through 10 present graphically the results of the study and permit a comparison with the study in air. All the curves for a given compound appear on the same graph. Each graph shows the continuous stress relaxation of a given compound in nitrogen and in air both with and without irradiation. Apart from the atmosphere, the measurements in air and in nitrogen were carried out under the same conditions.

2.3 Infrared Analysis of Radiation Damage in Vacuum

Analysis of thin cured rubber films by infrared absorption with a spectrophotometer reveals certain chemical changes which are induced by irradiation. Studies of this type havealready been made by irradiation with X-rays in lamp - grade nitrogen and with Cobalt 60 gamma rays in air. The present study involved gamma irradiation of similar cured rubber films sealed in a vacuum. Compounds 1GFA 2 through 11 were used (see Table V). Films having a nominal one *mil* thickness were pressed and cured and then mounted on one - inch diameter aluminum rings. This sample system permitted the gamma irradiation and infrared analysis of the sampleswithout disturbing them. During the course of irradiation the samples were removed periodically from the evacuated cylinder, analyzed, and resealed inside an evacuated glass cylinder for continued radiation exposure. The tube and contents were evacuated for a least two hours at a pressure of 5×10^{-7} mm. Hg or less before the container was resealed. Prior research indicates that this gives satisfactory evacuation. Analyses were made after radiation exposures of 0.1, 1, 5, 10, 35, 70, and 100 megareps.

2.4 Mass Spectral Analysis of Volatile Irradiation Products

The studies of radiation effects with the mass spectrometer under this contract have involved vulcanized rubber compounds until this year. The results of the past studies strongly indicated the advisability of using pure organic high polymers of known structure in our radiation research. That is, it became necessary to make the study more fundamental. A research program was begun with the goal of discovering what structural characteristics of polymers influence the formation of gaseous products during irradiation. One important question to be answered was whether the products result from the removal of side groups from the main chain or from scission of the main chain itself. The information gained from answering the latter question is to be applied to studies of polymeric systems of practical interest.

In order to learn what structural characteristics influence radiation damage to high polymers, various polymers of high purity were obtained with known side groups. It is essential to know the side groups, to have a pure polymer, and to have a sample from which the volatile irradiation products can escape. The evolved gases were studied qualitatively and quantitatively as a function of radiation dose and energy to determine whether they were formed from side groups. If the types of gases are independent of radiation dosage, it might be possible to reduce dose time. Also, it might be feasible to use ultraviolet in place of gamma rays to facilitate irradiation. Careful comparisons of the radiation products resulting from the two types of radiation were planned to assure that they give the same products.

The pure polymeric samples were obtained in the form of powders or of thin sheets. The samples were put in quartz tubes and were heated with an infrared lamp and evacuated to a pressure of 10^{-6} mm. Hg. This preliminary outgassing is necessary to minimize the desorption of background gases from the polymer and the vessel walls during ultraviolet irradiation. Water, hexane, and hydrogen are desorbed from an empty tube during the heating. The liberation of background gases can also be reduced by keeping most of the sample system covered with aluminum foil during irradiation. The ultraviolet irradiation was carried out with a General Electric UA-14 mecury vapor lamp having a spectrum ranging from 2537Å to 5780Å, operating at 1400 watts. The volatile products of irradiation were collected and transferred to the mass spectrometer sample system. Analysis for hydrogen and methane was made of the fraction of the sample which was volatile at -196°C. The sample which was volatile at room temperature was analyzed for saturated and unsaturated short chain hydrocarbons, carbon monoxide, carbon dioxide, and water. The analyses were both quantitative and qualitative and were designed to identify short chain branches and side groups in polymers. The ultimate aim is to learn what structural changes are caused in polymers by irradiation and to correlate them with changes in physical properties.

2.5 Dynamic Testing of Irradiated ASTM Rubber Compounds

With the available facilities for irradiation and testing it was not feasible either to test rubber end items or to study all the many special industrial rubber compounds. Instead, four representative gum compounds and four carbon black-reinforced compounds based on natural rubber, GR-S, Neoprene GN, and Hycar 1002 were used. The recipes appear in Table V. Samples of these compounds were given optimum cures and received Cobalt 60 gamma ray exposures of 0.1, 1.0, 10, 35, 70, and 100 megareps at Brookhaven Nation Laboratory, ending in December, 1955. Exposures of 500 and 1000 megareps were completed in October, 1956.

Nine tests were selected to produce thirteen physical property values for each rubber compound at each radiation dose. The tests comprise measurements with the Electrographic Stress-Strain Machine, the 100 per cent modulus machine, the Yerzley Oscillograph, the Goodrich Flexometer, the Gehman low temperature modulus machine, the Pico abrader, the Shore A Durometer, the compression set apparatus, and the Beatty belt flex tester. The thirteen physical properties which have been measured as a function of irradiation include tensile strength, ultimate elongation, and 100 per cent modulus for comparison with previous studies and static modulus, dynamic modulus, the load required to produce a 20 per cent deformation, dynamic resilience, low temperature modulus, brittle point, abrasion resistance, hardness, compression set, and belt flex resistance. Although none of these tests corresponds exactly to actual service testing, they provide qualitative data which reveal the changes in the mechanical properties with irradiation.

III. DISCUSSION OF RESULTS

3.1 The Selection of the 20 Best Anti-Rads

The data in Table II reveal two interesting facts. First, Anti-Rads are much more effective in preventing decreases in tensile strength and ultimate elongation than increases in 100 per cent modulus. Second, on the basis of their effectiveness in preventing changes in tensile strength and ultimate elongation with irradiation, the 90 Anti-Rads fall generally into distinct chemical classes. In order of deceasing effectiveness the classes are aromatic diamines, amines, quinones, hydroquinones, phenols and naphthols, and the unsubstituted homocyclic and heterocyclic aromatic compounds.

However, the ratings by class are not entirely clearcut and exclusive. Because of the range in effectiveness within a given class, there is overlapping of ratings of the classes. The number and identity of the substituent groups modify the effectiveness of the main molecule in preventing radiation damage and affect the spread in the class ratings. For example in Table II unsubstituted p-phenylenediamine ranks 87 as compared with 1 for N, N'-cyclohexylphenyl-p-phenylenediamine, 11 for N, N'-dioctyl-p-phenylenediamine, 12 for N, N'-dicyclohexyl-p-phenylenediamine, 42 for N, N'-diphenyl-p-phenylenediamine, and 63 for N, N'-di-secondary butyl-p-phenylenediamine. The rating for the control natural ber tread stock without added Anti-Rad is 89.

The physical test data which appear in Table II permit a correlation of the molecular structures of the 90 Anti-Rads with their abilities to inhibit radiation damage. This correlation is now in progress. The goal is to obtain criteria for the synthesis of improved, specific Anti-Rads. However, the correlation is not so simple as it might seem at first. The effectiveness of antioxidants depends upon solubility and migration rate in the rubber and upon volatility in addition to their chemical reactivity. It is likely that factors such as these play a part in the effectiveness of Anti-Rads and should be considered in any evaluation.

Table III shows the degree of protection afforded by the 20 best Anti-Rads. The data are included for the control stock, Compound 1GFA7, for comparison. The compound containing the best Anti-Rad, Compound 1GFA26, retained 99 per cent of its initial tensile strength and 88 per cent of its initial ultimate elongation after a Cobalt 60 gamma radiation dose of 100 megareps. In comparison, the control stock retained 36 per cent and 18 per cent, respectively, after the same exposure. Compound 1GFA 83 containing the Anti-Rad ranking twentieth retained 80 per cent and 58 per cent, respectively, after the same exposure. The addition of the 5 pphr of the best Anti-Rad extends the period of retention of tensile strength and ultimate elongation more than 10 times. That is, Compound 1GFA26 retained a larger per cent of its initial tensile strength (99 per cent) and ultimate elongation (88 per cent) after 100 megareps' exposure than did the control Compound 1GFA7 and 10 megareps' exposure (94 per cent and 85 per cent, respectively).

3.2 A Comparison of Radiation Damage in Air and in Nitrogen

The majority of our physical tests of irradiated samples measure the effect of net crosslinking. The effects of the chain scission which is induced are masked. It is important to evaluate the effect of chain scission because certain applications of rubber components involve continuous stretching. Also, a resolution of radiation damage into the components of chain scission and crosslinking as competing processes leads to a better understanding of the damage in terms of changes in molecular structure and is a step toward the synthesis of radiation-resistant elastomers.

An understanding of the extent to which oxygen (or air) accelerates chain scission is important and will aid in the development of Anti-Rads. It will indicate in terms of chain scission and equilibrium modulus the decrease in radiation damage which results from the prevention of oxidation and ozonization.

In the light of these statements let us consider Figures 1 through 10, which detail the continuous stress relaxation of gum rubber and carbon black-reinforced rubber compounds of natural rubber, GR-S, Neoprene GN , Hycar 1002, and butyl rubber with and without irradiation in air and in nitrogen atmospheres. The stress relaxation values are expressed relative to the initial stress. In this respect the ordinate values could be interpreted as equilibrium moduli, and the curves would represent changes in equilibrium modulus.

From Figure 1 it is seen that in the absence of oxygen chain scission proceeded very slowly in cured gum natural rubber. The relative stress was 0.96 after 600 hours. Irradiation markedly accelerated the chain scission, giving a relative stress of 0.36 after 600 hours' relaxation and an exposure of 9.7 x 10^7 reps. In comparison, the relative stress in air was 0.75 after 600 hours' relaxation. Irradiation in air for 400 hours, equaling 7.1 x 10^7 reps' exposure, gave a relative stress of 0.13, after which the six samples broke. The rate of relaxation increased in the order (1) in nitrogen without irradiation, (2) in air without irradiation, (3) in nitrogen with irradiation, and (4) in air with irradiation. During the first 125 hours of irradiation the rate of relaxation was the same in air and in nitrogen.

Figure 2 shows the corresponding changes for a cured GR-S gum rubber compound. The rate of relaxation increased in the order (1) in nitrogen without irradiation, (2) in nitrogen with irradiation, (3) in air without irradiation, and (4) in air with irradiation. The samples which were tested in air without irradiation all broke at less than 100 hours' relaxation. The curves for relaxation in air with and without irradiation nearly coincided during the first sixty hours. The samples which were irradiated in air relaxed for 600 hours, undergoing an exposure of 1.1 x 10^8 reps, without breaking. After 380 hours' relaxation, the relative stresses were (1) 0.93 in nitrogen, (2) 0.65 in nitrogen after an exposure of 6.1 x 10^7 reps, and (3) 0.26 in air after an exposure of 6.7 x 10^7 reps.

The cured Neoprene GN gum rubber was unique among the gum rubber compounds, as shown in Figure 3. The samples which were irradiated in air at first showed rapid stress relaxation. The relative stress passed through a minimum of 0.13 at 300 hours' relaxation, representing an exposure of 5.3 x 10^7 reps, and then increased to 0.18 at 600 hours' relaxation and 1.1 x 10^8 reps' exposure. The samples which were irradiated in nitrogen appeared to approach a minimum at 450 hours' relaxation and 7.34 x 10^7 reps' exposure. After 400 hours' relaxation the relative stresses were (1) 0.87 in nitrogen, (2) 0.59 in nitrogen after 6.4 x 10^7 reps' exposure, (3) 0.41 air, and (4) 0.13 in air after 7.1 x 10^7 reps' exposure.

Figure 4 gives the results for a cured Hycar 1002 gum rubber. Three of the six control samples broke in nitrogen before the first stress relaxation measurement could be made. All six samples broke during irradiation before the first measurement of relaxation could be made. The samples which were tested in air broke with and without irradiation before a measurement was possible.

Because of the rapid degradation of butyl rubber by nuclear radiation, no measurements were made in air. The data obtained during continuous stress relaxation in nitrogen are given in Figure 5 for cured gum butyl rubber. The relative stress decreased to 0.15 after only 50 hours' relaxation and an 8.0 x 10^6 rep exposure in nitrogen. The relative stress of the control sample was 0.98 after 50 hours' relaxation in nitrogen.

Figure 6 illustrates the continuous stress relaxation of a cured carbon black-reinforced natural rubber. After 600 hours' relaxation the relative stresses were (1) 0.86 in nitrogen, (2) 0.61 in air, (3) 0.37 in nitrogen after 9.7 x 10^7 reps' exposure, and (4) 0.09 in air after 1.1 x 10^8 reps' exposure.

For the cured carbon black-reinforced GR-S rubber the results appear in Figure 7. After 600 hours' relaxation the relative stresses were (1) 0.93 in nitrogen, (2) 0.55 in nitrogen after 9.7 x 10^7 reps' exposure, (3) 0.54 in air, and (4) 0.27 after 1.1 x 10^8 reps' exposure in air.

In Figure 8 the data are given for a cured carbon black-reinforced Neoprene GN rubber. After 500 hours' relaxation the relative stresses were (1) 0.85 in nitrogen, (2) 0.69 in nitrogen after 8.0 x 10^7 reps' exposure, (3) 0.46 in air, and (4) 0.17 in air after 8.8 x 10^7 reps' exposure.

In Figure 9 the data appear for a cured carbon black reinforced Hycar 1002 rubber. After 500 hours' relaxation the relative stresses were (1) 0.91 in nitrogen, (2) 0.54 in air, (3) 0.52 in nitrogen after 8.0 x 10^7 reps' exposure, and (4) 0.20 in air after 8.9 x 10^7 reps' exposure.

