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Handbook of Photothermal Test Data on Encapsulant Materials

R.H. Liang
K.L. Oda
S.Y. Chung
M.V. Smith
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May 1, 1983

Prepared for
U.S. Department of Energy
Through an Agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
California Institute of Technology
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Prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.

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ABSTRACT

This report describes laboratory tests performed to characterize candidate encapsulation materials with respect to changes in their physical and chemical properties caused by photothermal aging. Several key material properties relating directly to material degradation and deterioration of performance have been identified and have been monitored as functions of aging conditions and time. This handbook provides a status report on accelerated testing activities and presents experimental data collected before and during December 1982. It will be updated periodically as more data become available.

The use of these data in development and dissemination of predictive models describing the rate of aging as a function of stress parameters is a separate and ongoing task. A preliminary version of this model will be published soon in a separate Flat Plate Solar Array Project report.

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SECTION I

INTRODUCTION

A. BACKGROUND

The Environmental Isolation Task within the Flat-Plate Solar Array Project (FSA) has the responsibility of (1) developing new materials and processes required to achieve low-cost, durable encapsulation of photovoltaic (PV) modules at a total installed cost of $\$14/m^2$ for the encapsulation package and (2) performing assessment and prediction of deployed PV module lifetime, through development of a fundamental understanding of degradation processes and mechanisms of the encapsulation materials, and development of outdoor lifetime prediction models for encapsulated modules.

Toward this overall objective of life assessment and prediction, an effort was initiated directed to the characterization of chemical and physical responses of encapsulant materials to accelerated photothermal aging. This effort involves exposure of materials to ultraviolet and visible radiation, elevated temperatures, liquid water spray and various oxygen concentrations. The primary use of these data is in validating and refining analytical models describing chemical changes in materials occurring on long-term exposure. These data may also be used in ranking candidate materials that perform the same functions within the encapsulation package and that belong to the same generic chemical class of compounds with respect to their photothermal aging responses.

These tests are complemented by mechanistic studies performed on selected materials such as ethylene vinyl acetate (EVA), polymethyl methacrylate (PMMA), and poly-n-butyl acrylate (PnBA). The studies involve characterization and monitoring of chemical degradation caused by photothermal aging, i.e., photooxidation, crosslinking and chain scission in polymers. Transient species involved in the overall degradation process, e.g., chain radicals and electronically excited states, are monitored in real time using flash kinetic spectroscopy and transient electron-spin resonance (ESR) spectroscopy. A status report of this work can be found in References 1 through 8.

B. MATERIAL PROPERTIES MONITORED

The following properties have been monitored as a function of aging time:

(1) Optical Transmittance: Optical transmittance was measured on a Cary 219 spectrophotometer equipped with a 4-in. integrating sphere and ultraviolet (UV) optics. The collimated and total transmittance were obtained as a function of wavelength in the wavelength range 300-1200 nm. Besides providing a direct measure of chemical changes involving formation of oxidized species such as carbonyl groups in the polymer optical transmittance, measurements may also be used to monitor diminution of cell performance due to loss of transmittance of the encapsulant

material. Optical transmittance measurements also provide a monitor of the UV screening capability of outer-cover films.

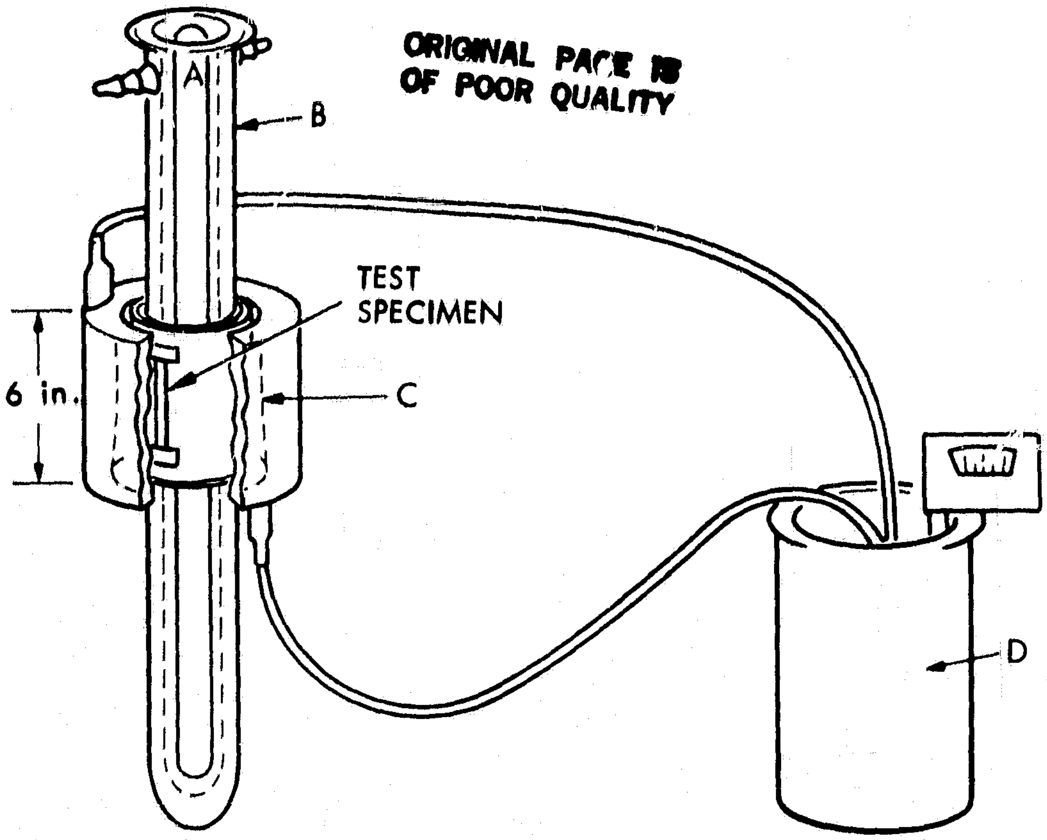
(2) Weight Loss: Weight-loss measurements allow monitoring of loss of polymer mass due to evaporation of plasticizers, leaching of additives and formation of volatile degradation products. Weight-loss measurements correlate with the rate of formation of voids in the encapsulation package, which may cause delamination and corrosion.

(3) Tensile Modulus: Uniaxial stress-strain response was monitored as a function of photothermal aging time. Measurements were made as a function of strain rate, up to yield. This stress-strain response can be used to calculate engineering or secant modulus of the material. Work by Spectrolab, Inc., indicates that the strain isolation function of the encapsulation package requires a tradeoff between the thickness of the pottant material and its maximum allowable Young's modulus (Reference 9). The measured stress-strain response also yields information on the stress-relaxation or creep behavior of these materials. Detailed creep measurements on EVA will be reported in a Jet Propulsion Laboratory (JPL) publication.

(4) Swelling and Sol/Gel Ratio: Crosslinked polymers are insoluble in any solvent, but they are subject to swelling. The extent of swelling is determined by the crosslink density of the materials and the match between its solubility parameters and those of the solvent. Partially crosslinked materials can be extracted to yield a sol fraction which has finite molecular weight and a remaining gel which has a crosslinked network. Determination of swelling behavior and sol/gel fraction yield fundamental information on the network crosslink density and network topology, which are critical chemical structural parameters in a polymer that control its physical-mechanical response. The mechanical response of a polymer changes on outdoor aging because aging causes changes in crosslink density and network topology. Hence, the ratio of changes in swelling behavior or sol/gel fraction after aging is a key measure of the outdoor stability of these polymers.

C. TEST DESIGN

Polymer samples were aged at 55°C, 70°C, 85°C, 105°C, and 135°C. Aging conditions for the four lower-temperature tests have been reported previously (Reference 10) and are described only briefly here. The source of UV radiation used in the four lower-temperature tests (55°C, 70°C, 85°C, and 105°C) was a filtered medium-pressure Hg arc lamp, approximately 200 W/in. of arc length in power. The lamp was placed inside a water-cooled Pyrex jacket. A transparent annular Pyrex oil bath was then fitted around the jacket. The samples were mounted in the space between the Pyrex jacket and the oil bath, and were in contact with the hot oil-bath jacket. The radiation apparatus is shown in Figure 1. Samples (3 x 1/2 in.) were mounted directly on the inner surface of the oil-bath jacket to allow free access of oxygen (open thermal aging).



A = 450-WATT MEDIUM PRESSURE Hg LAMP

B = PYREX H_2O COOLING JACKET

C = OIL JACKET

D = THERMOSTATICALLY CONTROLLED HOT OIL BATH
(SAMPLE SPECIMEN PLACED BETWEEN B AND C)

Figure 1. Photothermal Radiation Apparatus

Samples for limited-oxygen-access testing were placed between two sheets of Pyrex glass and the sandwich then was mounted on the bath. This arrangement (covered photothermal aging) allowed limited access of oxygen with its edge effects, as illustrated in Figure 1. Control experiments (with no UV) were also performed by aging samples in a dark stagnant oven.

Although satisfactory data were obtained by use of this radiation equipment, it lacked precise temperature control, especially at elevated temperatures; e.g., a 10°C rise in sample temperature was once observed during one of the 105°C tests. This was caused by enhanced absorbance of radiation by sample films turning yellow as a result of photothermal aging. While the oil bath maintained at 105°C was supplying most of the heating during the initial aging stage, the additional absorbance of photons resulted in the rise in sample temperature. Subsequently, an accelerated aging chamber, the Controlled Environmental Test Chamber (CER), was designed and constructed at JPL to achieve better temperature control.

A detailed description of the CER is to be found in Reference 11. Briefly, the irradiation source in the CER is a medium-pressure Hg lamp filtered to yield a photon flux of up to 6 suns of AM1 ultraviolet radiation in the 295-375 nm wavelength region. In addition, it can provide precise temperature control and simulated rain and fog. Detailed calibration of the photon flux was achieved by radiometry and actinometry. Parallel aging tests were performed inside the CER and at the JPL outdoor site in order to validate its use as an accelerated testing device and to estimate the accelerating factors achieved under specific conditions. The CER has also been demonstrated to be a valid accelerated outdoor simulator with respect to photooxidation (Reference 12). Figure 2 is a photograph of the CER.

The initial CER design allowed aging temperatures ranging from 25°C to 60°C. Subsequently, resistor-type heaters were added to the outside wall of the CER to enhance its high-temperature capability. Additionally, a thermostatted sample holder equipped with its own heat source was designed to reach a sample aging temperature of up to 135°C. All heaters were thermostatically controlled by the voltage output of a thermocouple that is attached directly to the sample films. Continous temperature control within ±3°C were obtained routinely by the CER, even at 135°C.

D. TEST SAMPLES

Samples tested were ethylene vinyl acetate copolymer (EVA, Springborn Laboratories, Inc., A-9918); polyvinyl butyral (PVB, Monsanto Co. Saflex); silicone rubber (room-temperature vulcanizing silicon elastomer, General Electric Co. RTV-615) ethylene methyl acrylate copolymer (EMA, Springborn A-13404); and poly-n-butyl acrylate (PnBA, Springborn A-13870). Two kinds of aliphatic polyurethanes manufactured by H.J. Quinn Co. and Development Associates (PU Z-2591) also were tested. Four commercially available outer-cover film materials are being evaluated. These are Korad (Xcel Corp.), Tedlar (Du Pont Co.), Acrylar (3M Co. X-22416), and Kynar (Pennwalt Corp.). The Tedlar sample tested was designated as UTB-100 and a new sample of Tedlar (100BG30UT) is now being evaluated. Table 1 is a matrix of samples tested and Table 2 is a matrix of the pottant samples versus aging conditions and aging time. Table 3 is a similar matrix for outer-cover materials.

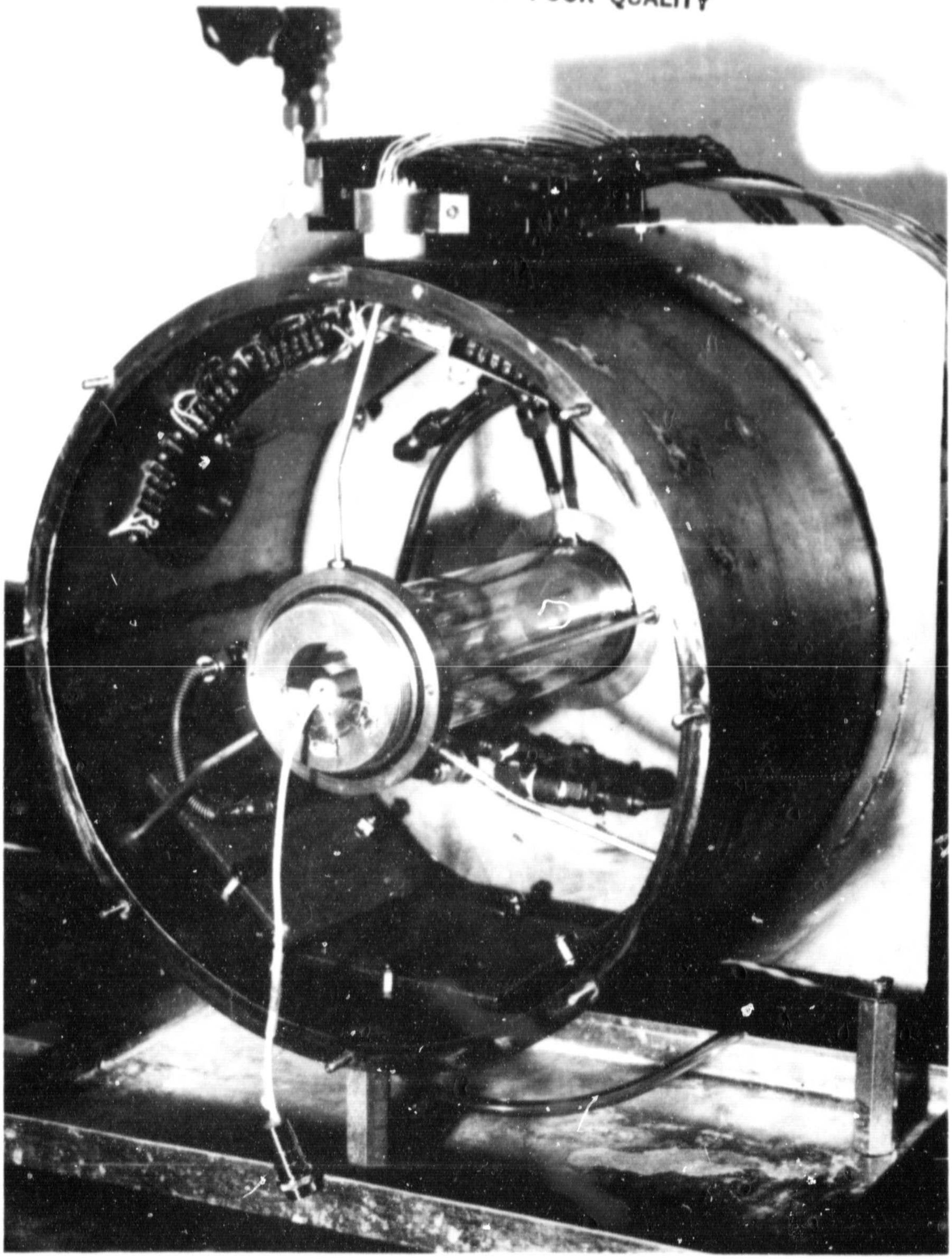


Figure 2. Controlled Environmental Reactor (CER)