As in the case of gum butyl rubber no measurements were made of carbon black-reinforced butyl rubber in air because of the rapid degradation produced by irradiation. As shown in Figure 10 the relative stress decreased to 0.12 after 50 hours' relaxation and 8.0 x 10^6 reps' exposure in nitrogen. In comparison the corresponding value without irradiation was 0.97.

An evaluation of all the stress relaxation data which have been obtained to date is now in progress in an attempt to determine the mechanism of the degradation reaction for each compound. Until this evaluation is completed, any discussion of results is accordingly restricted. In general the relative stress relaxation curves are also relative equilibrium modulus curves which show the effect of radiation to be expected on rubber products which undergo small continuous expansion or elongation. Also, each graph shows what decrease in radiation damage by chain scission can be effected by preventing oxidation of the rubber. The various curves permit a comparison of the rates and extents of chain scission or of decreases in equilibrium modulus which are induced by irradiation. The order of increasing rate of relaxation for the gum rubber compounds is GR-S, natural rubber, Neoprene GN, and butyl rubber during irradiation in air. For carbon black-reinforced rubber compounds during irradiation in air, the order of increasing rate of relaxation is GR-S, Hycar 1002, natural rubber, Neoprene GN, and butyl rubber. In the case of both gum rubber and carbon black-reinforced rubber compounds of Neoprene GN, irradiation in air produces such a high density of crosslinks that eventually the relative stress no longer decreases but instead begins to increase with irradiation. The relative stress of carbon black-reinforced Hycar 1002 rubber appears to be approaching a minimum, indicating a high rate of crosslinking, in the same manner as but at a slower rate than Neoprene GN. In general the carbon black-reinforced compounds have a lower rate of continuous stress relaxation than do the gum rubber compounds. The butyl rubber compounds are in exception; carbon black has no significant effect upon their relaxation rate. Also, with the exception of butyl rubber compounds, the prevention of oxidation during irradiation would markedly decrease the radiation damage in rubber compounds under elongation.

3.3 Results of Infrared Analysis of Radiation Damage in Vacuum

Under ideal conditions infrared analysis of gum rubber samples after irradiation in vacuum could detail (1) crosslinking by showing decreases in the concentration of hydrogen atoms and secondary carbon atoms and an increase in the number of tertiary carbon atoms, (2) chain scission by showing an increase in the ratio of methyl groups to methylene groups, and (3) oxidation and ozonization by showing an increase in the concentration of hydroxyl, carbonyl, and carboxyl groups and ether-type linkages. Infrared analyses of rubber samples which were irradiated in air were reported in Technical Report WADC TR 55-58 Part II (1). Oxidation effects predominated and obscured the other radiation-induced changes in molecular structure. Therefore, the present study was undertaken in an effort to avoid oxidation effects and so reveal other significant structural changes. Efforts would then be made to correlate changes in molecular structure with changes in physical properties.

With the exception of Neoprene GN, all the thin cured gum rubber films showed the same changes in infrared spectra after receiving identical radiation exposures ranging from 0.1 through 10 megareps. Specifically, the gum rubber compounds of natural rubber, GR-S, Hycar 1002, and butyl rubber underwent an apparent decrease in mass during the initial radiation exposure of 0.1 megareps. However, aside from a general decrease in infrared absorption, there were no changes in the infrared spectra. During the increment in exposure between 10 and 30 megareps, the butyl film failed completely and was reduced to a grease on the edges of the ring holder. The first observable changes in the spectra of natural rubber, GR-S, and Hycar 1002 gum rubber films also occurred in the latter exposure range. The natural rubber film showed increased absorption in the 2.7 to 3.2 and 8.5 to 10.1 micron ranges, indicating the formation of acidic hydroxyl groups. Thereafter, no change occurred in the spectrum with increasing exposure through 100 megareps. For the GR-S film infrared absorption increased in the 2.7 to 3.2, 5.7, and 8.5 to 10.1 micron regions of the spectrum, indicating the formation of hydroxyl and carbonyl groups which are characteristic of carboxyl (acid) groups. No subsequent change occurred in the spectrum as the irradiation continued through 100 megareps. Hycar 1002 gum rubber showed increased absorption in the 2.7 to 3.2 and 5.6 to 6.1 micron ranges, indicating increasing concentrations of hydroxyl and carbonyl groups characteristic of carboxyl groups. Continuing irradiation through 100 megareps caused slight continuing oxidation of the same type.

The Neoprene GN gum rubber films underwent unique changes in their infrared spectra. Before irradiation the control sample showed extreme infrared absorption due to hydroxyl groups, but no carbonyl absorption was apparent. From the beginning of the irradiation extreme general oxidation proceeded.

In general, then, oxidation was the only effect revealed by infrared analysis, and it is possible that the oxidation peaks obscured evidence of other structural changes. With the exception of Neoprene GN and butyl rubber compounds there was much less oxidation than that which occurred during irradiation in air. The occurrence of oxidation in samples which were irradiated in vacuum may be explained by the formation of free radicals in the rubber during irradiation and by oxidation after the samples were removed from the vacuum and before they could be stored in nitrogen. The much greater degree of oxidation of Neoprene GN could be explained by a greater ease of formation of free radicals during irradiation.

3.4 Results of the Mass Spectral Analysis of Irradiation Products

The technique described above has proved successful in determining the origin of the volatile irradiation products from pure high polymers. The predominant gaseous product of Cobalt 60 gamma irradiation other than hydrogen was consistently that molecule corresponding to the side group of the main polymer chain, such as benzene from polystyrene, hydrogen chloride from polyvinyl chloride, and methane from polyisoprene (natural rubber). Polyisobutylene, which is unique in that the net effect of irradiation is degradation to a grease, gives both methane and isobutylene, the monomer, as principal products in the approximate ratio of 2.5 to 1, respectively. These results support the hypothesis that permanent cleavage of C-C bonds occurs much more readily at a tertiary carbon atom (that is, at a branch or side group) than at a secondary carbon atom(that is, along an unbranched segment of the main chain). Table VI presents the results graphically. The irradiation of polyvinyl chloride evolves a small amount of benzene in contrast to the large amount evolved by thermal degradation. This indicates that chain scission is less important in radiation degradation than in thermal degradation. Polyisobutylene is the only polymer in the series studied which yields monomer in appreciable quantity when irradiated. It has been postulated that the presence of many methyl groups lowers flexibility of the chain and so reduces the ease of recombination.

In the above studies Cobalt 60 gamma radiation was used. The use of ultraviolet radiation proved to be less satisfactory under the described conditions. The products of ultraviolet irradiation were qualitatively the same as those of gamma irradiation but were quantitatively different. The relative yield of the products from the ultraviolet irradiation differed from that obtained from the gamma irradiations. The predominant gas evolved by ultraviolet irradiation does not correspond directly to the branch structure. Nevertheless, there is some correlation between the structure of the gaseous products and the branch length. The highest molecular weight product corresponds to the predominant branch length. It is possible that the gaseous products of ultraviolet irradiation are themselves further dissociated, since the energy absorption is much more efficient in the 5 ev than in the 1 mev range. The fact that the nature and amount of the other gaseous products is such that they could well have been formed by dissociation of the product with the highest molecular weight supports this hypothesis. Unless this complication can be overcome by more efficient and rapid trapping of the gaseous products after they are formed, ultraviolet irradiation will be regarded as less useful than gamma irradiation as a tool for measuring branch length.

In addition to branch length, branch density can be determined by the same technique of irradiation and mass spectral analysis. Branch density is the number of branches in a unit volume of polymer. In a series of polymers which have only methyl and hydrogen substituents along the chain, the methyl branch density is nearly proportional to the CH_3/CH_2 ratio. An experimental parameter which should be closely related to this ratio is the CH_4/H_2 ratio. There is a good correlation between the measured yield ratios of methane to hydrogen and the ratios of methyl to methylene groups which are derived from the polymer structures. Yet a one to one relationship between the measured and derived ratios does not exist. There are several reasons for this apparent lack of simplicity. The yield of a gaseous irradiation product depends implicitly on the diffusion rate of the gas out of the polymer. The diffusion rates of methane and hydrogen vary considerably in polymers. The gas yield also depends on the probability of dissociating a particular branch or side group. In spite of these difficulties accurate measurements of branch density have been made. Investigation of the effect of environment on the dissociation-recombination probability is desirable in order to learn why certain configurations of atoms are more stable under irradiation than are others. Such knowledge could prove helpful in synthesizing new polymers, both plastics and elastomers, with superior heat and radiation resistance.

3.5 Dynamic Test Results for Irradiated Rubber Compounds

At present the results of four dynamic tests have been evaluated for the eight standard ASTM rubber compounds. The tests are (1) Yerzley resilience, which is closely related to hysteresis, (2) abrasion loss, (3) permanent set, and (4) Gehman freeze point.

As shown in Table VII, gum stocks and carbon black-reinforced stocks of natural rubber and Neoprene GN showed no significant change in Yerzley resilience with irradiation. The capital letters denote the radiation exposures at which rubber samples became too hard to test. Each value represents the average for four samples. Natural rubber compounds showed a 2 per cent increase. Neoprene GN compounds showed a 1 to 2 per cent decrease. Both GR-S and Hycar 1002 gum rubber and carbon black-reinforced rubber compounds showed marked increases in resilience with radiation. The increases were 52 per cent for GR-S gum stock, 38 per cent for GR-S black stock, 25 per cent for Hycar 1002 gum stock, and 23 per cent for Hycar 1002 black stock.

The same pairing of elastomers occurred in the measurement of abrasion as shown in Table VIII. Natural rubber and Neoprene GN gum stocks each underwent an 89 per cent increase in abrasion loss. Natural rubber-black stock exhibited a 29 per cent increase in abrasion loss as compared with a 45 per cent increase for Neoprene GN-black stock. The increase in abrasion loss was almost identical for GR-S (78 per cent) and Hycar 1002 (74 per cent) gum stocks. The carbon black-reinforced stocks of these two elastomers were remarkable in that they both showed a decrease in abrasion loss: a 28 per cent decrease for GR-S and an 88 per cent decrease for Hycar 1002. This means that the abrasion resistance of black-reinforced rubber compounds of GR-S and Hycar 1002 actually improves with irradiation through a dose of 100 megareps.

In the change in permanent set with irradiation which is detailed in Table IX, natural rubber was far superior to the other three elastomers. Both its gum and black-reinforced compounds had relatively low initial permanent set (that is, before irradiation), and relatively little change occurred as a result of irradiation. The gum and black-reinforced stocks of GR-S, Neoprene GN, and Hycar 1002 all showed marked decreases in permanent set as a result of irradiation.

All the gum and black-reinforced rubber compounds showed small and approximately equal increases in the Gehman freeze point, ranging from 4° to 12°C., as Table X illustrates.

It is interesting to examine the practical significance of these four sets of data. Perhaps the most critical rubber components of a nuclear powered aircraft are its tires because of the effects of heat and radiation during flight and the physical punishment received during a landing. Considering the rubber alone in the tire for the moment and quickly admitting that laboratory tests do not duplicate actual tests of end components, we can make several broad statements. Because of its excellent retention of Yerzley resilience and hence hysteresis properties with irradiation along with its resistance to change in permanent set during flexing, natural rubber-black stock is the logical choice for the airplane tire carcass. The good all-round resistance of natural rubber to radiation damage is also in its favor. The moderate increase in the abrasion resistance of the GR-S-black stock, along with its improvement in Yerzley resilience and its good permanent set properties, make it a good choice for the tire tread. On the basis of studies independent of this contract by Mr. D. J. Harmon of the B. F. Goodrich Company Research Center, either Celanese X-36 or Dacron tire cords would prove the most satisfactory of the available organic cords in this tire. As to the retention of air by the tire, the most satisfactory construction would appear to be a tubeless tire with a special liner designed to maintain approximately its original viscosity during irradiation. Possibly a butyl-Hycar rubber blend would be satisfactory. It appears likely that such an airplane tire would survive at least one landing after receiving a radiation dose of 100 megareps at about 25°C., particularly if the rubber compounds and tire cord were protected from radiation damage by the addition of Anti-Rads.

These conclusions emphasize the fact that a transition from our basic investigations of the nature of radiation damage and how to prevent it in rubber compounds to applied studies directed toward the fabrication of radiation - resistant rubber end items has begun. Eight aircraft tires, size 26x6.6, 14PR, are being manufactured by the B. F. Goodrich Company for radiation testing at the Materials Laboratory of Wright Air Development Center. Four are standard tubeless tires which will serve as controls, and the other four are standard tubeless tires which have been modified by the incorporation of 5 pphr of the most effective Anti-Rad into the principal rubber compounds. The tires will be mounted on wheels, given a Cobalt 60 gamma ray exposure of 100 megareps, and tested to failure on conventional tire-testing equipment. The tires will be tested in tandem: two without irradiation and two after irradiation in both cases. The information which is obtained from the tests will be used to guide further development of radiation-resistant tires. The bottle-necks in this development-testing program will be the availability of suitable irradiation space and the time required for the tires to receive the high radiation doses. Also, a transition is being made toward the radiation testing and development of other rubber aircraft components such as hose, gaskets, fuel cells, and seals. Samples of the rubber compounds which are used in these components have been given a series of radiation doses and are ready for testing. Corresponding compounds containing Anti-Rads have undergone the same irradiations and are likewise ready for testing. The program for next year calls for an expansion of applied studies and includes testing of irradiated samples in service environments.

IV. SUMMARY AND CONCLUSIONS

4.1 Summary

4.1.1 This Technical Report is the third of the series. It marks a transition from predominantly basic research toward a much greater emphasis on applied studies of radiation damage and service life of aircraft rubber components.