Table 1. Matrix of Pottant and Outer Cover Materials Tested

APPLICATION	MATERIAL			
	ACRYLICS	POLYOLEFINS	FLUORO-CARBON	OTHER (SILICONES, POLYURETHANES)
POTTANT	EMA (SPRINGBORN A-13404) PnBA (SPRINGBORN A-13870)	EVA (SPRINGBORN A-9918) PVB (MONSANTO SAFLEX)		RTV (GE RTV-615) PU (QUINN) PU (DEVELOPMENT ASSOCIATES Z-2591)
OUTER COVER	ACRYLAR (3M X-22416) KORAD (XCEL)		TEDLAR (DU PONT UTB-100) KYNAR (PENNWALT)	

TEMP (°C)	CONDITION	AGING TIME, h						
		EVA (SPRINGBORN A-9918)	PVB	RTV	EMA	PnBA	PU QUINN	PU DEV. ASSOC.
55	THERMAL AGING	-	400	-	-	-	400	-
	OPEN PHOTOTHERMAL AGING	-	400	-	-	-	400	-
	COVERED PHOTOTHERMAL AGING	-	400	-	-	-	400	-
70	THERMAL AGING	500	400	500	-	-	400	-
	OPEN PHOTOTHERMAL AGING	500	400	500	-	-	400	-
	COVERED PHOTOTHERMAL AGING	500	400	500	-	-	400	-
85	THERMAL AGING	800	-	800	-	-		-
	OPEN PHOTOTHERMAL AGING	800	-	800	-	-	-	-
	COVERED PHOTOTHERMAL AGING	800	-	800	-	-	-	-
105	THERMAL AGING	800	-	800	-	-	-	-
	OPEN PHOTOTHERMAL AGING	800	-	800	-	-	-	-
	COVERED PHOTOTHERMAL AGING	800	-	800	-	-	-	-
135	THERMAL AGING	1008	1008	-	1008	1008	-	1008
	OPEN PHOTOTHERMAL AGING	1008	672	-	672	1008	-	672
	COVERED PHOTOTHERMAL AGING	1008	1008	-	1008	1008	-	1008

Table 2. Matrix of Pottant Samples versus Aging Conditions and Time

Table 3. Matrix of Outer Cover Samples versus Temperature and Time

TEMPERATURE, °C	AGING TIME, days			
	ACRYLAR X-22416	TEDLAR UTB-100	KORAD	KYNAR
55	600	365	0	200*
85	200	30	15	200
150				2

* AT 60°C

SECTION II

EVA (SPRINGBORN A-9918)

The following figures and tables offer data on optical transmittance (Figures 3 through 13); mechanical properties (Figures 14 through 25, Tables 4 through 6); weight loss (Figures 26 through 28); other properties (Tables 7 through 9) of EVA (Springborn A-9918).

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A. OPTICAL TRANSMITTANCE

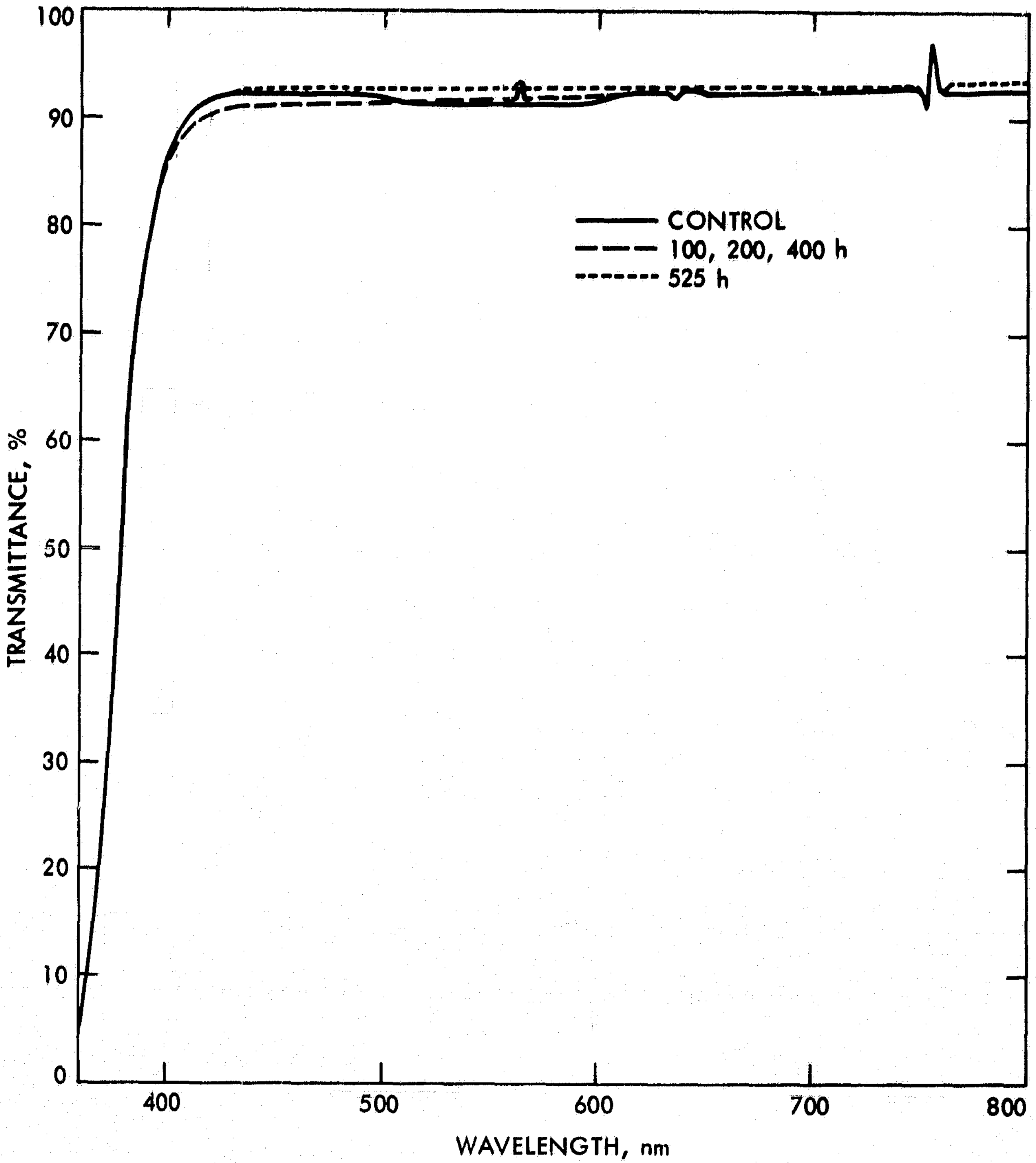

Figure 3. Change in Optical Transmittance as a Function of Open Photothermal Aging of EVA at 70°C

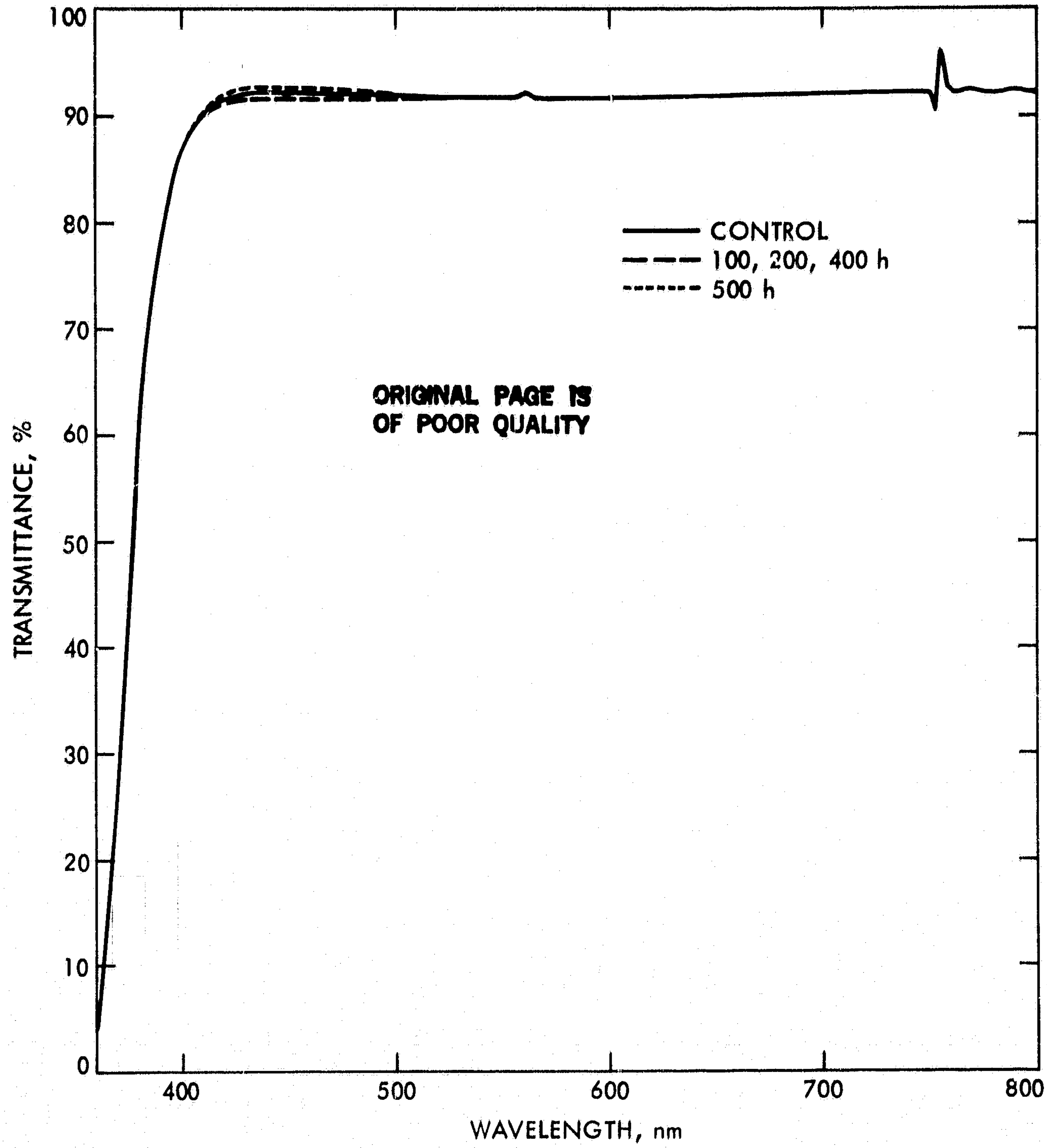

Figure 4. Change in Optical Transmittance as a Function of Covered Photothermal Aging of EVA at 70°C

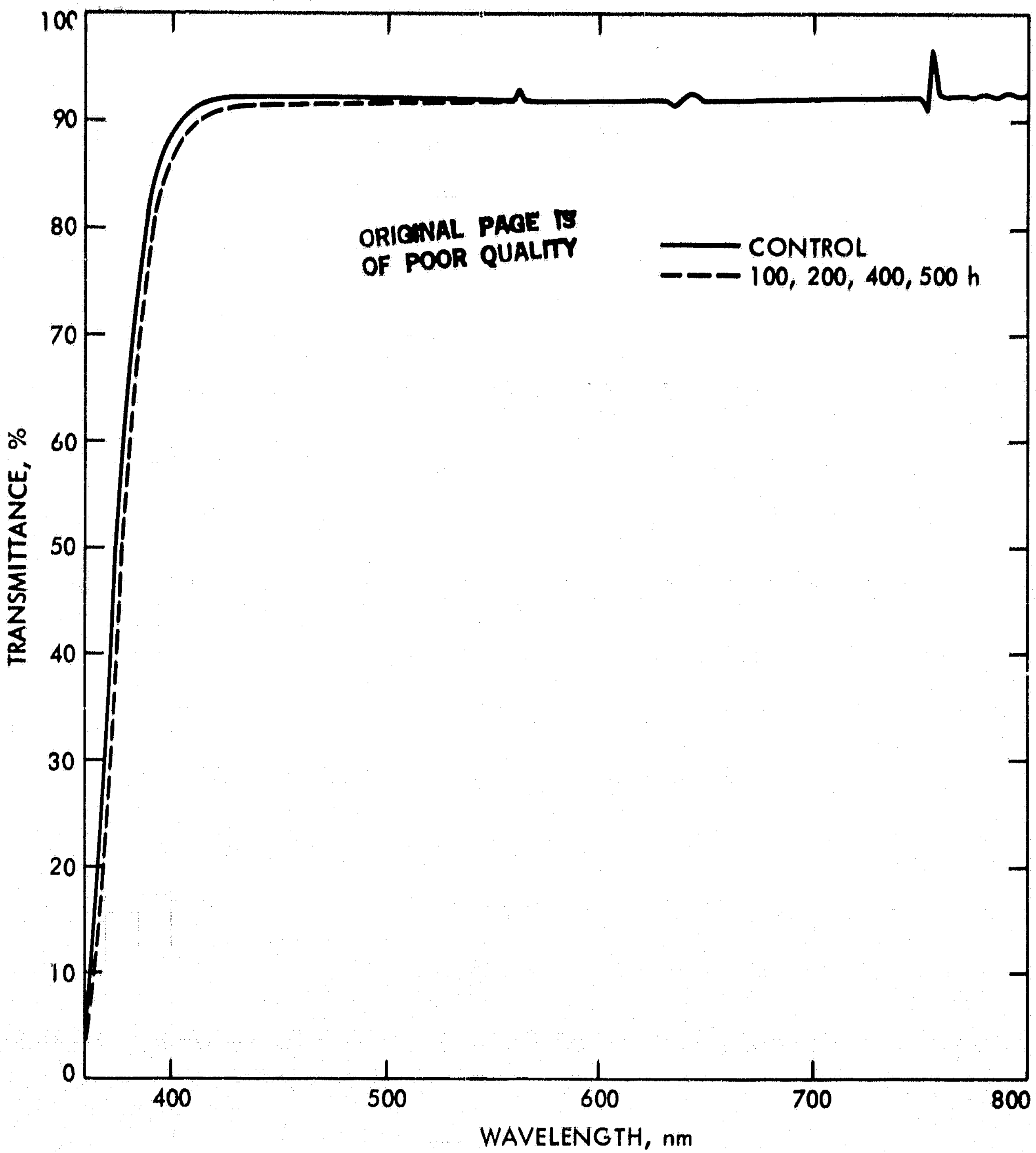

Figure 5. Change in Optical Transmittance as a Function of Thermal Aging of EVA at 70°C