4.1.2 Of the 101 potential Anti-Rads chosen for screening, 90 were successfully compounded into a standard ASTM natural rubber tread stock. After optimum cure and irradiation, 88 of the 90 potential Anti-Rads inhibited radiation damage to varying degrees. The best Anti-Rad, N,N'-cyclohexylphenyl-para-phenylenediamine, resulted in the retention of 99 per cent of the initial tensile strength and

88 per cent of the initial ultimate elongation compared with 36 and 18 per cent, respectively, for the normally-protected control rubber compound. The screening study revealed certain criteria for selecting more effective Anti-Rads.

4.1.3 Graphs of the comparative effects of gamma irradiation in air and in nitrogen upon the rates of continuous stress relaxation of ten rubber compounds detail the role of oxygen and ozone in the chain scission of representative rubber compounds in a radiation field. An extensive study of the effects of radiation upon the stress relaxation of rubber compounds is nearing completion. It involves a fundamental evaluation of the effects and has begun to shed light on the reaction mechanisms of radiation damage to rubber.

4.1.4 A potentially very useful technique has been explored for the mass spectral analysis of volatile products of the irradiation of rubber. The principal gaseous product besides hydrogen is that molecule which corresponds to the side group or groups of the main polymer chain. The absence of monomer fragments appears to indicate that main-chain scission is less important in radiation degradation than in thermal degradation. This new technique permits the determination of the identity and concentration of side groups. This approach therefore promises to be valuable in evaluating the radiation stability of any given configuration of atoms and groups in a polymer. It should prove the best instrumental aid which has yet been found to obtain criteria for synthesizing radiation-resistant polymers.

4.1.5 The analysis by infrared absorption of gum rubber compounds which had been irradiated in vacuum failed to show any molecular changes except oxidation. It is felt that oxidation occurred after irradiation during the short exposure of the thin rubber films to the air. Except in the case of Neoprene GN, very little oxidation occurred. It is therefore difficult to see how infrared analysis can be of further assistance in detailing radiation damage other than oxidation.

4.1.6 The tabulation of the dynamic test data for the eight representative irradiated rubber compounds is nearly completed. The results are reported here from four tests: Yerzley resilience, abrasion loss, permanent set, and Gehman freeze point. They indicate that the tendency has been to underrate the ability of rubber compounds to withstand irradiation in terms of mechanical service. Some mechanical properties of certain rubber compounds actually improve during irradiation. Therefore, eight aircraft tires are being manufactured, four containing the best Anti-Rad, for gamma irradiation and simulated service testing. Similarly, the compounds used in aircraft rubber components, with and without Anti-Rads, have been irradiated and are about to be tested. Future plans give increased emphasis to such in-service and simulated-service testing of irradiated compounds which are to be used in the actual rubber components.

4.2 Conclusions

4.2.1 The Anti-Rad screening program showed that the period of retention of the initial tensile strength and ultimate elongation of natural rubber tread stock can be extended more than tenfold by the addition of an Anti-Rad.

4.2.2 The Anti-Rad screening program provided criteria for selecting specific, superior Anti-Rads and indicated that as effective Anti-Rads can be found for elastomers in addition to natural rubber.

4.2.3 A new technique of mass spectral-analysis promises to be very helpful in obtaining criteria for selecting radiation-resistant polymers.

4.2.4 The time has come to apply our basic knowledge to the development and testing of radiation-resistant rubber components for the nuclear powered aircraft.

4.2.5 Close liaison with research groups and engineering groups within the Aircraft Nuclear Propulsion Program is a growing necessity to coordinate efforts, avoid overlapping, and speed progress.

BIBLIOGRAPHY

(1) Born, John W., A Study of the Effects of Nuclear Radiations on Elastomeric Compounds and Compounding Materials, WADC Technical Report 55-58 Part II, The B. F. Goodrich Company Research Center, December, 1955.

(2) Loughborough, D. L.; Juve, A.E.; Beatty, J.R.; and Born, J.W.; A Study of the Effects of Nuclear Radiations on Elastomeric Compounds and Compounding Materials, WADC Technical Report 55-58, Part I, The B. F. Goodrich Company Research Center, December, 1954.

(3) ASTM Committee D-11 on Rubber Products, "Methods of Testing Specifications", ASTM Standards on Rubber Products (with Related Information), May, 1951.

TABLE I

Rubber Compounds for Screening Potential Anti-Rads

All rubber compounds listed below comprise Compound 1GFA7 plus 5 parts of the potential Anti-Rad in question per 100 parts of natural rubber. That is, each screening compound has the same general recipe:

Parts by Weight	Pigment
100	Natural Rubber
3	Stearic Acid
5	Zinc Oxide
3	Sulfur
1	Benzothiazyl Disulfide
1	Phenyl-Beta-Naphthylamine
50	EPC Carbon Black
5	Potential Anti-Rad

Compound 1GFA	Potential Anti-Rad
13	p, p'-Dimethoxydiphenyl amine
14	Dioctyldiphenyl amine
15	p-(p-Tolylsulfenylamido)-diphenylamine
16	Phenyl-alpha-naphthyl amine
17	Diphenylamine-acetone product
18	Acetone-aniline product
19	Butyraldehyde-aniline product
20	Phenyl-beta-naphthyl amine
21	Phenyl-beta-naphthylamine-acetone product
22	Aldol-alpha-naphthylamine product
23	Diphenylamine-di-isobutylene
24	N-phenyl-N'-o-tolylethylene diamine
25	Di-o-tolylethylene diamine
26	N, N'-cyclohexylphenyl-p-phenylene diamine
27	N, N'-diphenyl-p-phenylene diamine
28	N-p-tolyl-N'-p-toluenesulfonyl-p-phenylene diamine
32	o-Phenylphenol
33	p-Benzyloxyphenol
34	2, 2'-Methylene-bis-(4-methyl-6-t-butyl-phenol)
35	Coumarone-indene resin
36	N, N'-di-sec-butyl-p-phenylene diamine
37	2, 6-Di-t-butyl-p-cresol
38	Nickel dibutyl dithiocarbamate

TABLE I, CONTINUED

Rubber Compounds for Screening Potential Anti-Rads

Compound 1GFA	Potential Anti-Rad
39	Copper inhibitor X-872-L
40	N, N'-Dioctyl-para-phenylene diamine
42	Nonox WSL
43	Aromatic hydrocarbon resin
45	Iron-, copper-, and manganese-inhibitor
46	Mercaptobenzothiazole
47	2, 5-Di-t-butyl-p-quinone
50	3 CD 810
51	3 CD 777
52	8 FE 99
53	8 FE 78AII
54	3 CD 769
55	6 FE 301
56	Age-rite Resin D
57	20 CC 59A
58	20 CC 11C
59	3 CF 163
60	3 CE 16
61	20 CC 130
62	3 CF 167
63	3 CD 221
64	3 CF 615
65	3 CE 251
66	3 CE 52
67	3 CF 159
68	3 CD 804
69	3 CE 250B
70	3 CF 162
71	3 CE 214
72	3 CE 237
73	3 CE 39
74	3 CE 242
75	15 CC 74A
77	Beta-naphthyl amine
78	Diphenyl amine
79	Diphenylethylene diamine
80	p-Phenylene diamine
81	Quinoline
82	8-Hydroxyquinoline
83	p-Quinone

TABLE I, CONTINUED

Rubber Compounds for Screening Potential Anti-Rads

Compound 1GFA	Potential Anti-Rad
84	1,4-Naphthoquinone
86	Quinhydrone
87	Benzophenone
88	Acridone
89	Hydroquinone
90	2,5-Di-t-butyl-hydroquinone
91	Phenyl hydroquinone
92	Hydroquinone monobenzyl ether
93	Hydroquinone dibenzyl ether
94	Naphthalene
95	Anthracene
96	Chrysene
97	Acridine
98	Phenothiazine
99	Pyrrole
100	p-Cresol
101	p-Aminophenol
102	p-Methoxyphenol
103	p-Dimethoxybenzene
104	p-Benzylphenol
105	Beta-naphthol
106	4,4'-Dihydroxybenzophenone
108	Pyrogallol
109	1,5-Dihydroxynaphthalene
110	2,7-Dihydroxynaphthalene
111	Anthraquinone
112	2-Hydroxyquinoline
113	35% Diphenyl-para-phenylenediamine plus 65% phenyl-alpha-naphthylamine

TABLE II

The Effect of Gamma Irradiation On The Physical Properties Of The Anti-Rad Screening Compounds

Compound 1GFA	Physical Properties	Cobalt 60 Gamma Radiation Dose (Megareps) 0	0.1	1	10	35	70	100
	TS (psi)	4350	4650	4430	5070	3930	2330	1360
2	UE (%)	640	620	600	560	500	310	170
	Mod (psi)	100.7	102.1	104.1	111.5	123.3	125.7	136.4
	TS (psi)	1460	1160	1810	1060	1050	1250	1200
3	UE (%)	570	750	660	390	280	210	170
	Mod (psi)	63.9	59.8	61.4	84.3	123.6	163.4	207.4
	TS (psi)	1420	1880	1360	1400	630	Broke	Broke
4	UE (%)	270	350	240	240	26	on Bending	
	Mod (psi)	201.4	225.9	214.1	215.5	Failed	Failed	Failed
	TS (psi)	1310	1380	840	930	1150	1240	1280
5	UE (%)	230	270	160	80	180	60	40
	Mod (psi)	219.5	204.0	162.3	190.3	240.7	Failed	Broke
	TS (psi)	6080	5990	6360	5740	4670	3000	2200
7	UE (%)	340	340	360	290	220	140	60
	Mod (psi)	468.8	455.4	431.7	519.1	659.1	725.5	793.2
	TS (psi)	4880	4220	4470	4800	4460	3660	2680
8	UE (%)	370	350	340	280	210	150	80
	Mod (psi)	319.5	288.4	308.0	370.0	505.3	641.7	1000
	TS (psi)	3210	3390	3610	2840	1740	Broke	Broke
9	UE (%)	180	170	180	140	50	on Bending	
	Mod (psi)	508.1	451.0	518.7	622.4	Failed	Failed	Broke
	TS (psi)	3980	4080	3900	4300	3700	3270	3320
10	UE (%)	300	320	260	200	140	70	40
	Mod (psi)	395.3	363.3	375.8	651.8	1040.4	Failed	Broke
	TS (psi)	5650	6050	5560	5320	4840	5090	4320
13	UE (%)	500	470	470	460	410	360	270
	Mod (psi)	289.0	268.0	266.7	278.8	330.5	411.0	483.6

TABLE II, CONTINUED

The Effect of Gamma Irradiation On The Physical Properties Of The Anti-Rad Screening Compounds

Compound	Physical	Cobalt 60 Gamma Radiation Dose (Megareps)						
1GFA	Properties	0	0.1	1	10	35	70	100
	TS (psi)	5540	5980	5370	5550	5480	4950	3910
14	UE (%)	460	490	430	460	350	300	240
	Mod (psi)	322.8	328.4	321.0	430.0	413.6	464.2	580.4
	TS (psi)	5650	5550	5810	5220	4760	4680	3900
15	UE (%)	450	430	440	380	360	280	210
	Mod (psi)	403.4	394.8	391.0	508.0	485.6	520	646.6
	TS (psi)	5860	5420	5670	5100	5390	4800	3580
16	UE (%)	430	460	430	400	340	240	240
	Mod (psi)	348.2	347.0	349.3	441.6	428.7	531.8	579.7
	TS (psi)	5780	3440	5020	5360	5060	4410	3950
17	UE (%)	490	470	480	460	420	370	270
	Mod (psi)	286.6	289.2	256.6	316.5	324.1	381.8	493.3
	TS (psi)	5180	5150	5460	5010	5480	4760	3980
18	UE (%)	510	460	490	510	420	380	330
	Mod (psi)	277.0	259.0	260.0	351.3	343.0	443.0	520.1
	TS (psi)	5820	5580	5980	5690	5760	4280	3880
19	UE (%)	500	450	490	450	390	280	250
	MOD (psi)	372.2	355.6	289.7	358.0	417.3	495.1	583.4
	TS (psi)	5540	5800	5840	5460	5250	5360	3590
20	UE (%)	390	430	420	390	330	270	190
	Mod (psi)	359.0	382.3	372.1	493.1	490.7	620.6	745.0
	TS (psi)	5300	5470	5170	5220	4620	4070	2660
21	UE (%)	480	500	490	470	340	270	220
	Mod (psi)	389.0	349.5	299.8	467.4	461.3	449.8	544.9
	TS (psi)	5680	5680	6190	5210	5260	4720	4470
22	UE (%)	510	510	490	460	390	330	280
	Mod (psi)	350.9	355.2	341.5	414.5	412.2	505.2	597.1
	TS (psi)	5810	5500	5390	5270	4360	3620	2840
23	UE (%)	480	470	470	450	360	300	230
	Mod (psi)	310.5	308.8	296.4	330.8	342.5	410.0	442.2

TABLE II, CONTINUED

The Effect of Gamma Irradiation On The Physical Properties Of The Anti-Rad Screening Compounds