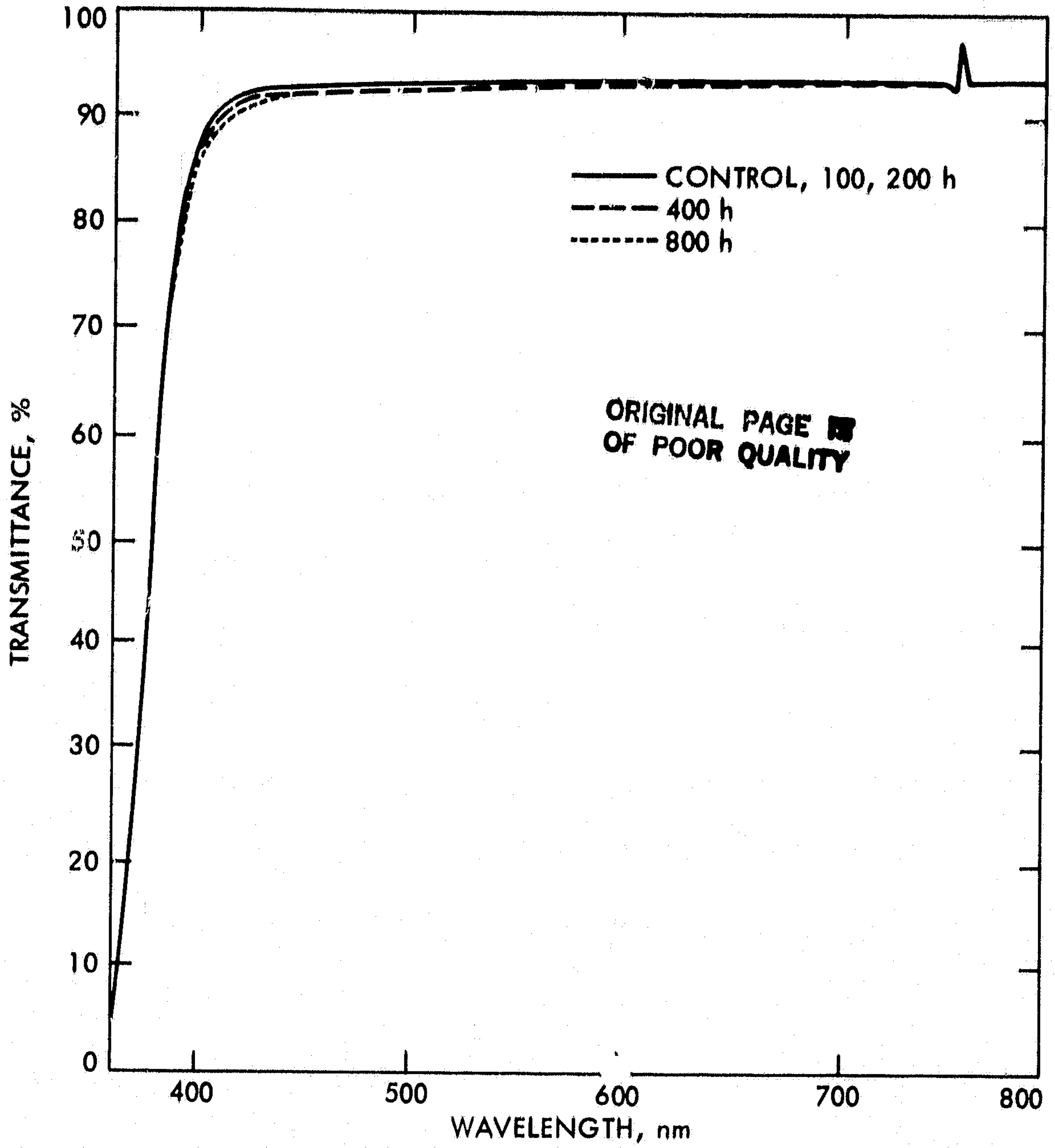

Figure 6. Change in Optical Transmittance as a Function of Open Photothermal Aging of EVA at 85°C

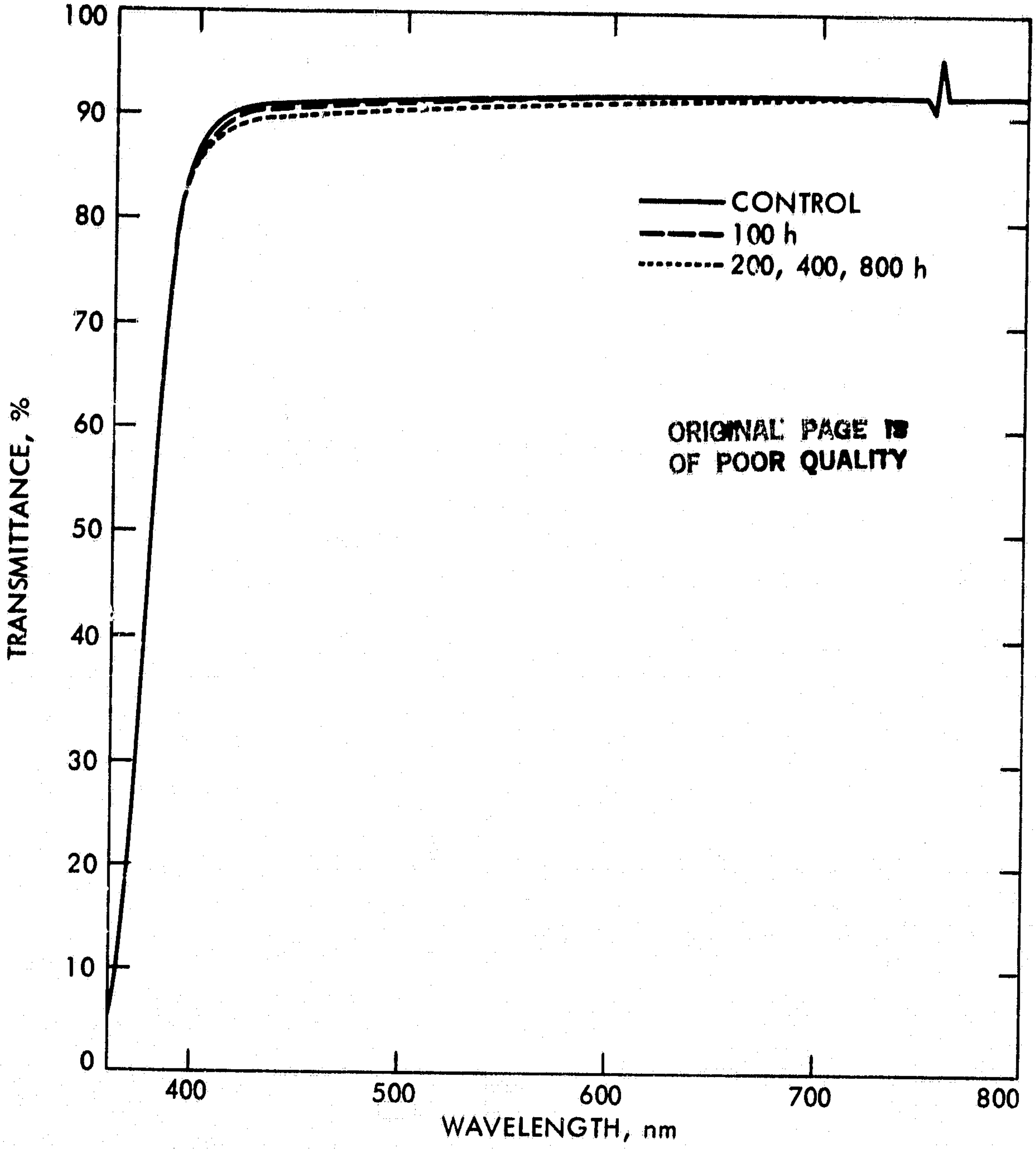

Figure 7. Change in Optical Transmittance as a Function of Covered Photothermal Aging of EVA at 85°C

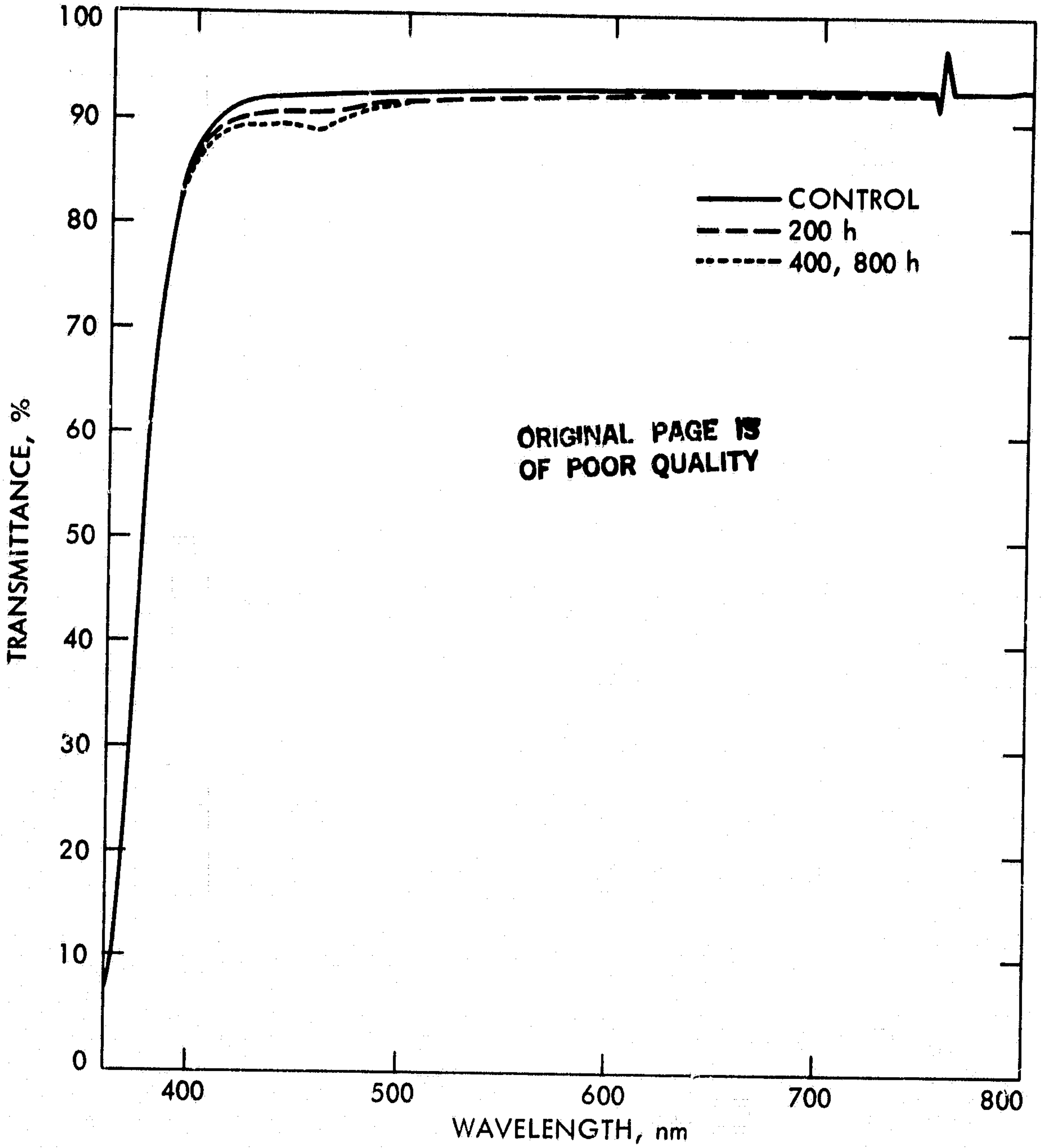

Figure 8. Change in Optical Transmittance as a Function of Thermal Aging of EVA at 85°C

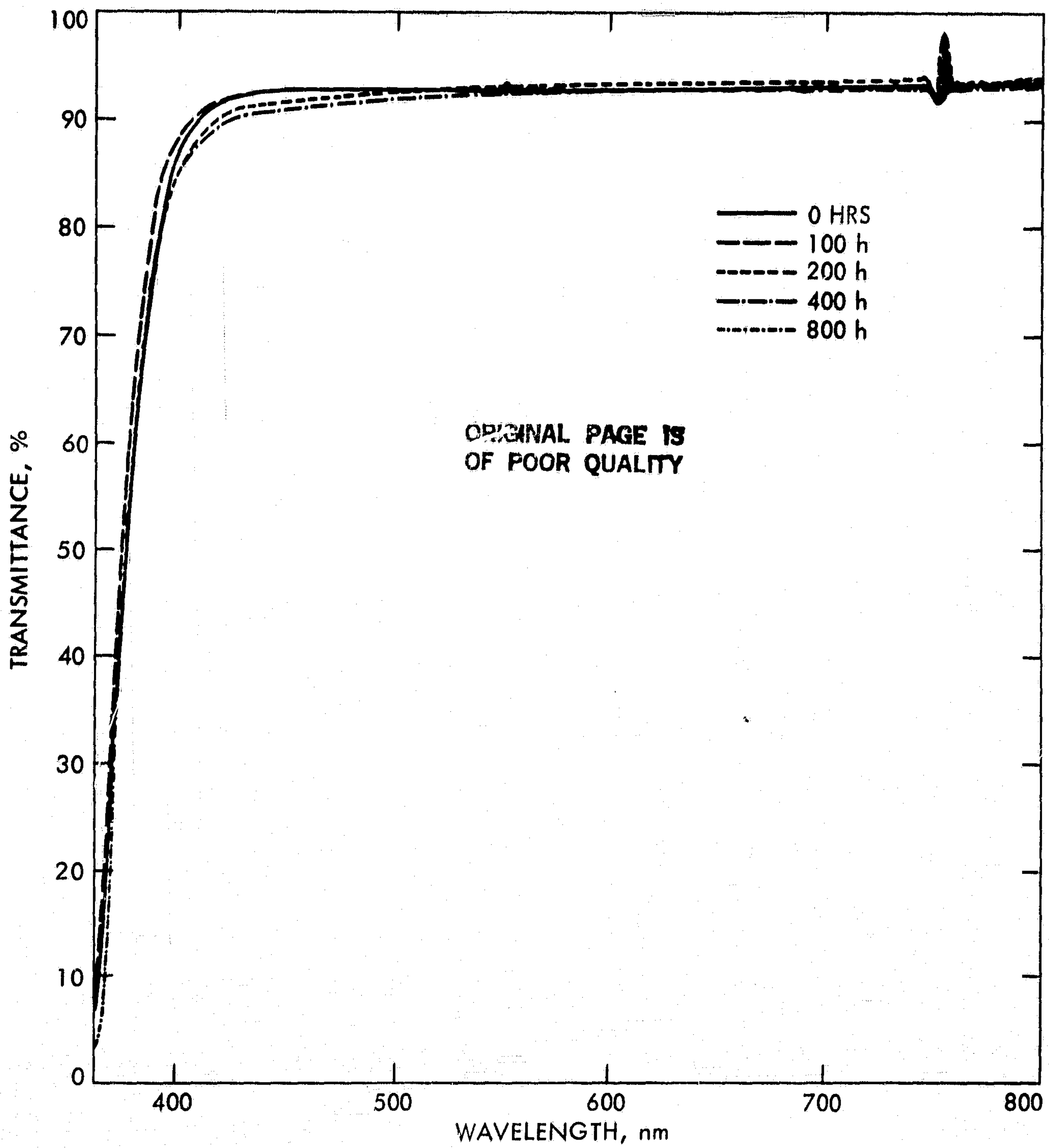

Figure 9. Change in Optical Transmittance as a Function of Open Photothermal Aging of EVA at 105°C

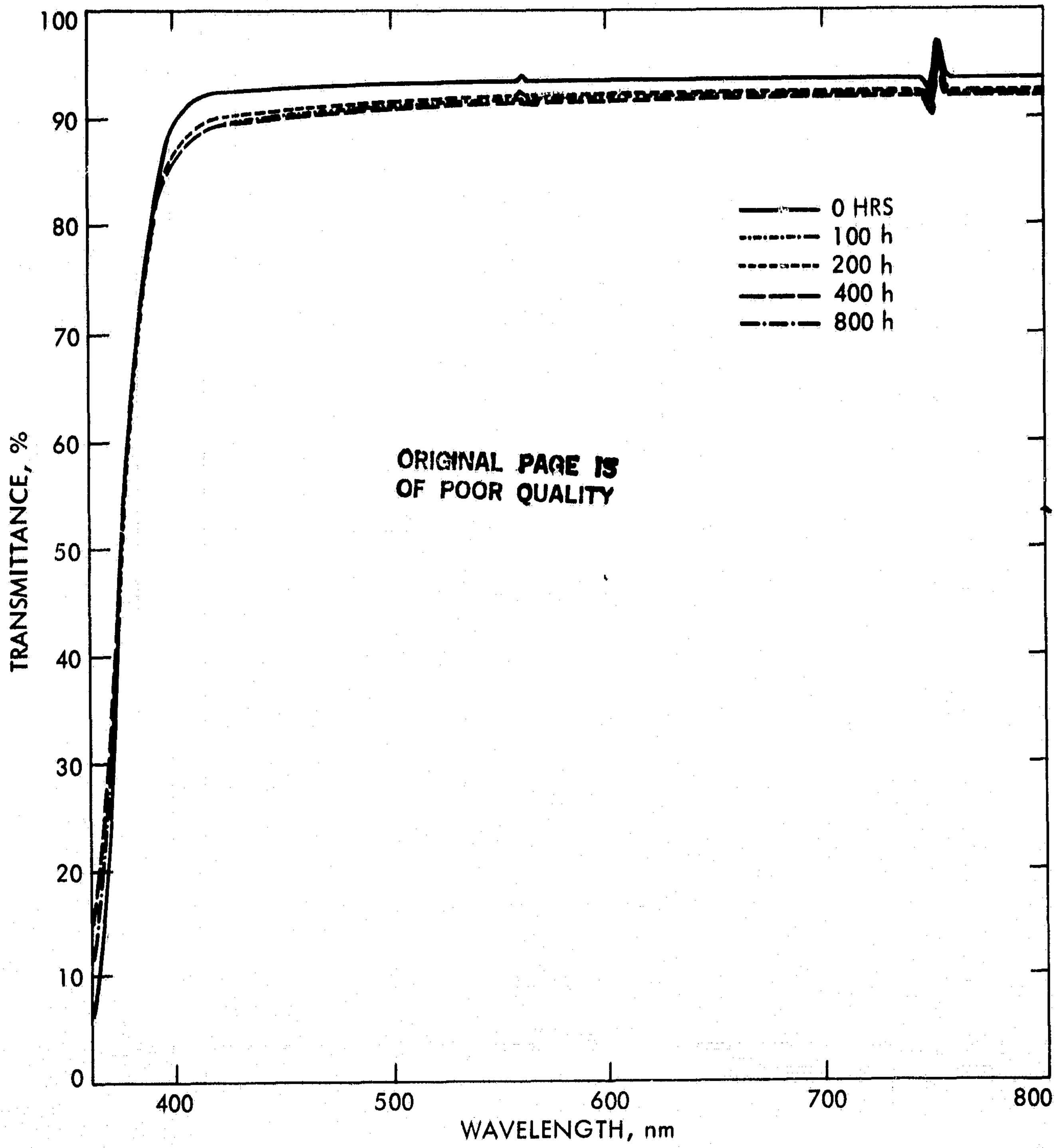

Figure 10. Change in Optical Transmittance as a Function of Covered Photothermal Aging of EVA at 105°C

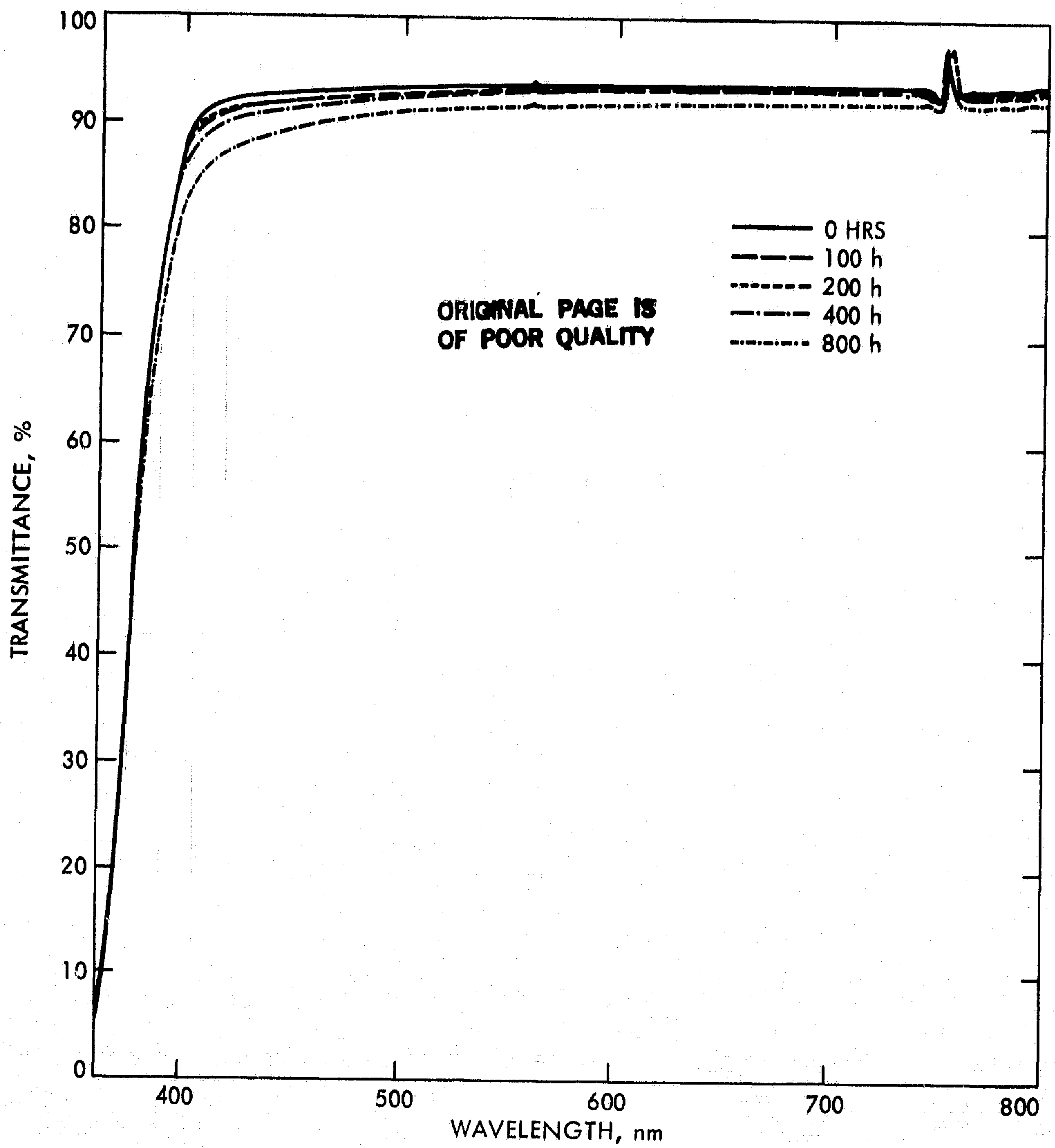

Figure 11. Change in Optical Transmittance as a Function of Thermal Aging of EVA at 105°C

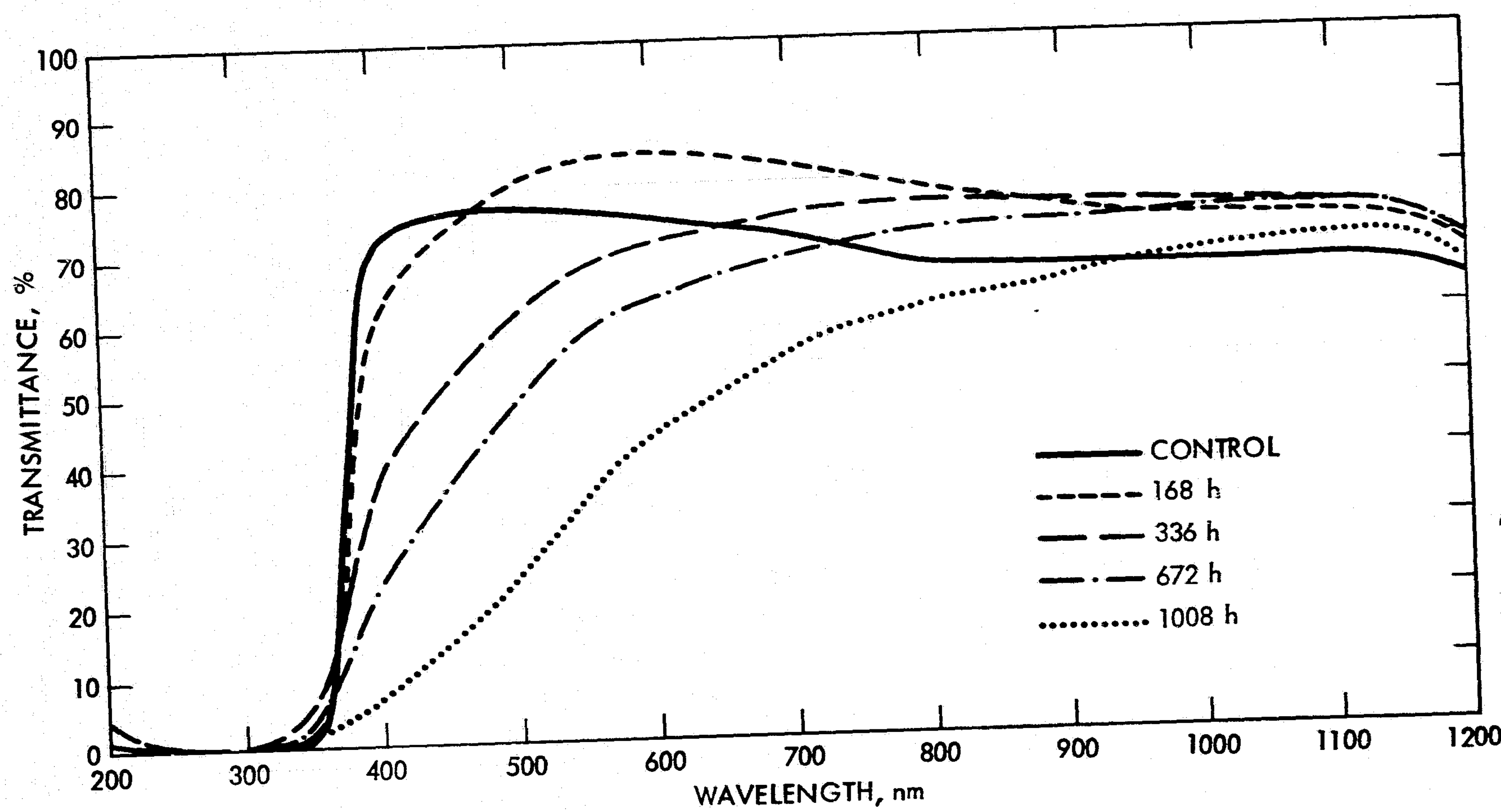

Figure 12. Change in Optical Transmittance as a Function of Covered Photothermal Aging of EVA at 135°C