Compound	Physical	Cobalt 60 Gamma Radiation Dose (Megareps)						
1GFA	Properties	0	0.1	1	10	35	70	100
24	TS (psi)	5890	5820	5720	5770	5540	5240	4880
	UE (%)	470	470	470	440	440	370	340
	Mod (psi)	271.5	251.2	273.7	306.9	354.6	406.6	485.0
25	TS (psi)	6070	5660	5880	5430	5240	4020	2950
	UE (%)	500	380	440	430	350	250	180
	Mod (psi)	392.1	382.6	370.7	483.0	482.6	502.5	619.1
26	TS (psi)	4850	5210	5180	4880	5270	4980	4800
	UE (%)	450	460	470	490	450	420	390
	Mod (psi)	220.6	229.4	224.9	234.0	281.0	324.1	379.8
27	TS (psi)	5920	5820	6010	5560	5420	4630	3500
	UE (%)	480	440	440	440	360	300	250
	Mod (psi)	356.6	387.9	380.3	412.0	431.2	540.5	550.2
28	TS (psi)	4670	5260	5330	5090	5010	4490	4270
	UE (%)	500	480	510	490	460	400	350
	Mod (psi)	255.4	251.9	267.1	292.3	298.1	351.9	389.1
32	TS (psi)	5720	5640	5600	5470	4890	3880	2650
	UE (%)	440	340	430	380	290	220	160
	Mod (psi)	370.0	392.6	369.5	432.1	479.9	515.6	563.1
33	TS (psi)	5410	5050	5490	5300	5300	4150	3100
	UE (%)	430	350	360	340	300	210	150
	Mod (psi)	421.4	446.6	419.6	489.7	511.3	776.9	783.7
34	TS (psi)	5020	4890	5240	5230	4990	4440	3980
	UE (%)	450	480	460	460	420	340	270
	Mod (psi)	305.0	298.1	300.4	333.4	363.0	487.9	514.5
35	TS (psi)	5340	5530	5710	5510	5000	4160	2770
	UE (%)	490	440	480	430	320	280	150
	Mod (psi)	306.4	323.3	319.9	427.1	459.1	543.2	545.5
36	TS (psi)	5600	6360	5360	5290	4880	4380	2960
	UE (%)	470	470	430	430	360	280	180
	Mod (psi)	348.6	252.6	346.5	397.5	437.2	493.0	511.9

TABLE II, CONTINUED

The Effect of Gamma Irradiation On the Physical Properties Of The Anti-Rad Screening Compounds

Compound	Physical	Cobalt 60 Gamma Radiation Dose (Megareps)						
1GFA	Properties	0	0.1	1	10	35	70	100
38	TS (psi)	5480	5600	5810	5320	4630	4070	3620
	UE (%)	430	410	430	400	330	260	250
	Mod (psi)	231.7	362.4	354.3	437.5	460.3	474.8	471.1
39	TS (psi)	6370	6110	6120	5830	5530	5030	4020
	UE (%)	480	440	460	430	370	300	250
	Mod (psi)	404.6	409.8	394.6	438.9	498.9	567.1	616.1
40	TS (psi)	6080	6070	5740	5670	5420	5370	5000
	UE (%)	490	490	490	450	430	420	340
	Mod (psi)	253.3	263.6	271.4	274.9	318.0	354.7	445.8
42	TS (psi)	5470	5180	4790	5480	5230	4240	3840
	UE (%)	440	450	410	410	350	290	230
	Mod (psi)	311.3	324.0	307.8	393.4	438.6	484.6	503.2
43	TS (psi)	5590	5050	5550	5150	5020	3930	3060
	UE (%)	440	470	420	440	370	280	190
	Mod (psi)	317.2	319.2	332.1	369.7	429.5	517.9	501.5
45	TS (psi)	4620	4010	4320	4000	3920	3040	2310
	UE (%)	340	320	330	290	270	190	130
	Mod (psi)	389.1	367.5	368.8	441.3	484.0	644.2	662.0
46	TS (psi)	6150	5990	6330	6320	5530	5470	3980
	UE (%)	380	390	390	390	340	300	190
	Mod (psi)	448.0	441.5	446.6	469.4	543.8	611.0	736.3
47	TS (psi)	5040	5240	5000	5100	4640	4340	3830
	UE (%)	500	450	450	430	390	330	260
	Mod (psi)	309.4	276.6	283.9	339.0	342.4	446.6	489.0
50	TS (psi)	4890	5190	5850	5240	4880	4000	3480
	UE (%)	450	490	540	510	450	370	290
	Mod (psi)	269.5	273.1	259.3	286.9	362.0	437.1	473.1
51	TS (psi)	5160	5300	5410	5410	4660	3970	3730
	UE (%)	480	430	460	420	390	310	250
	Mod (psi)	402.2	393.8	390.4	383.0	424.1	477.6	562.5

TABLE II, CONTINUED

The Effect of Gamma Irradiation On the Physical Properties Of The Anti-Rad Screening Compounds

Compound 1GFA	Physical Properties	Cobalt 60 Gamma Radiation Dose (Megareps)						
		0	0.1	1	10	35	70	100
52	TS (psi)	4650	4950	4990	4710	2920	3080	1900
	UE (%)	400	410	460	350	260	160	110
	Mod (psi)	391.6	369.2	396.8	432.9	485.6	544.0	575.2
53	TS (psi)	4520	4800	4510	4920	3540	2830	1940
	UE (%)	400	410	380	380	250	180	120
	Mod (psi)	397.1	378.5	413.3	385.3	511.3	584.7	552.7
54	TS (psi)	5030	5560	5360	5420	5040	4810	4040
	UE (%)	490	520	480	470	490	390	340
	Mod (psi)	331.3	325.0	336.5	302.4	344.1	473.5	469.5
55	TS (psi)	5050	5020	5180	5090	4440	4770	3850
	UE (%)	520	480	490	460	410	340	280
	Mod (psi)	336.9	337.8	327.3	330.0	399.8	522.6	582.6
56	TS (psi)	5060	5130	4970	5000	4800	4480	3820
	UE (%)	510	530	550	490	430	340	270
	Mod (psi)	280.0	282.0	279.8	307.4	379.9	476.5	521.8
57	TS (psi)	4440	3500	2990	3930	3710	3360	3180
	UE (%)	570	540	600	510	550	460	470
	Mod (psi)	157.6	131.7	157.2	193.3	133.6	180.6	209.9
58	TS (psi)	4660	4940	5120	4970	4600	4270	4080
	UE (%)	500	500	480	490	430	380	270
	Mod (psi)	267.8	241.2	267.8	305.4	337.2	368.8	437.2
59	TS (psi)	4860	5030	5270	5100	4520	3160	2050
	UE (%)	450	460	450	420	330	200	150
	Mod (psi)	316.5	303.9	304.9	353.0	419.9	490.4	549.4
60	TS (psi)	4110	4430	4380	4270	3510	2210	1500
	UE (%)	380	370	330	340	240	130	120
	MOD (psi)	347.3	325.1	336.5	389.9	408.0	418.6	503.1
61	TS (psi)	2180	2290	2400	2490	3060	3120	2210
	UE (%)	490	520	550	480	430	350	240
	Mod (psi)	130.6	112.8	132.7	153.3	242.5	310.2	374.2

TABLE II, CONTINUED

The Effect of Gamma Irradiation On The Physical Properties Of The Anti-Rad Screening Compounds

Compound	Physical	Cobalt 60 Gamma Radiation Dose (Megareps)						
1GFA	Properties	0	0.1	1	10	35	70	100
62	TS (psi)	4330	4640	4410	4310	3300	2650	1560
	UE (%)	410	410	400	350	270	180	120
	Mod (psi)	294.8	308.5	316.6	365.5	604.9	477.9	474.3
63	TS (psi)	4390	3200	4250	4620	4100	3190	2040
	UE (%)	420	440	410	410	310	200	150
	Mod (psi)	304.1	309.6	354.2	349.9	427.1	458.8	468.4
64	TS (psi)	4410	5200	4720	5020	4440	3740	2730
	UE (%)	490	500	450	420	350	240	190
	Mod (psi)	285.0	295.0	328.7	318.6	422.4	470.5	529.7
65	TS (psi)	3980	4830	4100	4470	3440	2150	1620
	UE (%)	420	460	420	400	320	220	130
	Mod (psi)	286.3	280.0	318.3	322.2	380.5	394.5	473.0
66	TS (psi)	4310	4600	4190	4440	3600	2710	1610
	UE (%)	410	410	380	360	280	160	110
	Mod (psi)	390.3	385.0	429.3	413.9	496.1	564.9	599.5
67	TS (psi)	4290	4440	4300	4020	2410	1210	1020
	UE (%)	370	380	370	290	200	12	25
	Mod (psi)	484.2	460.8	507.8	470.8	565.4	545.9	Broke
68	TS (psi)	4530	4710	4570	4870	4220	3060	2320
	UE (%)	470	500	460	460	410	260	180
	Mod (psi)	334.7	292.4	363.1	321.6	446.5	457.4	519.1
69	TS (psi)	4670	4850	4620	4800	4930	4030	3050
	UE (%)	450	470	460	430	400	240	200
	Mod (psi)	338.6	335.7	369.7	357.1	437.4	490.1	576.0
70	TS (psi)	4470	4660	4600	4800	4650	3880	2350
	UE (%)	450	490	420	420	380	260	170
	Mod (psi)	361.8	292.0	357.1	347.8	417.4	519.4	567.8
71	TS (psi)	4380	4600	4560	4800	4120	3810	1980
	UE (%)	480	480	490	470	410	280	150
	Mod (psi)	298.0	279.2	292.1	326.3	440.8	474.5	551.1

TABLE II, CONTINUED

The Effect of Gamma Irradiation On The Physical Properties Of The Anti-Rad Screening Compounds

Compound	Physical	Cobalt 60 Gamma Radiation Dose (Megareps)						
1GFA	Properties	0	0.1	1	10	35	70	100
72	TS (psi)	4590	4890	4710	4850	3590	2550	1300
	UE (%)	490	480	450	430	330	180	140
	Mod (psi)	295.6	320.9	345.5	365.1	416.2	442.3	446.9
73	TS (psi)	4840	4470	4510	4780	4190	3100	2210
	UE (%)	460	480	460	430	370	200	190
	Mod (psi)	313.8	326.0	360.1	359.8	445.0	493.8	504.6
74	TS (psi)	4120	4710	4510	4090	3500	2490	1130
	UE (%)	380	410	410	310	240	140	86
	Mod (psi)	411.6	397.7	441.2	494.4	568.5	657.1	660.1
75	TS (psi)	3870	4240	3960	4000	3350	1710	1090
	UE (%)	350	380	340	310	240	130	60
	Mod (psi)	354.0	335.1	420.0	392.8	525.5	532.5	576.2
77	TS (psi)	5500	5730	5410	5450	5200	5120	4670
	UE (%)	500	520	500	490	450	430	350
	Mod (psi)	248.1	253.5	251.3	257.9	277.4	325.0	401.7
78	TS (psi)	5180	4920	5370	5120	5290	4670	3950
	UE (%)	470	490	480	460	410	360	260
	Mod (psi)	288.6	249.2	255.3	275.1	322.7	472.8	489.8
79	TS (psi)	5720	5430	5800	5650	5380	5070	4530
	UE (%)	470	450	500	460	420	350	290
	Mod (psi)	314.6	320.2	303.0	302.1	399.1	489.0	533.5
80	TS (psi)	5490	5020	5660	5120	4460	3020	2360
	UE (%)	330	290	310	300	210	120	60
	Mod (psi)	625.1	580.6	557.1	613.4	792.5	1042.1	1373.7
81	TS (psi)	5600	5130	5670	5130	5100	4650	4000
	UE (%)	480	500	480	500	450	390	280
	Mod (psi)	203.3	190.7	206.5	226.0	253.7	321.0	372.4
82	TS (psi)	5490	5690	5650	5770	4450	3540	2590
	UE (%)	400	390	290	340	370	390	130
	Mod (psi)	592.4	538.2	516.2	559.5	548.6	682.6	725.1

TABLE II, CONTINUED

The Effect of Gamma Irradiation On The Physical Properties Of The Anti-Rad Screening Compounds

Compound	Physical	Cobalt 60 Gamma Radiation Dose (Megareps)						
1GFA	Properties	0	0.1	1	10	35	70	100
83	TS (psi)	5590	5850	6140	5540	5450	4980	4800
	UE (%)	360	340	360	340	270	250	210
	Mod (psi)	500.8	490.3	495.0	561.2	621.8	734.4	731.9
84	TS (psi)	5350	5520	5690	5720	4830	4490	4070
	UE (%)	450	430	470	450	350	330	290
	Mod (psi)	347.0	342.6	367.1	378.5	423.3	500.6	531.2
86	TS (psi)	4710	5670	5600	5440	4760	4590	4280
	UE (%)	420	420	470	410	310	320	310
	Mod (psi)	365.8	394.0	407.1	419.4	456.6	560.4	596.1
87	TS (psi)	5370	6050	5970	5980	4840	3990	2530
	UE (%)	400	400	400	380	270	200	140
	Mod (psi)	393.4	376.2	394.7	393.1	560.0	654.3	571.5
88	TS (psi)	5220	5530	5380	5660	3870	2560	2670
	UE (%)	340	360	350	360	220	150	120
	Mod (psi)	435.1	458.3	454.1	411.5	613.7	676.0	653.1
89	TS (psi)	5290	5400	5190	5020	3710	3230	2900
	UE (%)	280	320	330	270	210	140	110
	Mod (psi)	594.2	617.1	629.2	591.4	725.9	861.6	912.3
90	TS (psi)	5720	5520	5760	5530	4800	4050	3990
	UE (%)	410	400	420	400	310	240	240
	Mod (psi)	339.2	408.3	415.2	478.8	478.3	576.5	674.5
91	TS (psi)	4840	5090	5210	4890	4550	4570	4200
	UE (%)	440	460	430	420	360	320	300
	Mod (psi)	307.6	305.9	335.8	345.1	403.5	478.6	532.8
92	TS (psi)	5700	5390	5720	5470	5140	4720	4160
	UE (%)	470	450	440	440	360	320	270
	Mod (psi)	319.5	300.4	320.4	331.0	402.4	489.3	596.8
93	TS (psi)	6730	5530	5990	5640	4890	4340	3920
	UE (%)	400	420	420	380	250	210	180
	Mod (psi)	397.8	386.3	416.0	457.3	560.5	711.3	829.1