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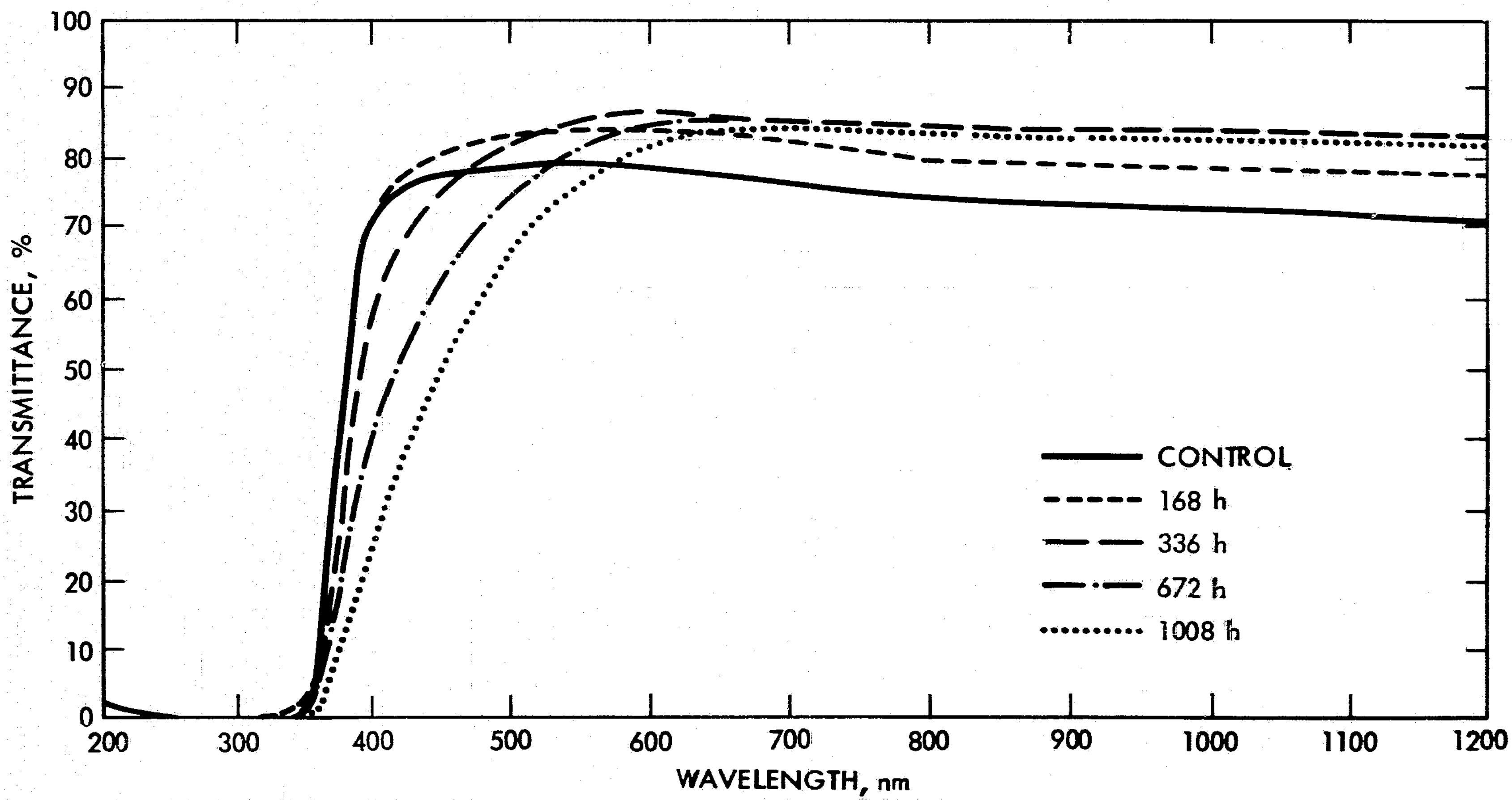

Figure 13. Change in Optical Transmittance as a Function of Thermal Aging of EVA at 135°C

B. MECHANICAL PROPERTIES

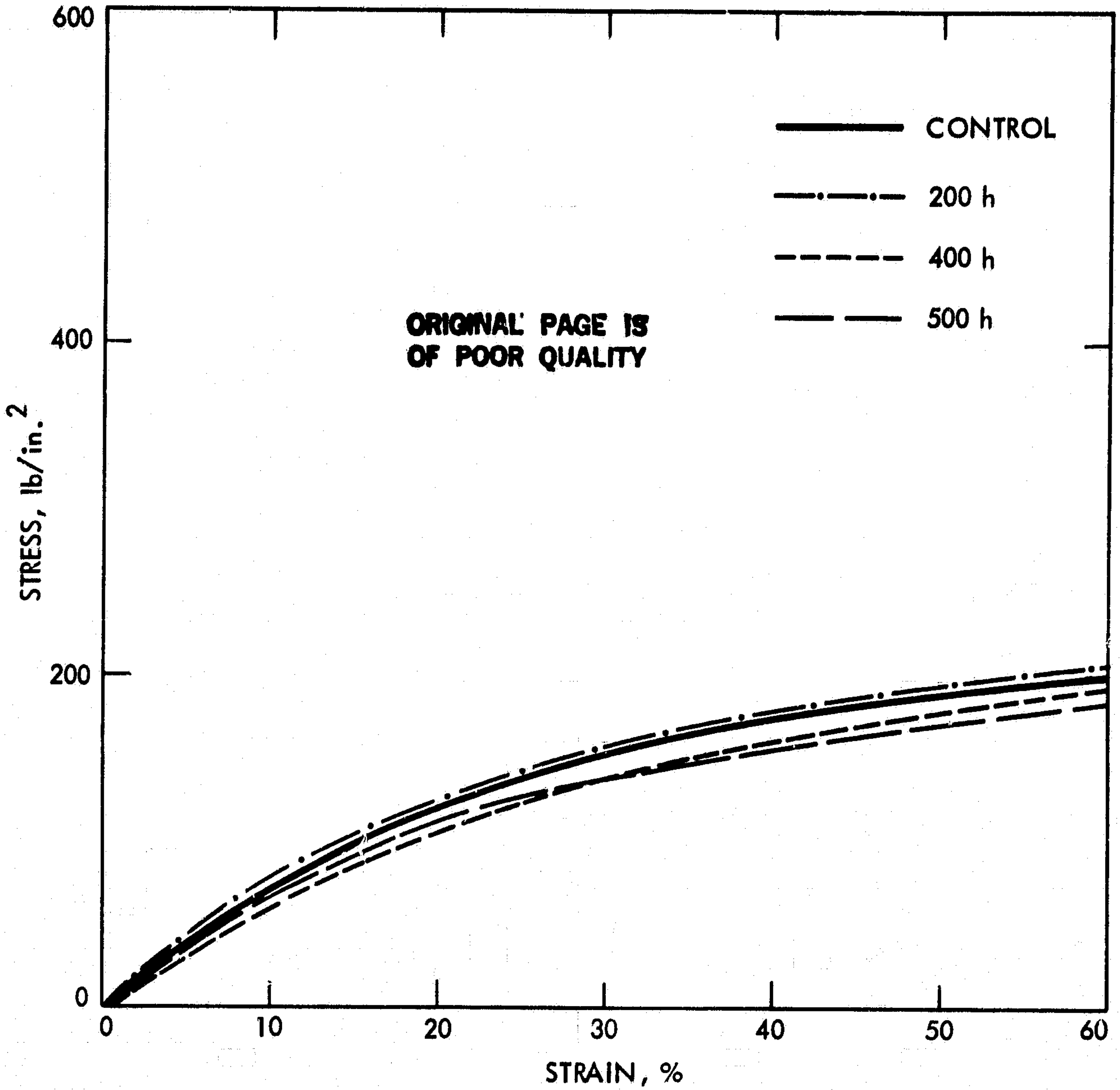

Figure 14. Change in Stress/Strain Response as a Function of Open Photothermal Aging of EVA at 70°C

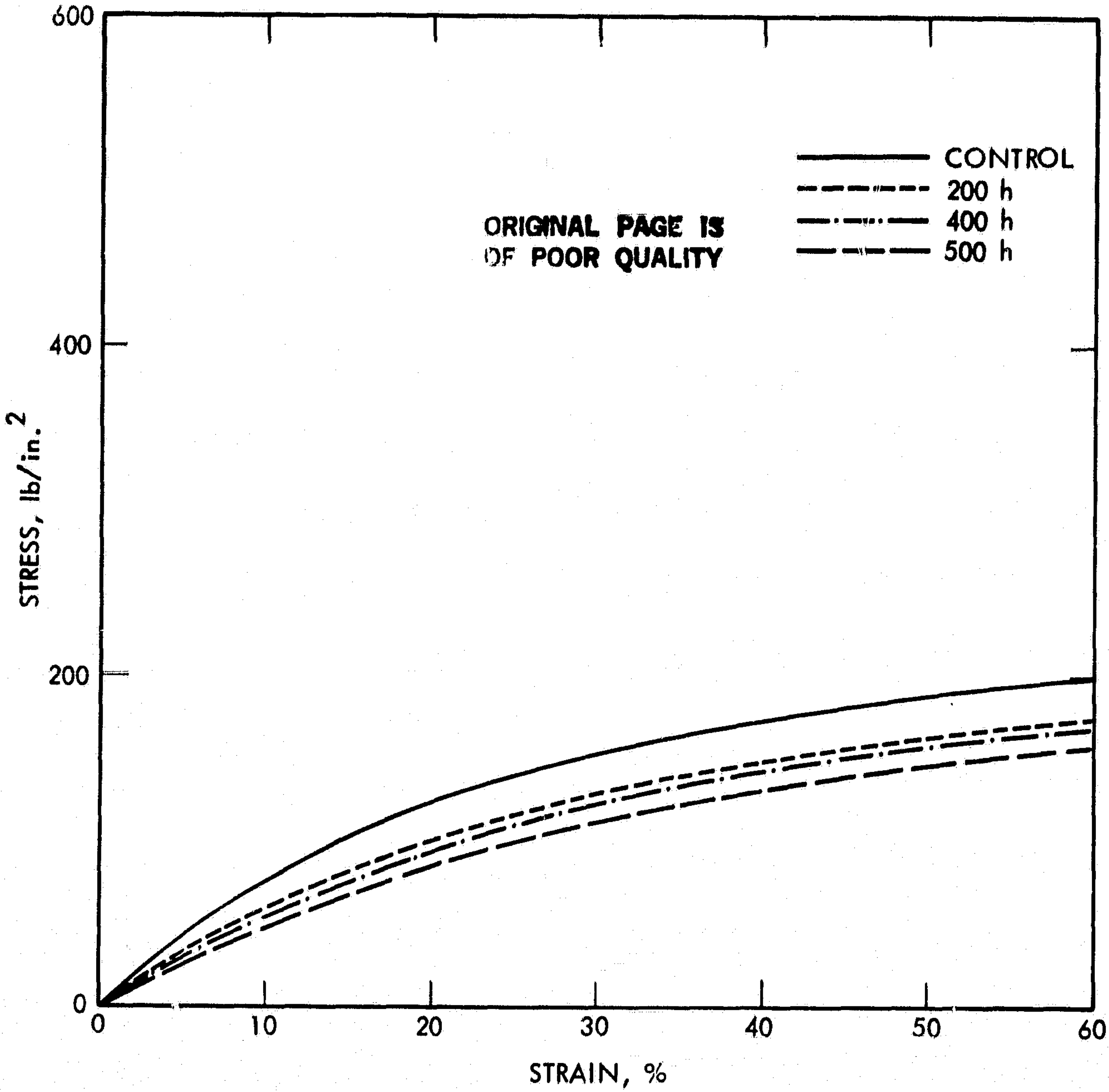

Figure 15. Change in Stress/Strain Response as a Function of Covered Photothermal Aging of EVA at 70°C