TABLE II, CONTINUED

The Effect of Gamma Irradiation On The Physical Properties Of The Anti-Rad Screening Compounds

Compound 1GFA	Physical Properties	Cobalt 60 Gamma Radiation Dose (Megareps)						
		0	0.1	1	10	35	70	100
94	TS (psi)	6130	6330	5980	5860	4620	3530	3150
	UE (%)	370	400	410	390	250	190	170
	Mod (psi)	419.2	393.1	441.8	416.2	592.0	636.5	594.1
95	TS (psi)	5530	5740	5650	5770	5070	3660	2950
	UE (%)	390	410	400	390	300	220	170
	Mod (psi)	369.9	385.3	411.3	397.8	520.7	580.3	508.6
96	TS (psi)	5900	5730	5740	4950	4420	3870	2910
	UE (%)	360	390	400	320	220	190	130
	Mod (psi)	428.1	420.9	458.7	458.8	586.7	694.4	666.1
97	TS (psi)	6080	5970	6120	5450	5200	4760	3940
	UE (%)	420	430	420	460	380	350	240
	Mod (psi)	377.1	351.0	410.1	311.8	360.4	420.4	561.1
98	TS (psi)	5240	5530	5850	5490	5150	4650	4110
	UE (%)	390	430	450	400	290	280	240
	Mod (psi)	364.8	385.7	395.4	434.1	546.9	609.6	563.8
99	TS (psi)	6130	6540	6480	6180	4800	3410	3190
	UE (%)	390	410	390	400	210	170	150
	Mod (psi)	419.3	399.2	446.9	480.9	621.4	744.4	634.1
100	TS (psi)	6170	5910	6040	5550	4620	3590	3060
	UE (%)	390	420	410	370	260	200	180
	Mod (psi)	397.0	366.7	433.1	439.8	535.5	604.1	560.7
101	TS (psi)	5380	5540	5970	5180	4420	4030	3660
	UE (%)	360	350	350	300	230	180	160
	Mod (psi)	573.3	554.3	544.0	599.4	756.2	872.9	912.8
102	TS (psi)	5810	5620	6020	5840	4140	3790	4060
	UE (%)	370	410	410	380	280	230	210
	Mod (psi)	411.6	385.2	405.8	436.1	541.0	634.0	663.2
103	TS (psi)	5530	5930	5620	5870	4590	3950	3240
	UE (%)	380	410	380	350	280	220	190
	Mod (psi)	411.1	394.8	385.0	438.5	341.0	591.3	587.7

TABLE II, CONTINUED

The Effect of Gamma Irradiation On The Physical Properties Of The Anti-Rad Screening Compounds

Compound	Physical	Cobalt 60 Gamma Radiation Dose (Megareps)						
1GFA	Properties	0	0.1	1	10	35	70	100
104	TS (psi)	5930	5710	5860	5870	4550	4120	3230
	UE (%)	420	430	450	390	290	230	190
	Mod (psi)	390.9	395.4	365.8	417.9	515.9	613.4	571.0
105	TS (psi)	4520	4150	4530	4580	4600	4110	3830
	UE (%)	520	530	510	560	460	390	370
	Mod (psi)	180.0	111.0	178.2	227.6	270.1	306.8	382.9
106	TS (psi)	5130	5510	5300	5380	3690	3310	2400
	UE (%)	320	350	340	320	220	170	130
	Mod (psi)	482.2	458.0	433.0	502.1	609.2	688.8	609.6
108	TS (psi)	3650	3330	3570	4190	3970	3830	3640
	UE (%)	410	390	390	370	330	290	270
	Mod (psi)	175.8	170.3	186.6	221.5	307.6	396.5	416.3
109	TS (psi)	5530	5830	5600	5460	4750	4190	3830
	UE (%)	390	420	410	380	260	240	210
	Mod (psi)	517.3	458.7	508.5	494.3	597.8	719.3	673.5
110	TS (psi)	5380	5220	5370	4890	5030	3820	3170
	UE (%)	430	420	420	400	310	250	190
	Mod (psi)	452.4	437.0	453.4	493.0	544.9	622.7	643.2
111	TS (psi)	5270	5180	5410	5270	5030	4460	3790
	UE (%)	420	500	420	440	410	340	280
	Mod (psi)	282.0	264.3	285.0	307.1	371.6	430.4	440.6
112	TS (psi)	5550	5920	5800	5180	4040	3540	2990
	UE (%)	320	340	320	280	190	160	130
	Mod (psi)	510.8	522.0	581.9	618.7	767.0	831.5	1000.5
113	TS (psi	5790	5530	5640	5350	5550	5130	4970
	UE (%)	490	490	450	430	410	390	370
	Mod (psi)	276.1	271.5	318.6	284.6	404.2	470.4	473.5

TABLE III

Efficiency Rating of Anti-Rads
Based on Tensile Strength and Ultimate Elongation

(Radiation Exposure = 10^8 Reps)

Compound IGFA	Per cent of Initial Value Tensile Strength	Elongation	Relative Rating
26	99	88	1
113	86	76	2
86	91	74	3
28	91	70	4
24	83	72	5
105	85	71	6
77	85	70	7
57	72	82	8
108	100	66	9
91	87	68	10
40	82	69	11
54	80	69	12
111	72	67	13
18	77	65	14
84	76	64	15
79	79	62	16
98	78	62	17
34	79	60	18
50	71	64	19
83	80	58	20
7	36	18	89

TABLE IV

Efficiency Rating of Anti-Rads Based on 100% Modulus
(Radiation Exposure = 10^8 Reps)

Compound 1GFA	Final Modulus (psi)	Per cent of Initial Modulus	Relative Rating
82	725.1	122.4	1
65	473.1	122.4	2
106	609.6	126.4	3
109	673.4	130.1	4
57	210.0	133.2	5
95	508.6	137.5	6
53	552.7	139.2	7
21	544.9	139.7	8
51	562.5	139.8	9
100	560.7	141.2	10
94	594.1	141.2	11
54	469.5	141.7	12
110	643.2	142.1	13
23	442.2	142.4	14
103	587.7	142.9	15
60	503.1	144.8	16
88	633.1	145.5	17
104	570.9	146.0	18
83	732.0	146.1	19
52	575.2	146.8	20
7	793.2	169.2	56

TABLE V

The Recipes of the A.S.T.M. Rubber Compouns

Pigment	1GFA2	1GFA3	1GFA4	1GFA5	1GFA6
Natural Rubber (Hevea)	100				
GR-S (Fatty Acid Base)		100			
Neoprene GN			100		
Hycar 1002				100	
Butyl Rubber (GR-I 18)					100
Stearic Acid	1		0.5		3
Zinc Oxide	5	5	5	5	5
Sulfur	2.5	2		1.5	2
Benzothiazyl Disulfide	1	1.75		1	
Tetramethylthiuram Disulfide					1
Phenyl-Beta-Naphthylamine	1				
Magnesium Oxide			4		
Specific Gravity	0.98	0.99	1.31	1.03	0.97

Pigment	1GFA7	1GFA8	1GFA9	1GFA10	1GFA11
Natural Rubber (Hevea)	100				
GR-S (Fatty Acid Base)		100			
Neoprene GN			100		
Hycar 1002				100	
Butyl Rubber (GR-I 18)					100
Stearic Acid	3		1		3
Zinc Oxide	5	5	5	5	5
Sulfur	3	2		1.5	2
Benzothiazyl Disulfide	1	1.75		1	0.5
Tetramethylthiuram Disulfide					1
Phenyl-Beta-Napgthylamine	1				
Magnesium Oxide			4		
EPC Black	50	40	35		50
SRF Black				50	
Specific Gravity	1.14	1.13	1.40	1.20	1.13

TABLE VI

Comparison of Gaseous Yield with Polymer Structure

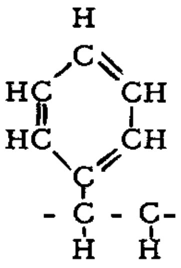
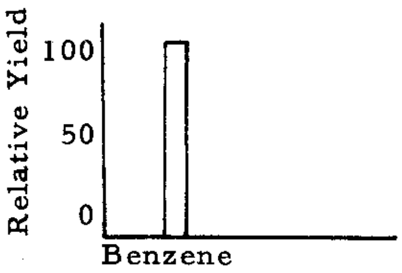
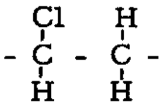
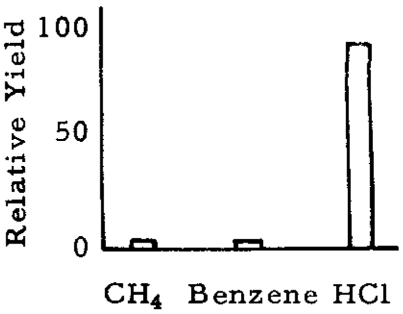
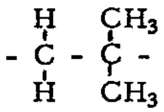
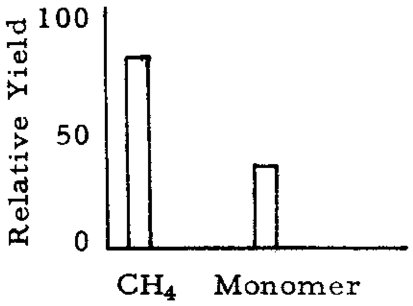
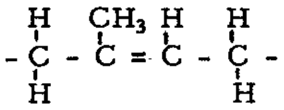
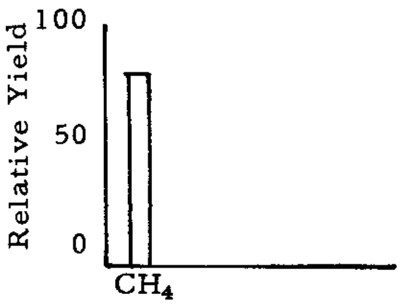
Polymer	Repeating Unit	Relative Product Yield
Polystyrene		
Polyvinyl Chloride	 $-\underset{H}{\overset{Cl}{C}}-\underset{H}{\overset{H}{C}}-$	
Polyiso-butylene	 $-\underset{H}{\overset{H}{C}}-\underset{CH_3}{\overset{CH_3}{C}}-$	
Natural Rubber	 $-\underset{H}{\overset{H}{C}}-\overset{CH_3}{C}=\overset{H}{C}-\underset{H}{\overset{H}{C}}-$	

TABLE VII

The Change in Yerzley Resilience (Per cent) with Gamma Irradiation

(Total Gamma Ray Exposure = 10^8 Reps)

Compound 1GFA	Initial Value	Final Value	Per cent of Initial	Change in Per cent
2	93.8	95.5	101.9 ± 0.8	+ 1.9
3	58.3	88.4	151.7 ± 2.3	+ 51.7
4	85.4	83.2 (E)	97.5 ± 1.8 (E)	- 2.5 (E)
5	70.8	88.2	124.7 ± 1.8	+ 24.7
7	74.6	76.0	101.9 ± 1.0	+ 1.9
8	55.5	76.5	137.8 ± 0.5	+ 37.8
9	71.5	70.6 (C)	98.8 ± 0.8 (C)	- 1.2 (C)
10	62.1	76.6 (D)	123.2 ± 1.4 (D)	+ 23.2 (D)

(C) The total radiation exposure was 10 megareps.

(D) The total radiation exposure was 35 megareps.

(E) The total radiation exposure was 70 megareps.

TABLE VIII

The Change in Pico Abrasion Index with Gamma Irradiation

$$\text{Abrasion Index} = \frac{\text{Volume loss of standard}}{\text{volume loss of sample}} \times 100\%$$

Compound 1GFA	Radiation Dose (Megareps)							Per cent of Initial	Per cent Change
	0	1	5	10	35	70	100		
2	28.3	26.9	26.6	26.8	23.5	14.7	3.2	11.3	-88.7
3	16.9	16.5	16.2	11.5	6.2	7.2	3.8	22.4	-77.6
4	45.0	42.0	41.7	27.5	6.0	4.9	4.8	10.7	-89.3
5	18.7	19.8	16.1	9.8	5.6	5.1	4.9	26.2	-73.8
7	96.8	96.6	97.8	94.4	90.7	85.2	68.4	70.6	-29.4
8	82.2	83.0	83.0	82.8	89.0	100.2	105.2	128.1	+28.1
9	105.4	100.6	101.4	98.6	102.9	71.4	57.8	54.8	-45.2
10	70.8	70.1	72.7	86.0	101.2	163.5	133.0	187.9	+87.9

TABLE IX

The Change in Permanent Set with Gamma Irradiation

$$\text{Permanent Set} = \frac{\text{Initial Height} - \text{Recovered Height}}{\text{Initial Height}} \times 100\%$$

Compound 1GFA	Radiation Dose (Megareps)							Change in Permanent Set
	0	1	5	10	35	70	100	
2	2.9	3.7	3.8	3.4	3.8	3.2	2.6	- 0.3
3	(too soft to test)			30.1	8.0	3.7	2.2	-(large)
4	40.0	41.2	36.9	15.8	2.8	1.6	TH	-40.0
5	10.2	9.8	6.6	1.7	0.6	0.3	0.3	- 9.9
7	11.0	11.4	12.0	11.6	10.0	9.4	7.1	- 3.9
8	15.8	13.9	17.4	9.9	4.7	3.4	2.0	-13.8
9	27.4	28.4	24.8	13.1	(too hard to test)			-27.4
10	11.0	11.1	8.0	1.8	0.4	(too hard)		-11.0

TABLE X

The Change in Gehman Freeze Point (°C.) with Gamma Irradiation

Compound	Radiation Dose (Megareps)							Overall
1GFA	0	1	5	10	35	70	100	Change
2	-59	-58	-59	-58	-58	-56	-53	+ 6
3	-52	-52	-52	-52	-52	-50	-48	+ 4
4	-40	-37	-38	-37	(+7)	-35	-28	+12
5	-23	-23	-23	-23	-23	-19	-14	+ 9
7	-57	-56	-56	-56	-56	-52	-50	+ 7
8	-49	-49	-49	-49	-49	-46	-45	+ 4
9	-37	-37	-37	-36	-31	-37	-30	+ 7
10	-25	-24	-24	-24	-21	-19	-19	+ 6

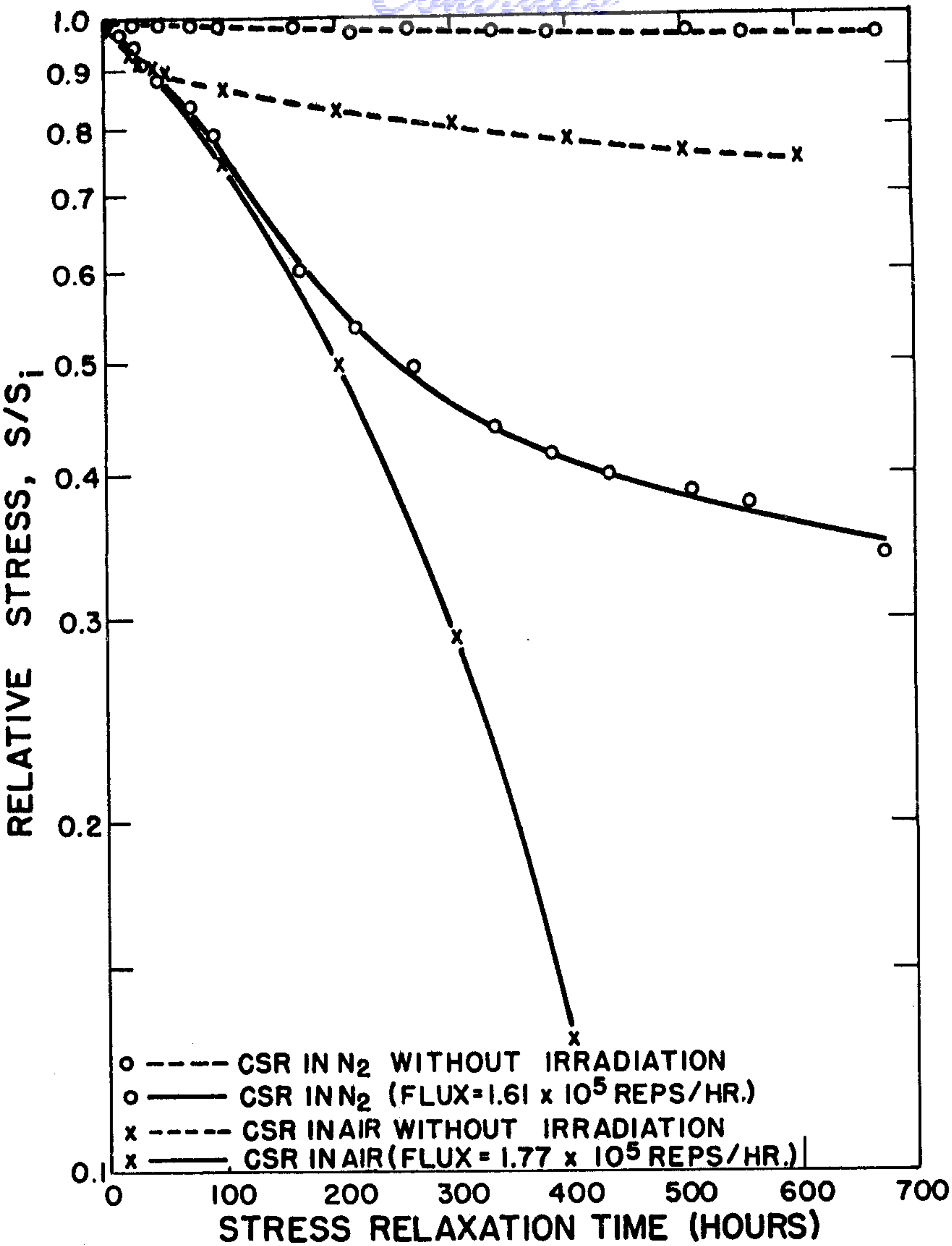


FIGURE I. THE EFFECT OF GAMMA IRRADIATION ON THE CONTINUOUS STRESS RELAXATION OF COMPOUND IGFA2.

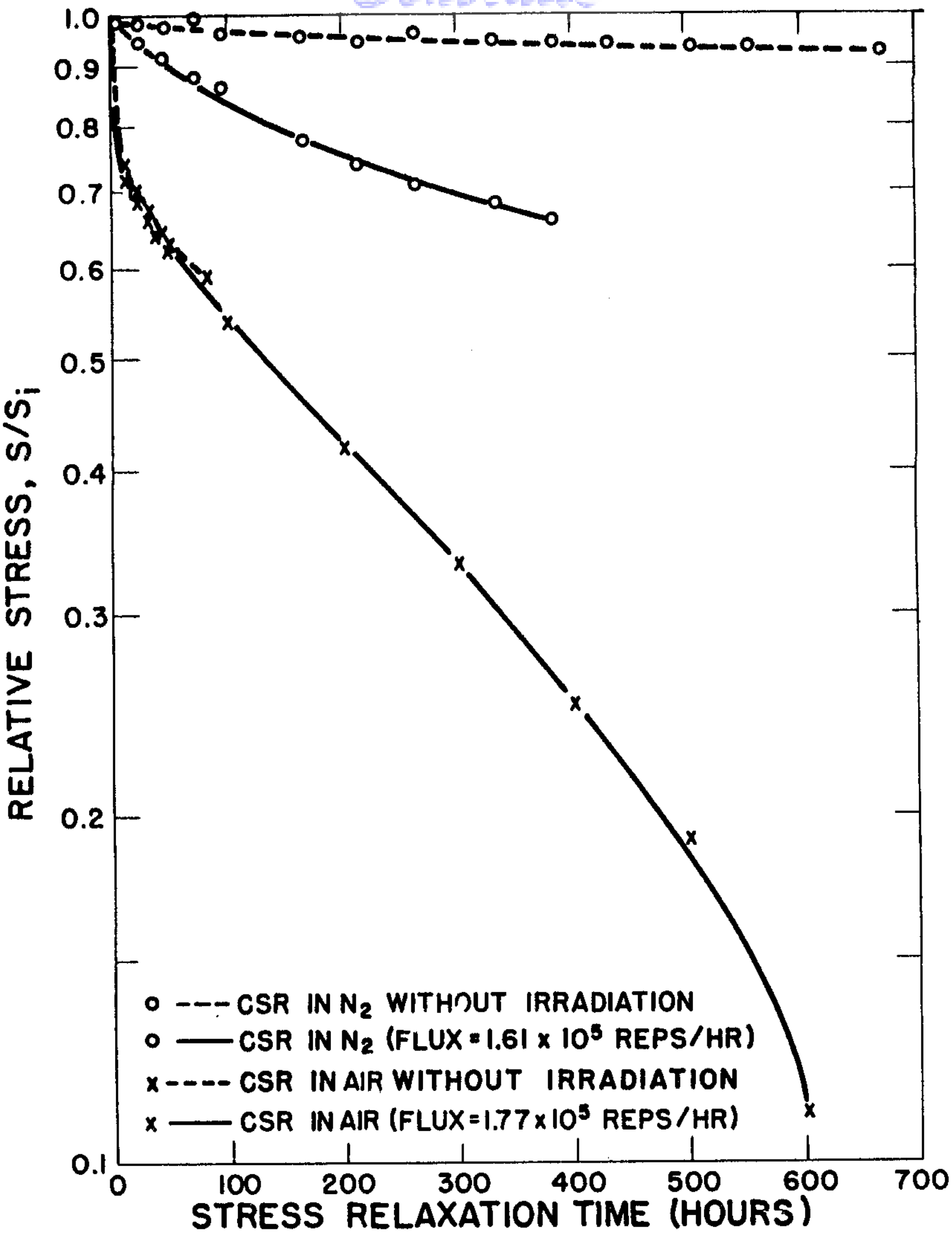


FIGURE 2. THE EFFECT OF GAMMA IRRADIATION ON THE CONTINUOUS STRESS RELAXATION OF COMPOUND IGFA3.

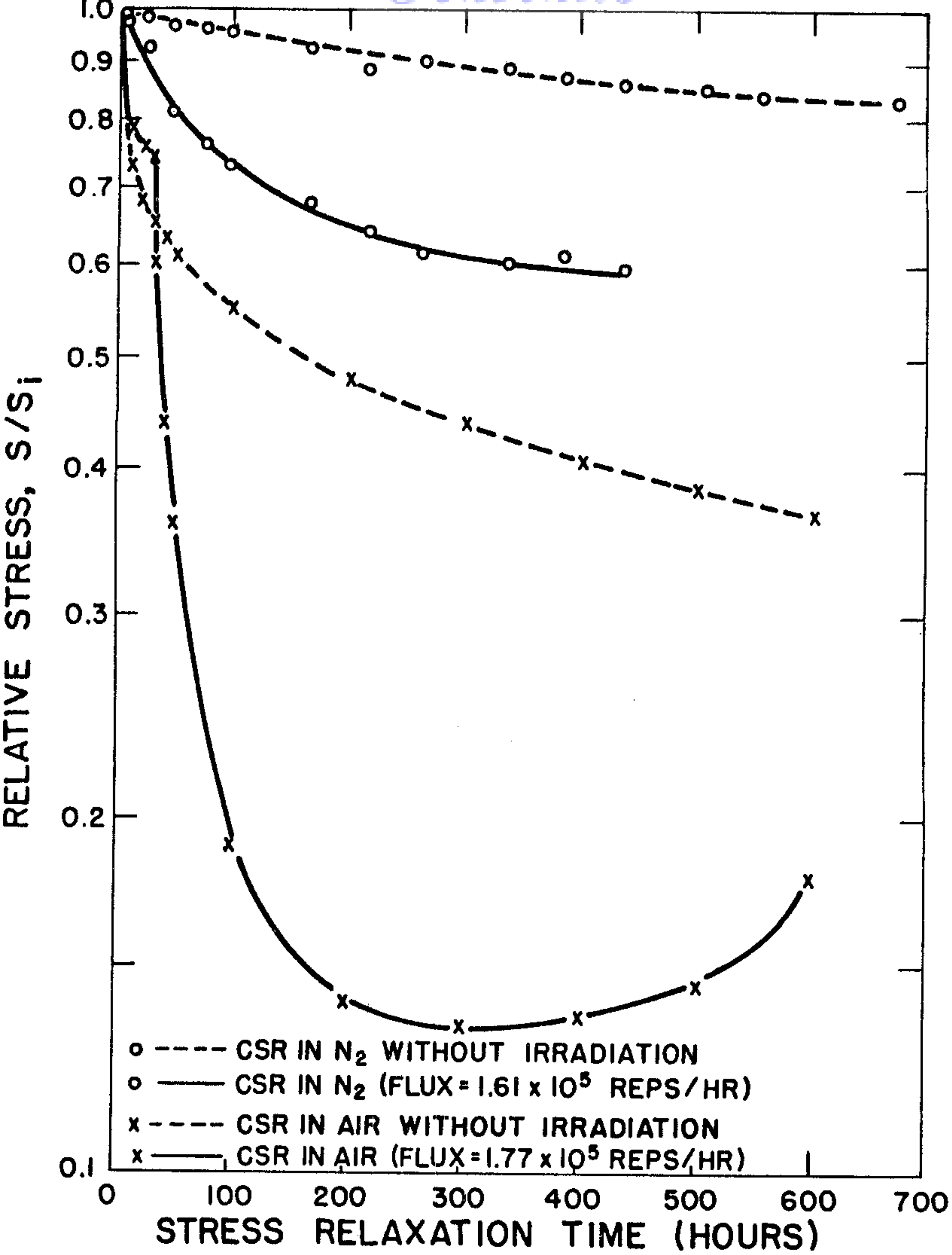


FIGURE 3. THE EFFECT OF GAMMA IRRADIATION ON THE CONTINUOUS STRESS RELAXATION OF COMPOUND IGFA4.