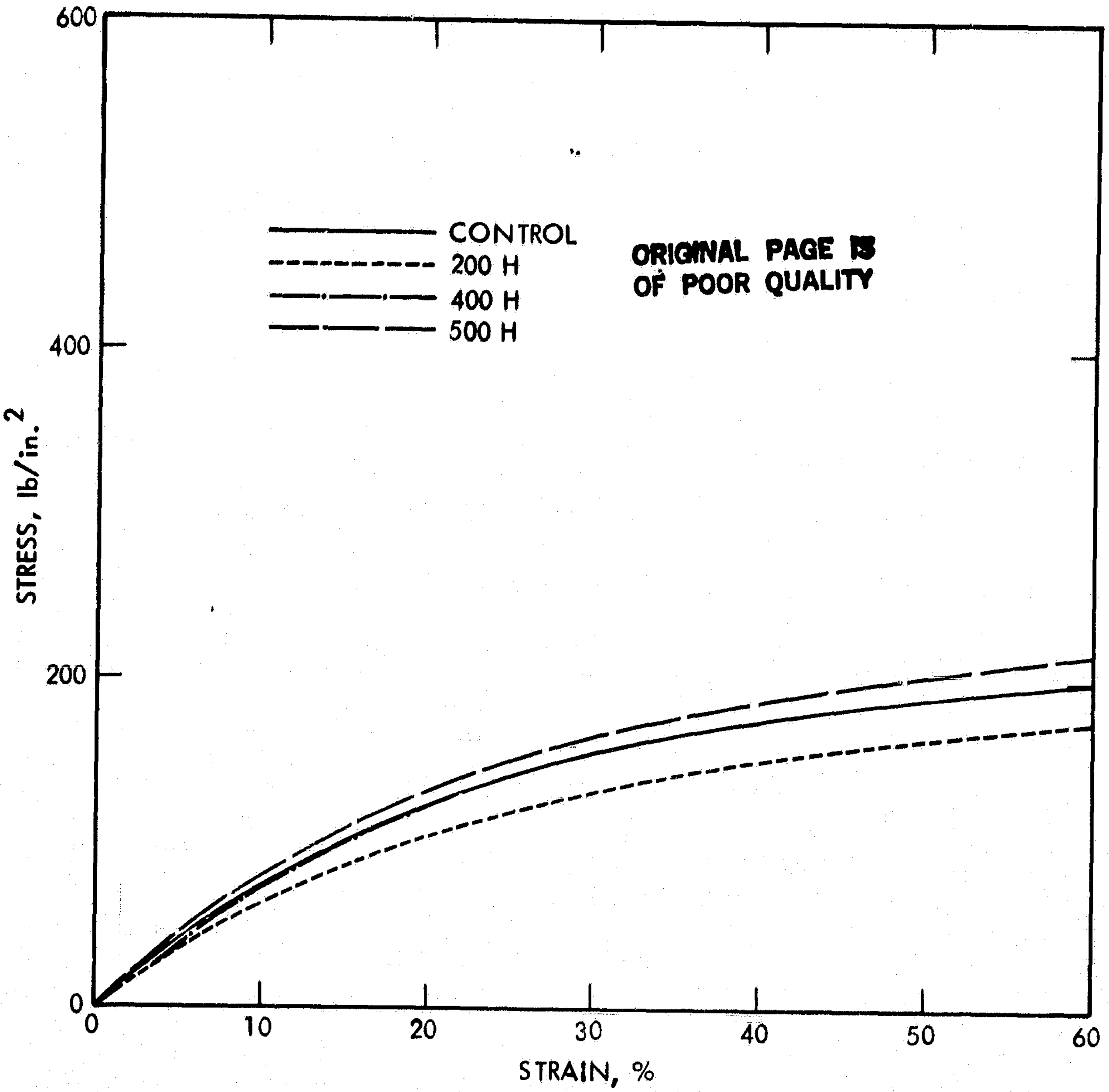

Figure 16. Change in Stress/Strain Response as a Function of Thermal Aging of EVA at 70°C

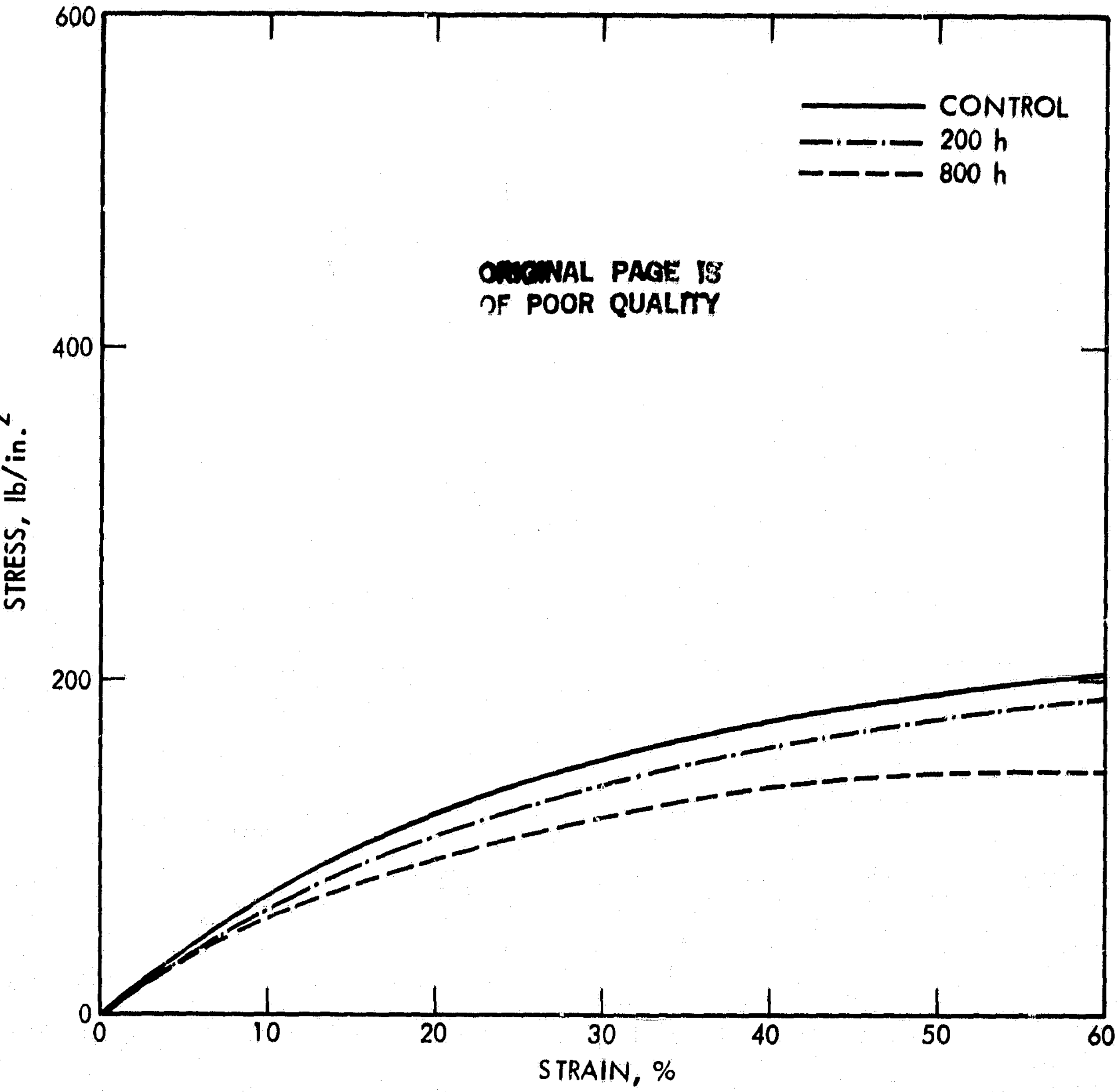

Figure 17. Change in Stress/Strain Response as a Function of Open Photothermal Aging of EVA at 85°C

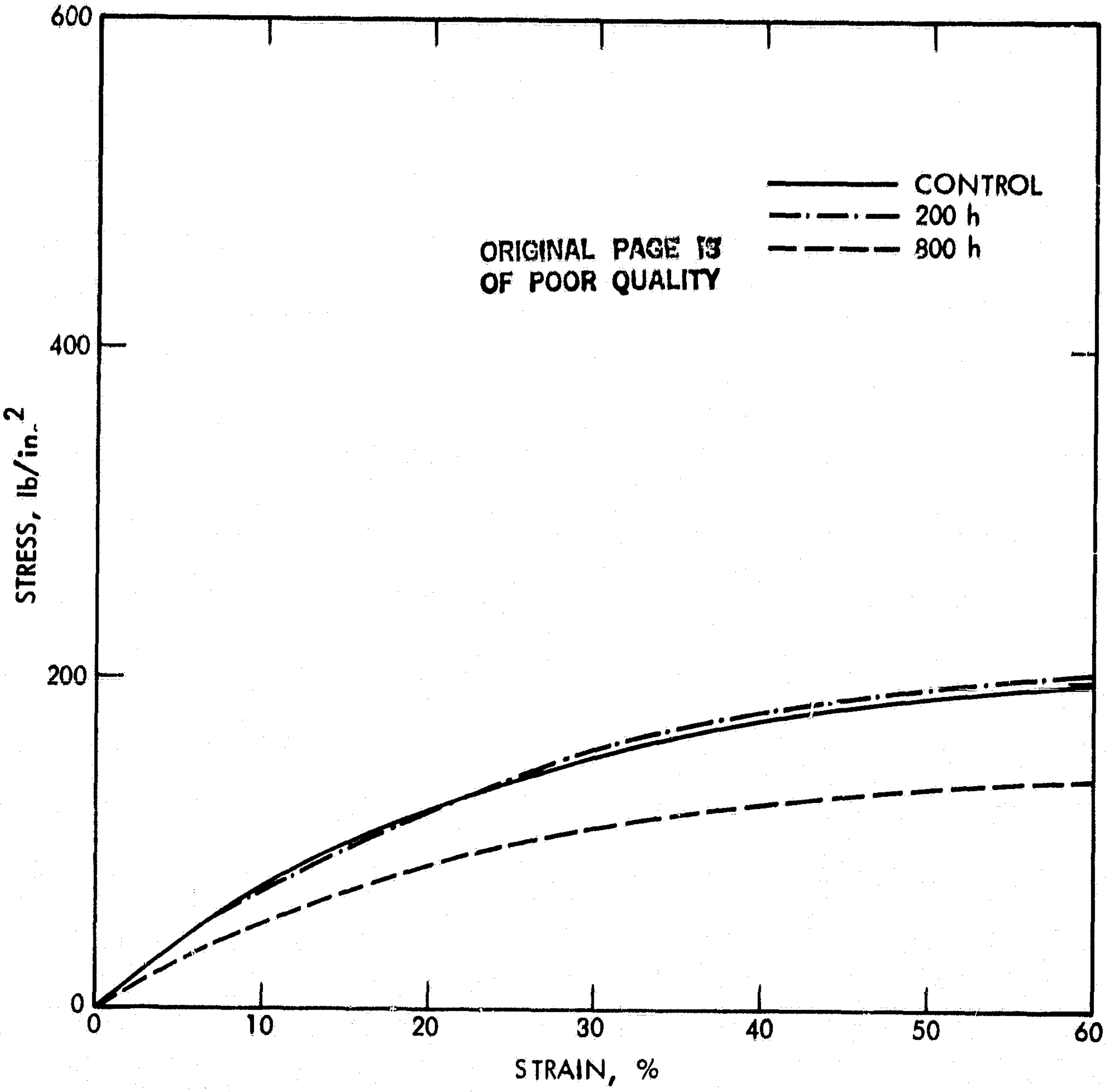

Figure 18. Change in Stress/Strain Response as a Function of Covered Photothermal Aging of EVA at 85°C

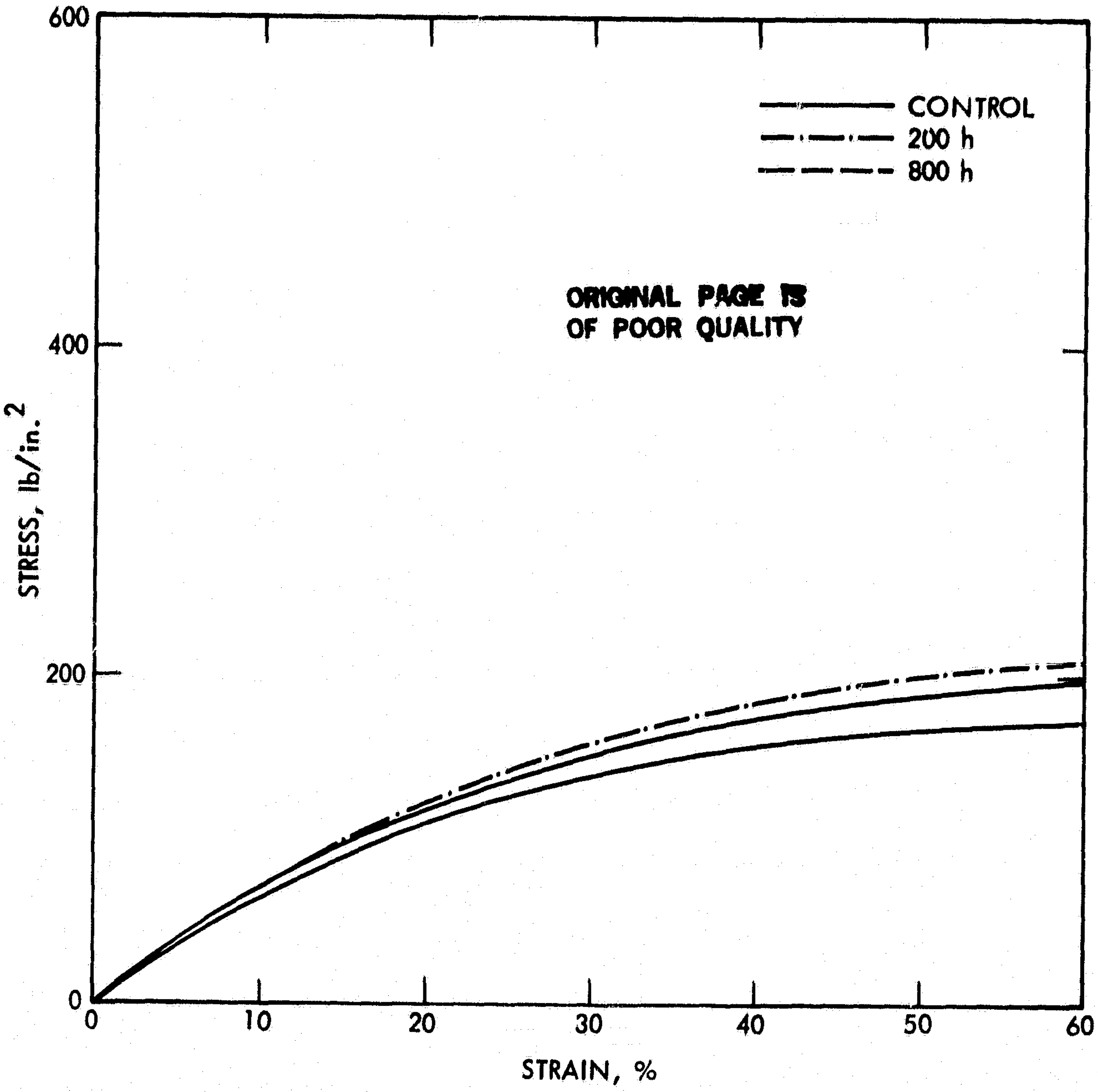

Figure 19. Change in Stress/Strain Response as a Function of Thermal Aging of EVA at 85°C

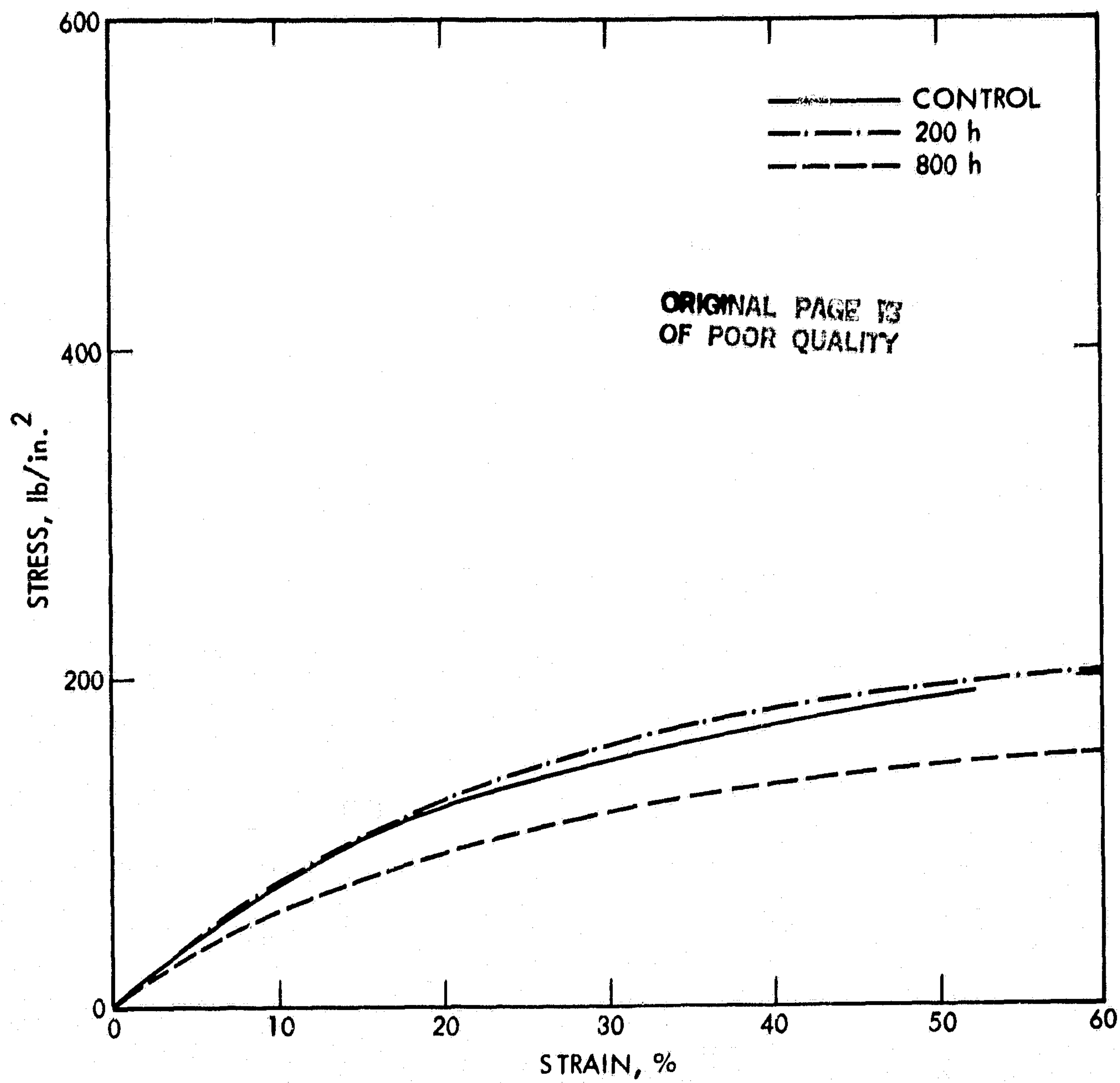

Figure 20. Change in Stress/Strain Response as a Function of Open Photothermal Aging of EVA at 105°C

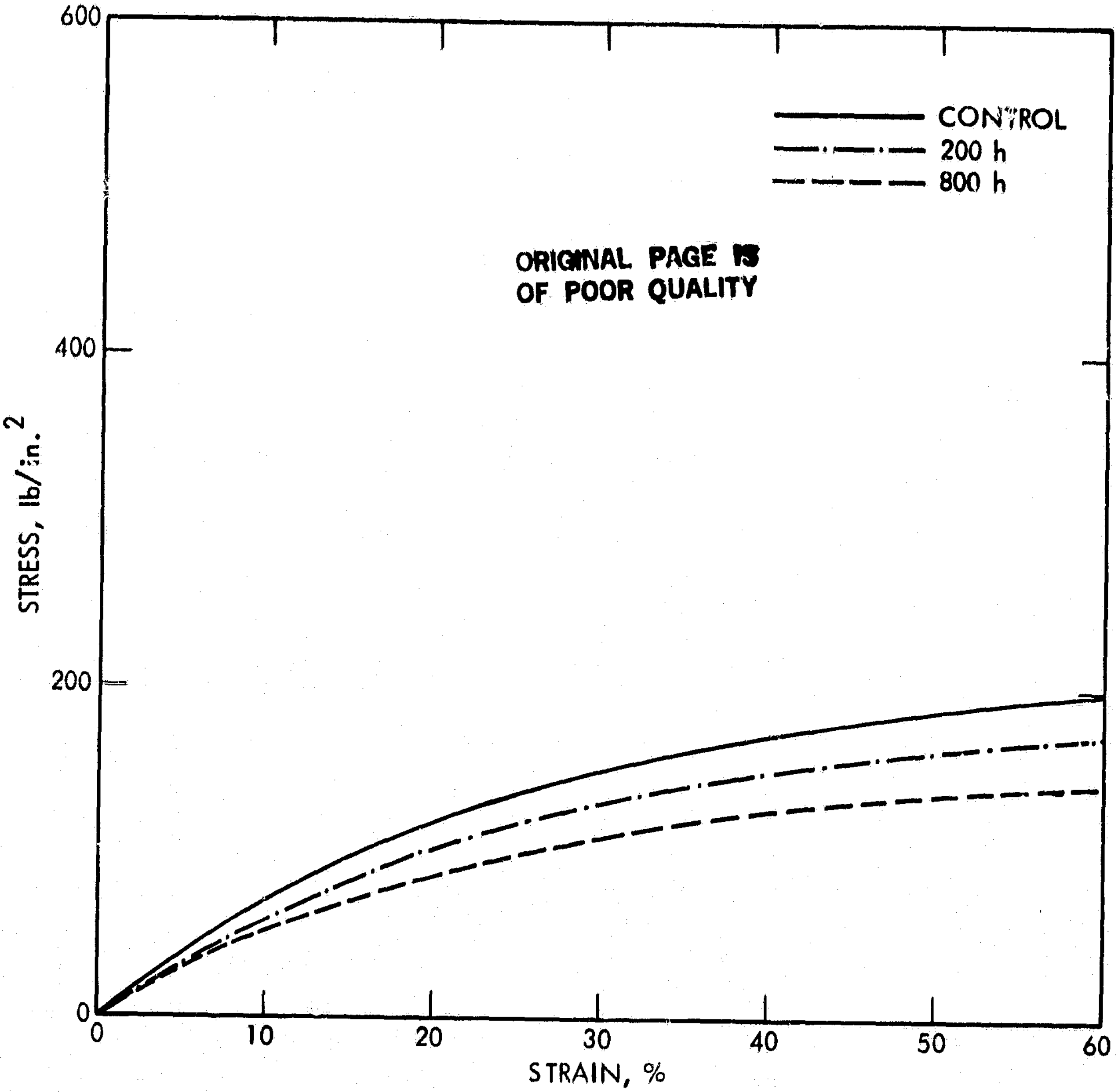

Figure 21. Change in Stress/Strain Response as a Function of Covered Photothermal Aging of EVA at 105°C

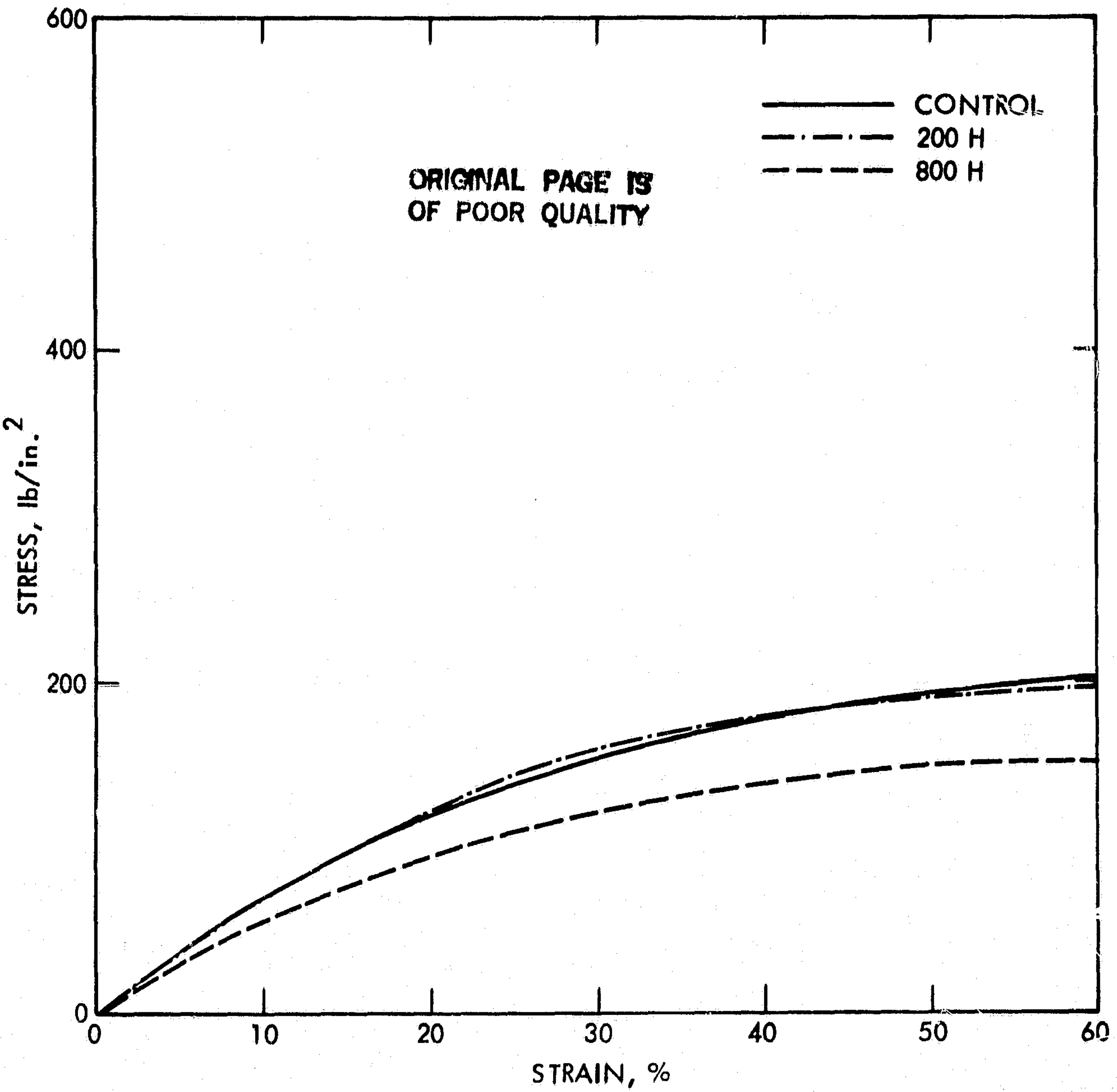

Figure 22. Change in Stress/Strain Response as a Function of Thermal Aging of EVA at 105°C

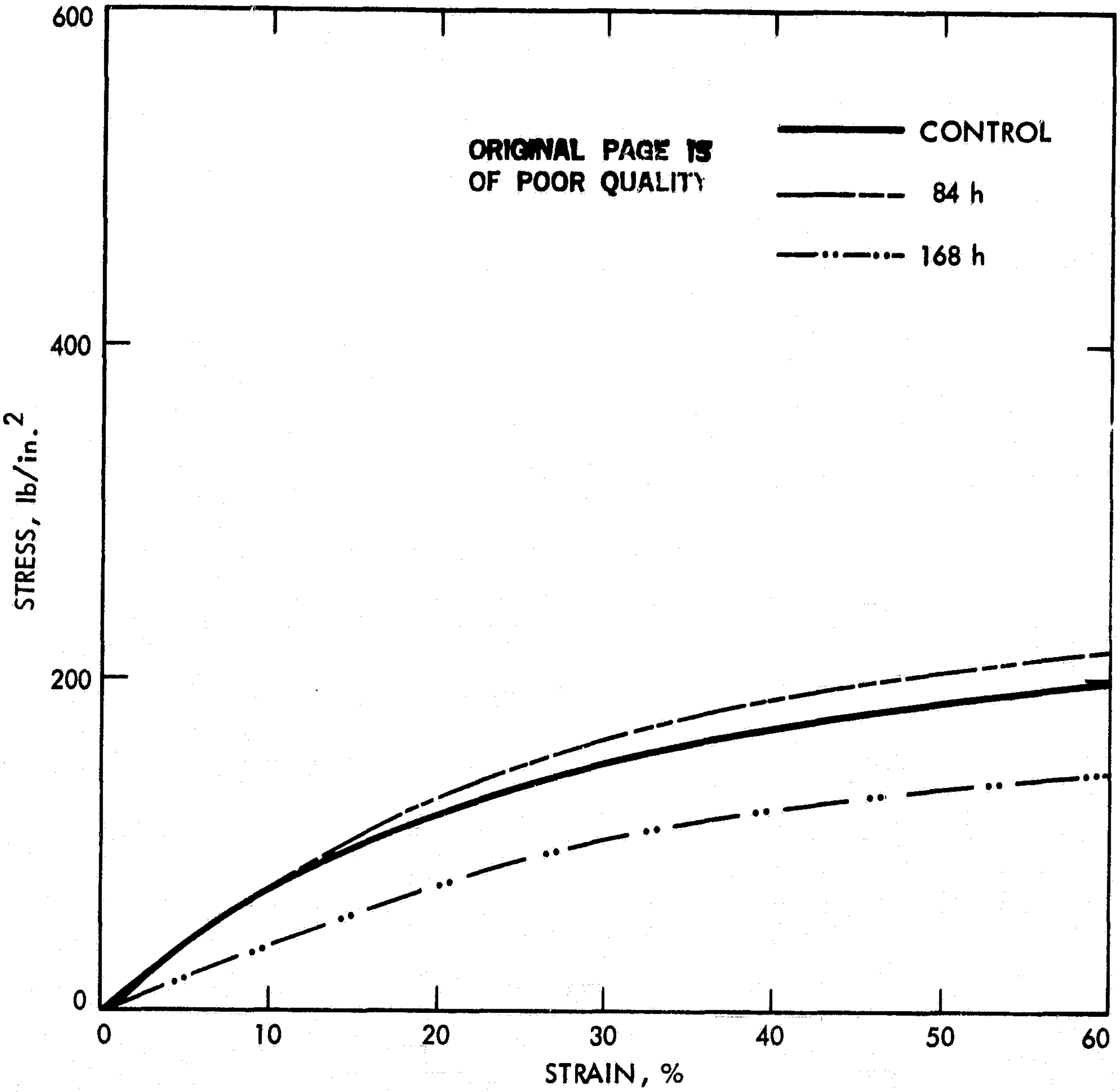

Figure 23. Change in Stress/Strain Response as a Function of Open Photothermal Aging of EVA at 135°C