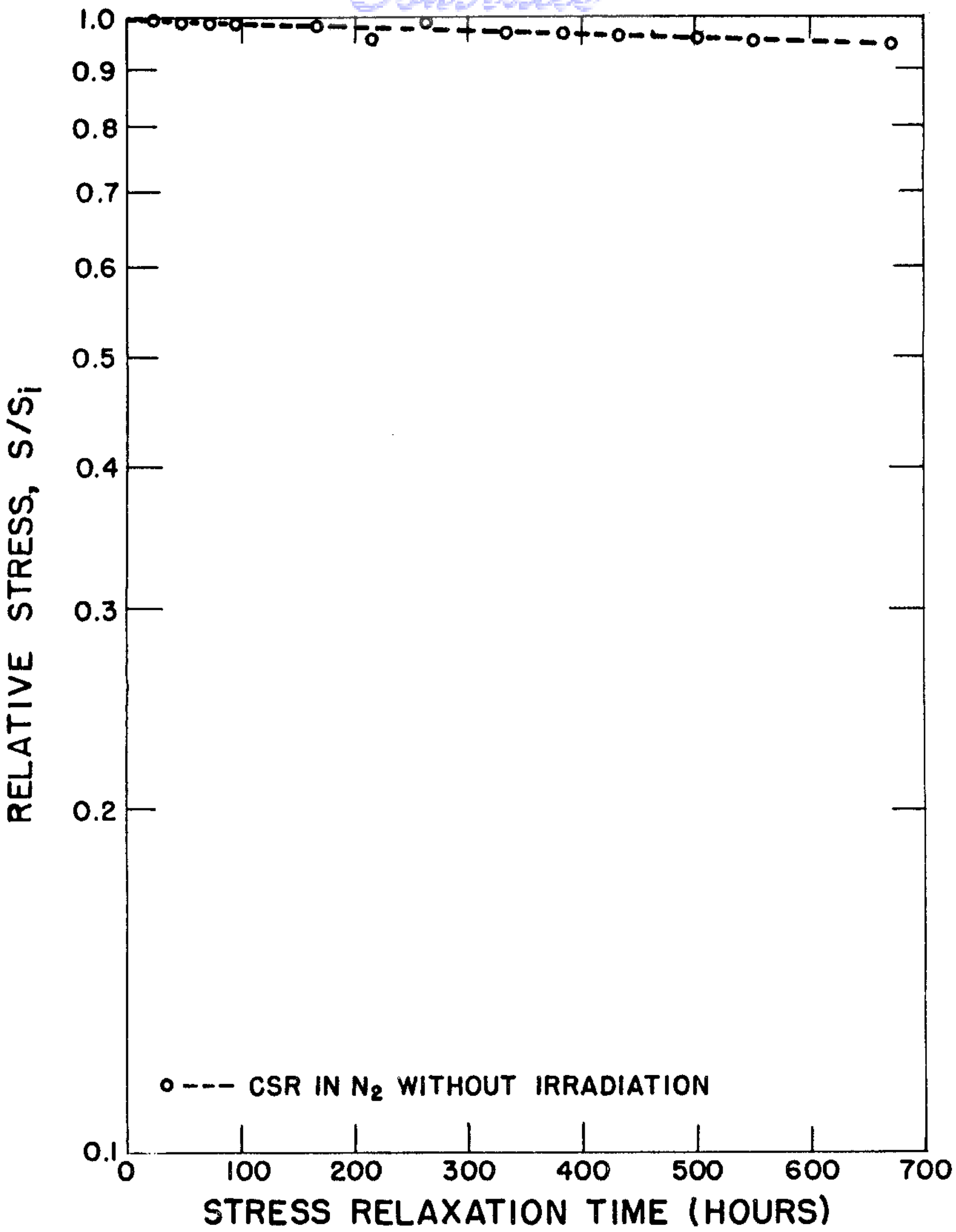


FIGURE 4. THE EFFECT OF GAMMA IRRADIATION ON THE CONTINUOUS STRESS RELAXATION OF COMPOUND IGFA5

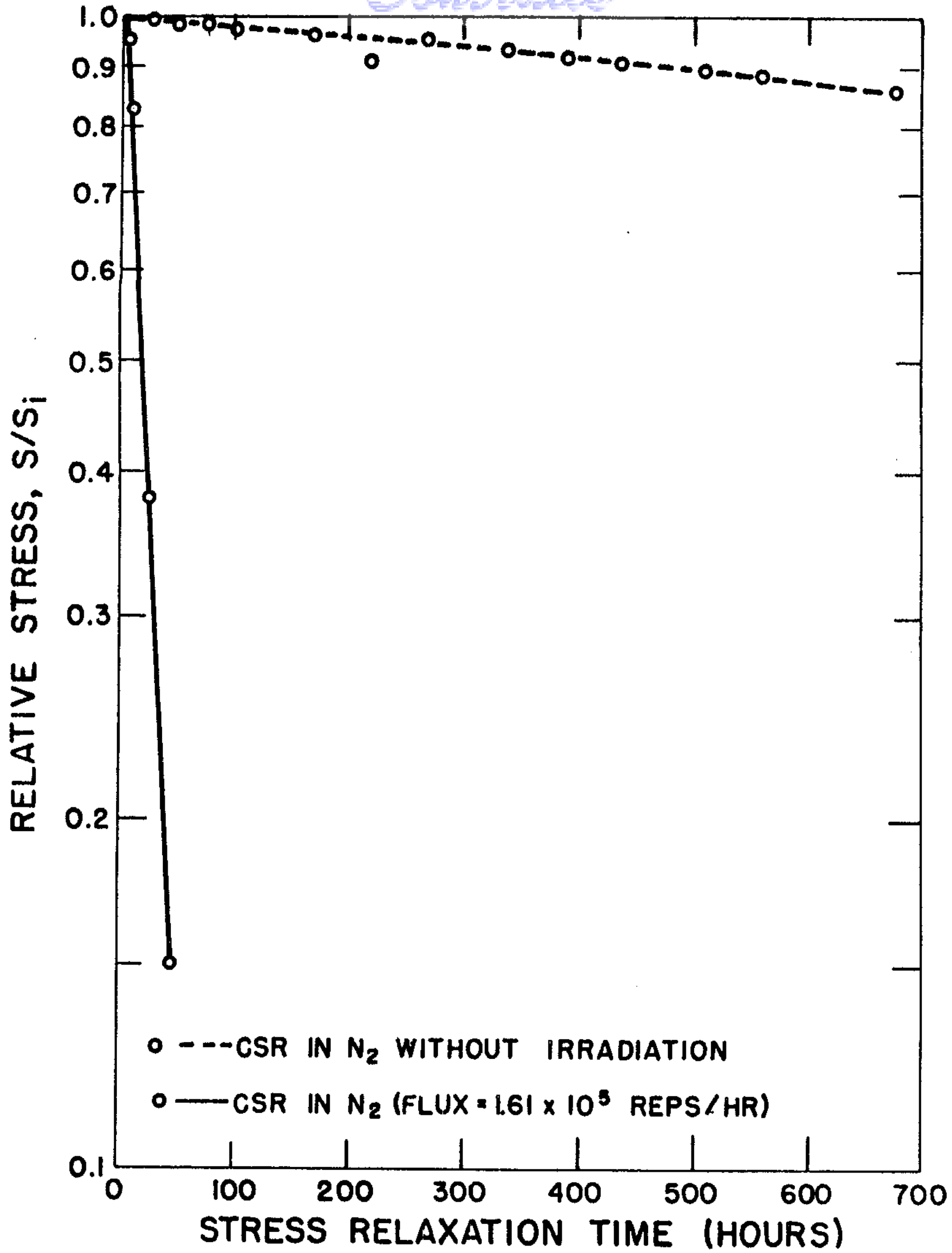


FIGURE. 5. THE EFFECT OF GAMMA IRRADIATION ON THE CONTINUOUS STRESS RELAXATION OF COMPOUND IGFA6.

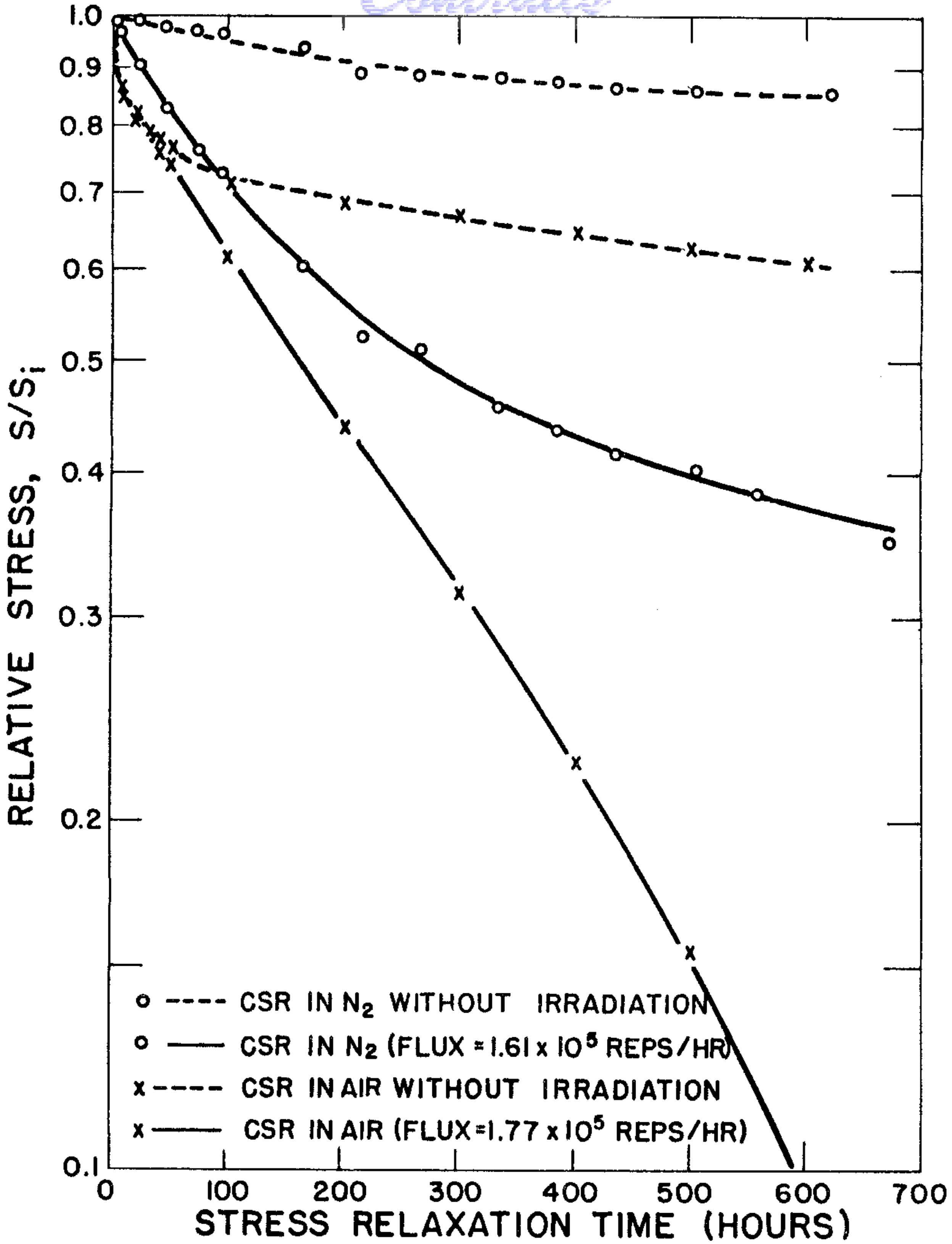


FIGURE 6. THE EFFECT OF GAMMA IRRADIATION ON THE CONTINUOUS STRESS RELAXATION OF COMPOUND IGFA7.

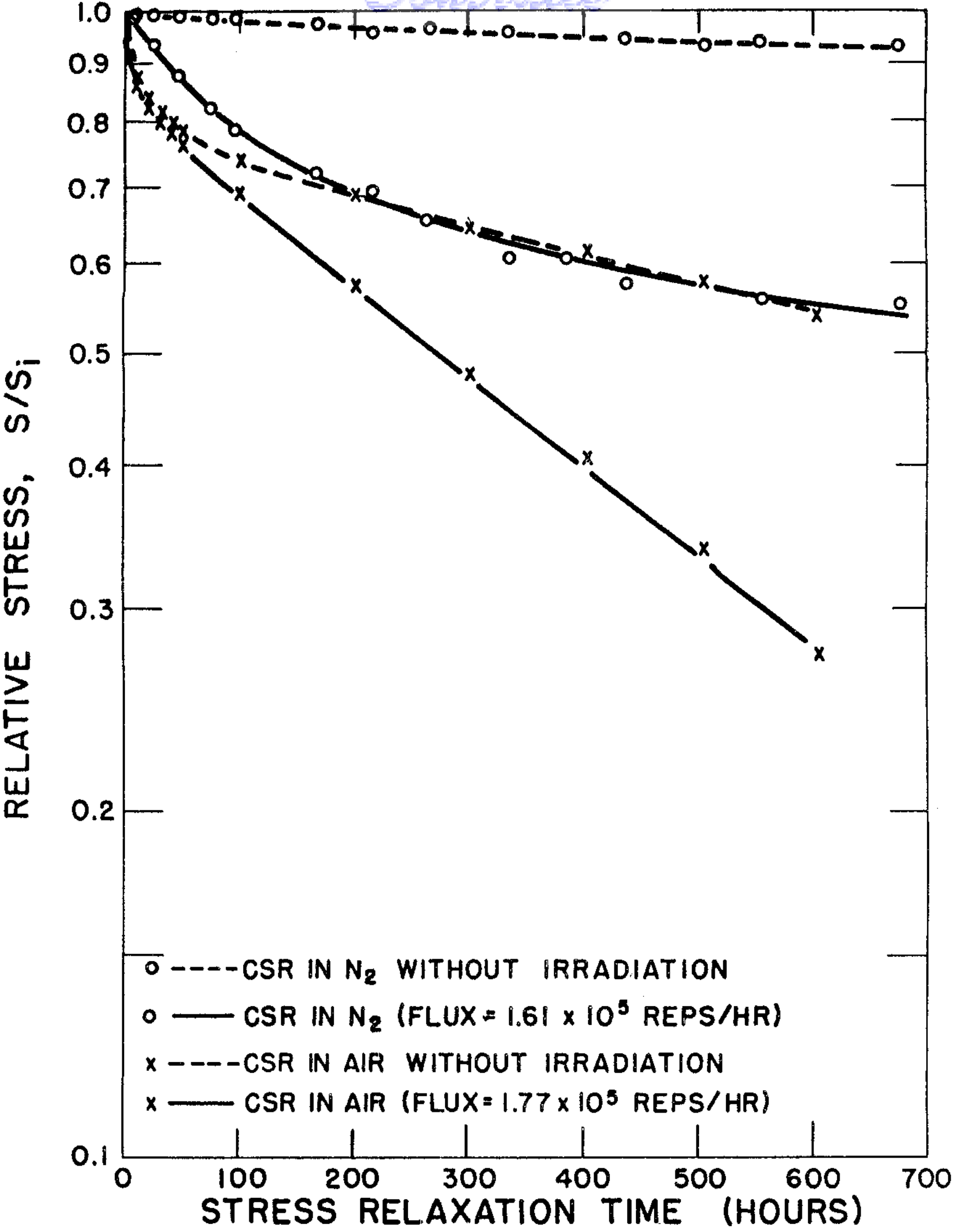


FIGURE 7. THE EFFECT OF GAMMA IRRADIATION ON THE CONTINUOUS STRESS RELAXATION OF COMPOUND IGFA8

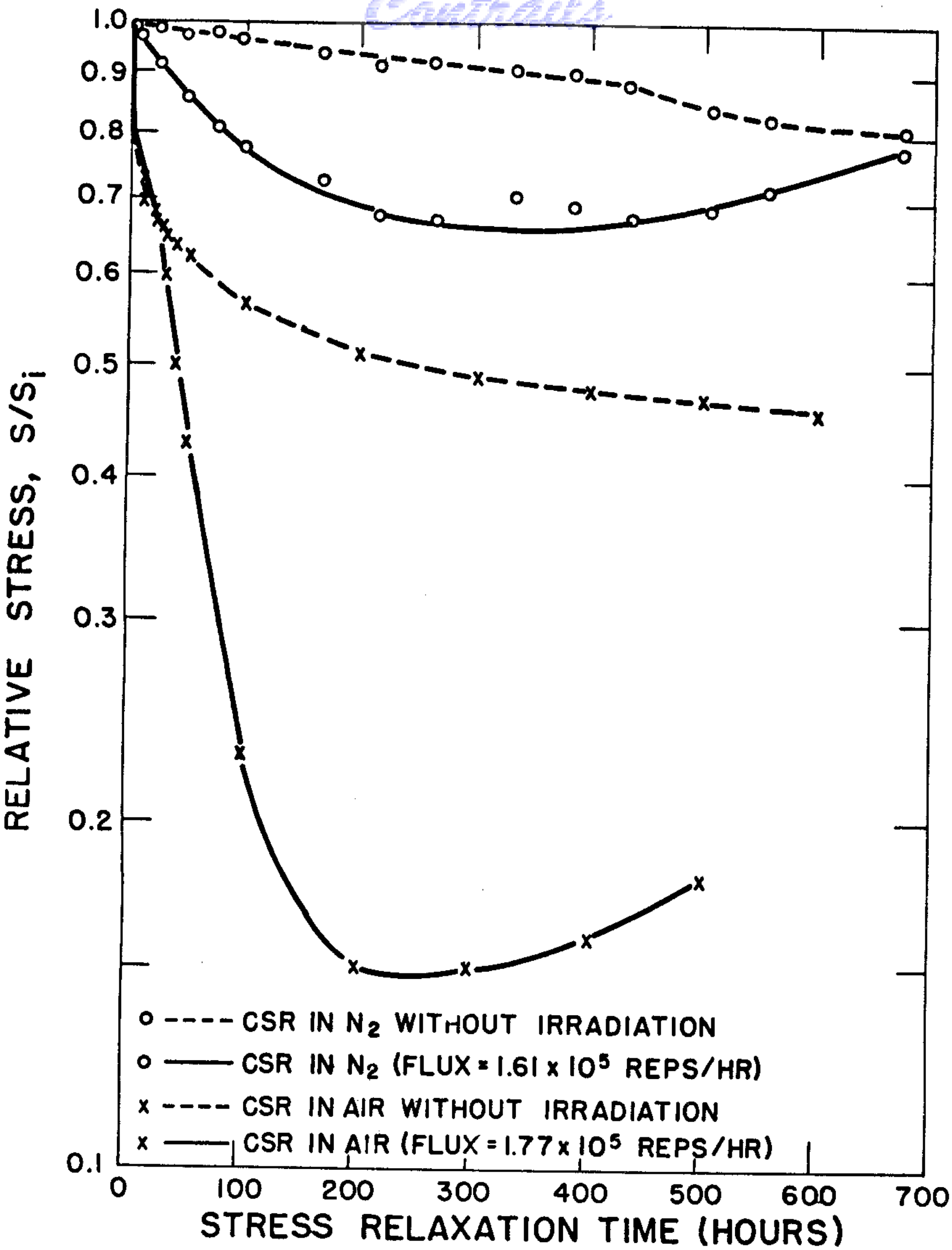


FIGURE 8. THE EFFECT OF GAMMA IRRADIATION ON THE CONTINUOUS STRESS RELAXATION OF COMPOUND IGFA9.

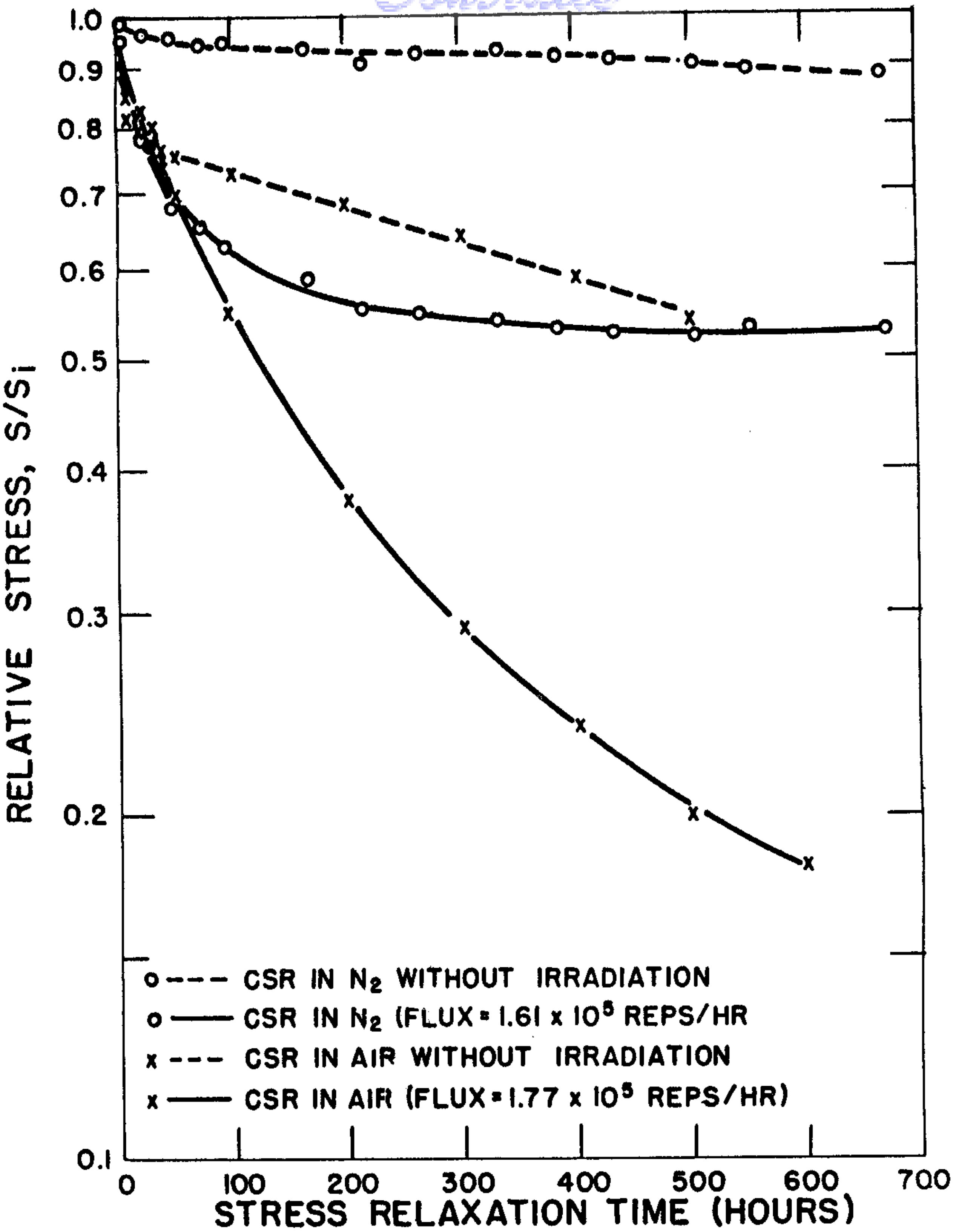


FIGURE 9. THE EFFECT OF GAMMA IRRADIATION ON THE CONTINUOUS STRESS RELAXATION OF COMPOUND IGFAIO.

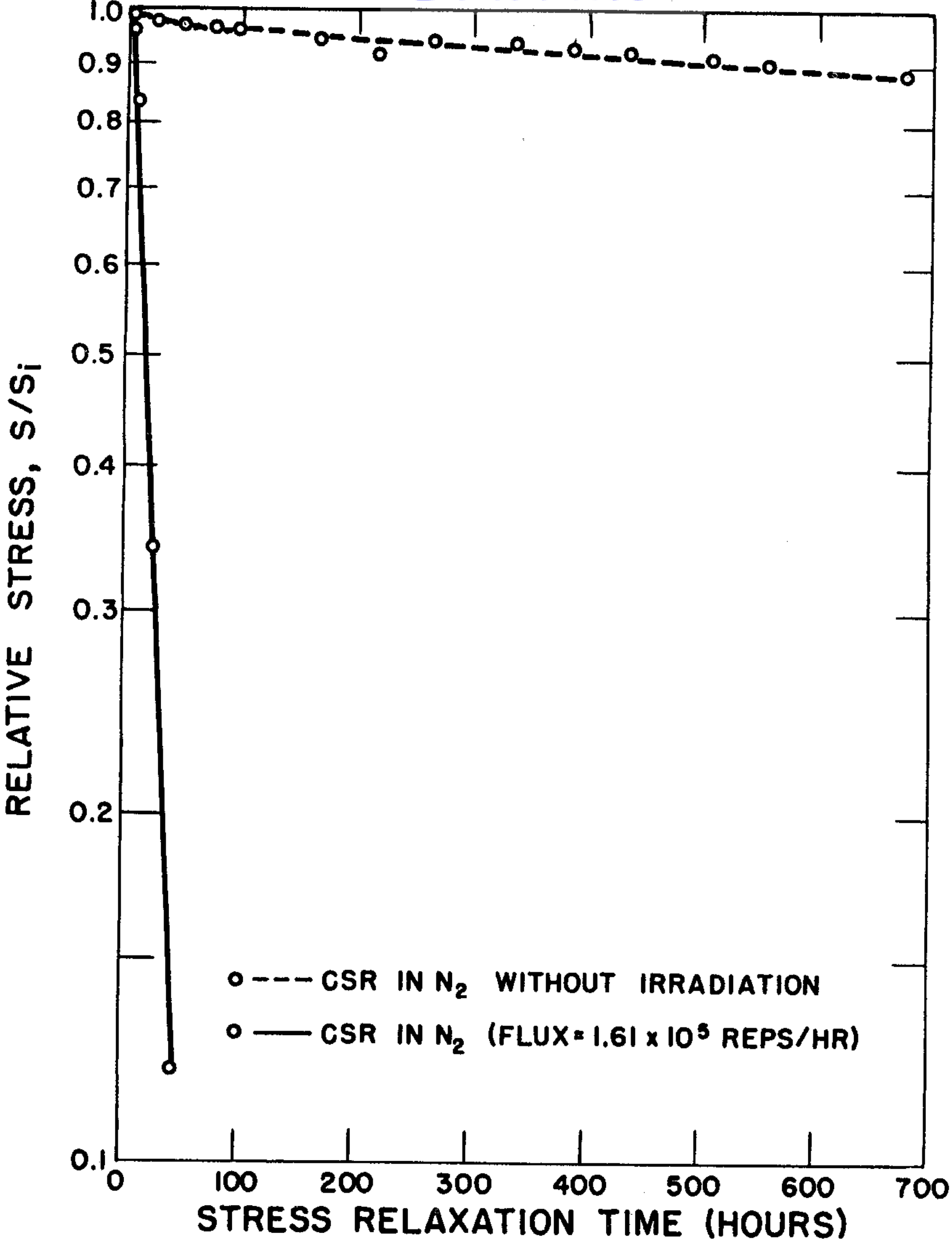


FIGURE 10. THE EFFECT OF GAMMA IRRADIATION ON THE CONTINUOUS STRESS RELAXATION OF COMPOUND IGFA11.