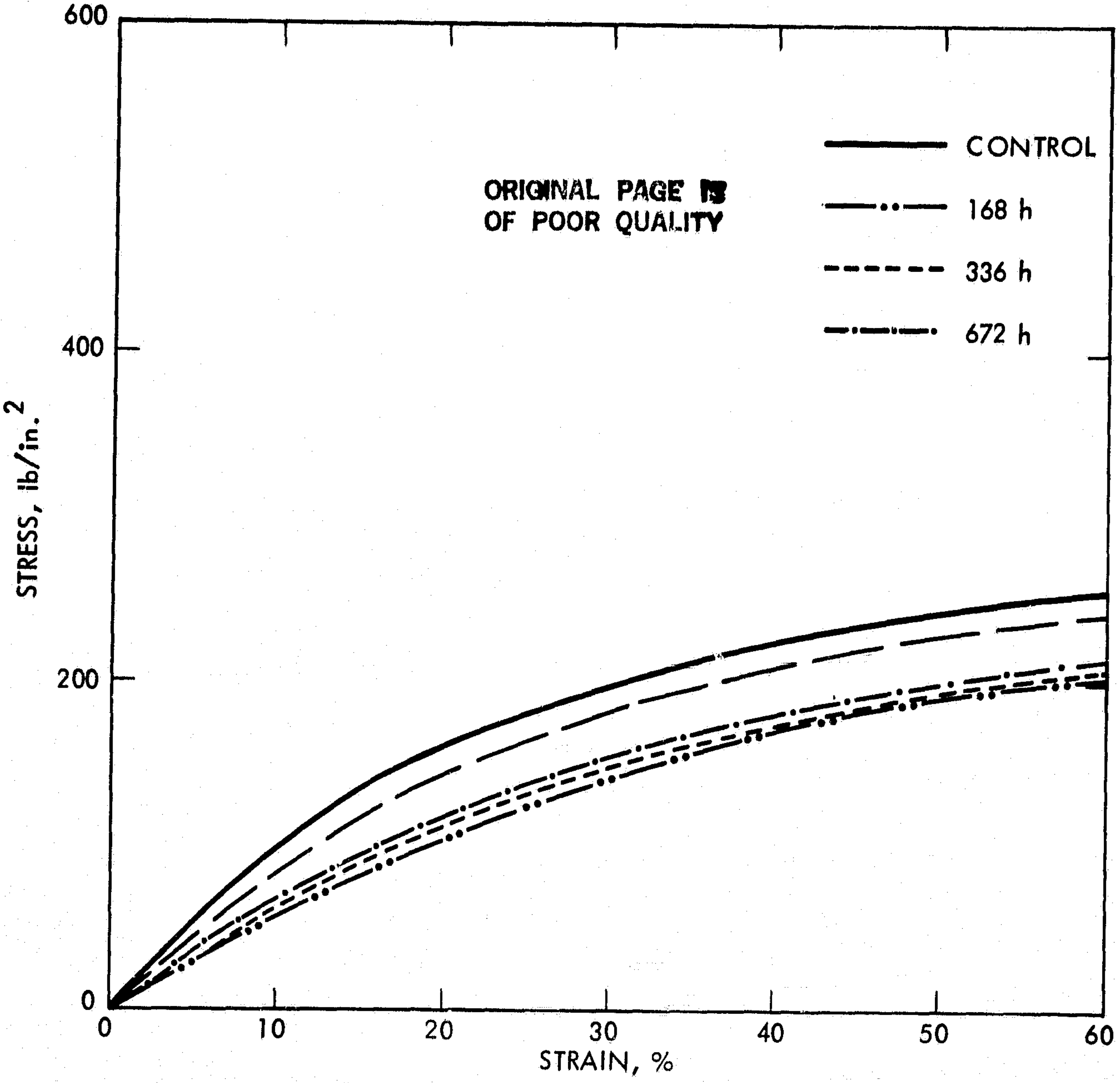

Figure 24. Change in Stress/Strain Response as a Function of Covered Photothermal Aging of EVA at 135°C

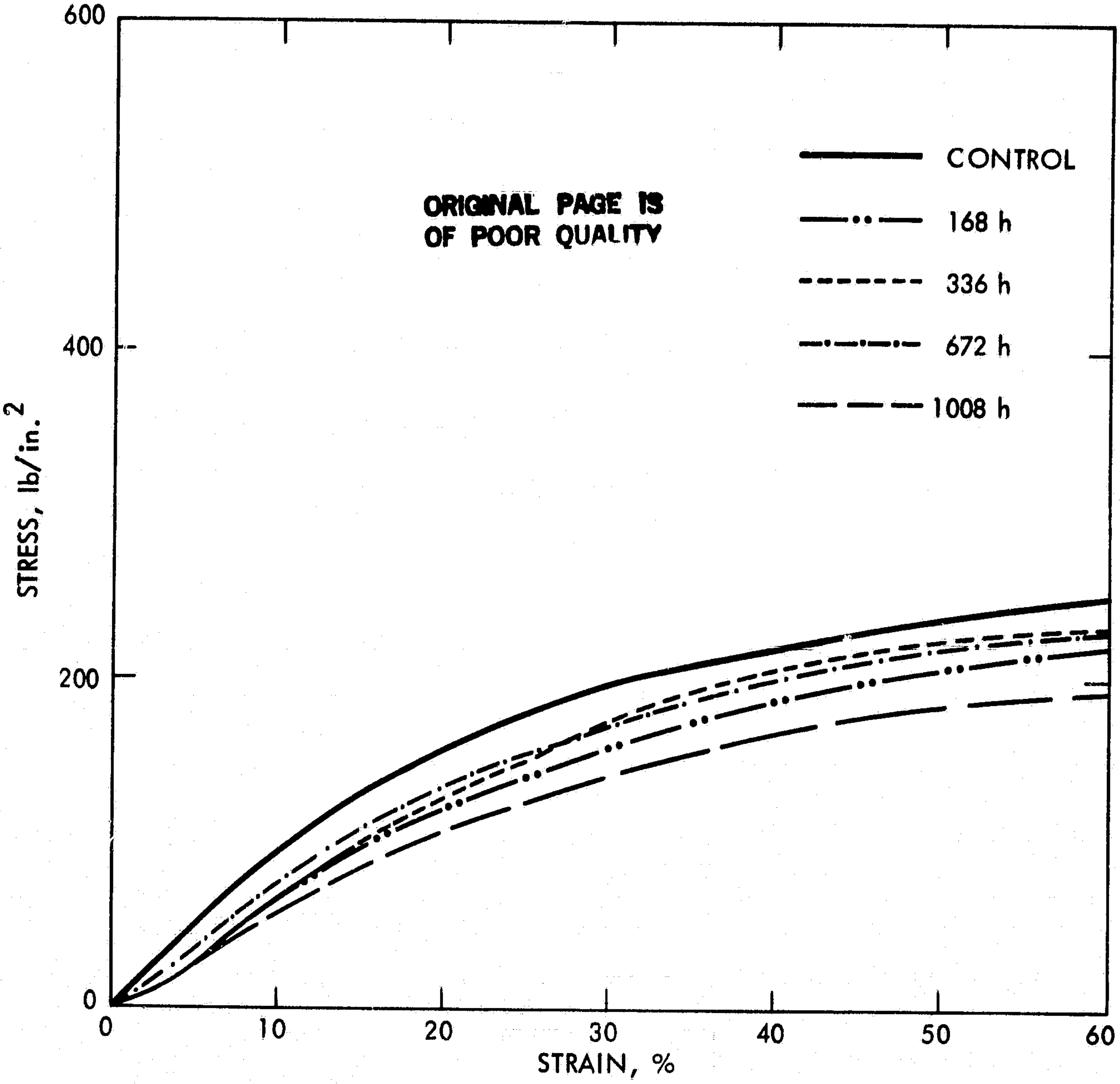

Figure 25. Change in Stress/Strain Response as a Function of Thermal Aging of EVA at 135°C

Table 4. Modulus at 5% Strain as a Function of Open Photothermal Aging of EVA at 30°C, 70°C, 85°C, 105°C, and 135°C

TEMPERATURE °C	TIME OF AGING, h	MODULUS, $lb/in.^2$ 5% STRAIN
ROOM TEMP. (30)	0.0	1015
70	400 500	586 650
85	200 800	582 628
105	200 800	836 566
135	84 168	734 *

*SAMPLE DEGRADED, UNABLE TO OBTAIN MODULUS DATA

Table 5. Modulus at 5% Strain as a Function of Covered Photothermal Aging of EVA at 30°C, 70°C, 85°C, 105°C, and 135°C

TEMPERATURE, °C	TIME OF AGING, h	MODULUS, lb/in.^{2} 5% STRAIN
ROOM TEMP. (30)	0	1015
70	200 500	671 630
85	200 800	846 504
105	200 800	550 664
135	168 336 672 1008	600 580 625 869

Table 6. Modulus at 5% Strain as a Function of Thermal Aging of EVA at 30°C, 70°C, 85°C, 105°C, and 135°C

TEMPERATURE, °C	TIME OF AGING, h	MODULUS, lb/in.^{2} 5% STRAIN
ROOM TEMP. (30)	0	1015
70	200 400 500	855 554 640
85	200 800	577 700
105	200 800	786 610
135	168 336 672 1008	560 582 742 870

C. WEIGHT LOSS

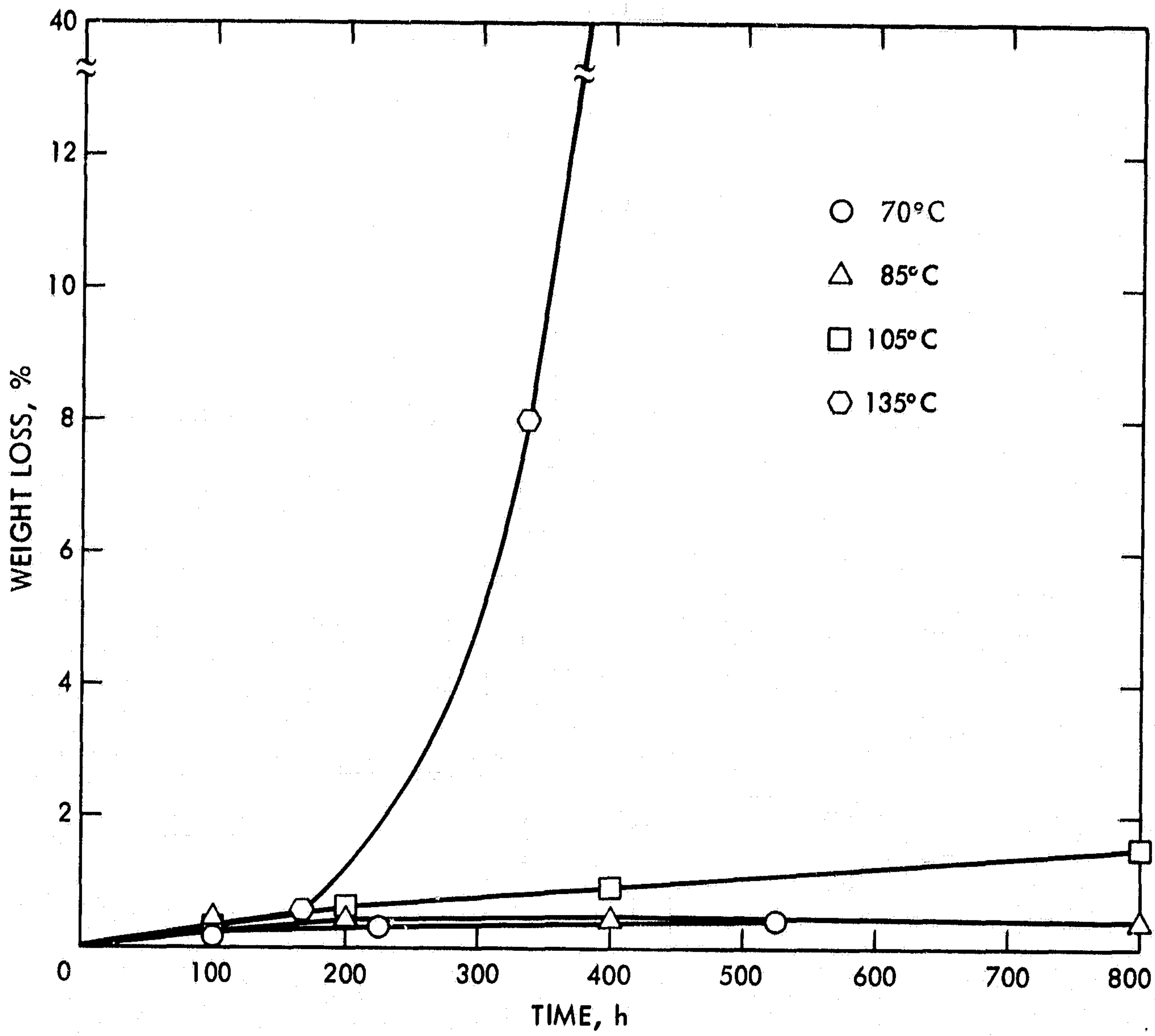

Figure 26. Weight Loss as a Function of Open Photothermal Aging of EVA at 70°C, 85°C, 105°C, and 135°C

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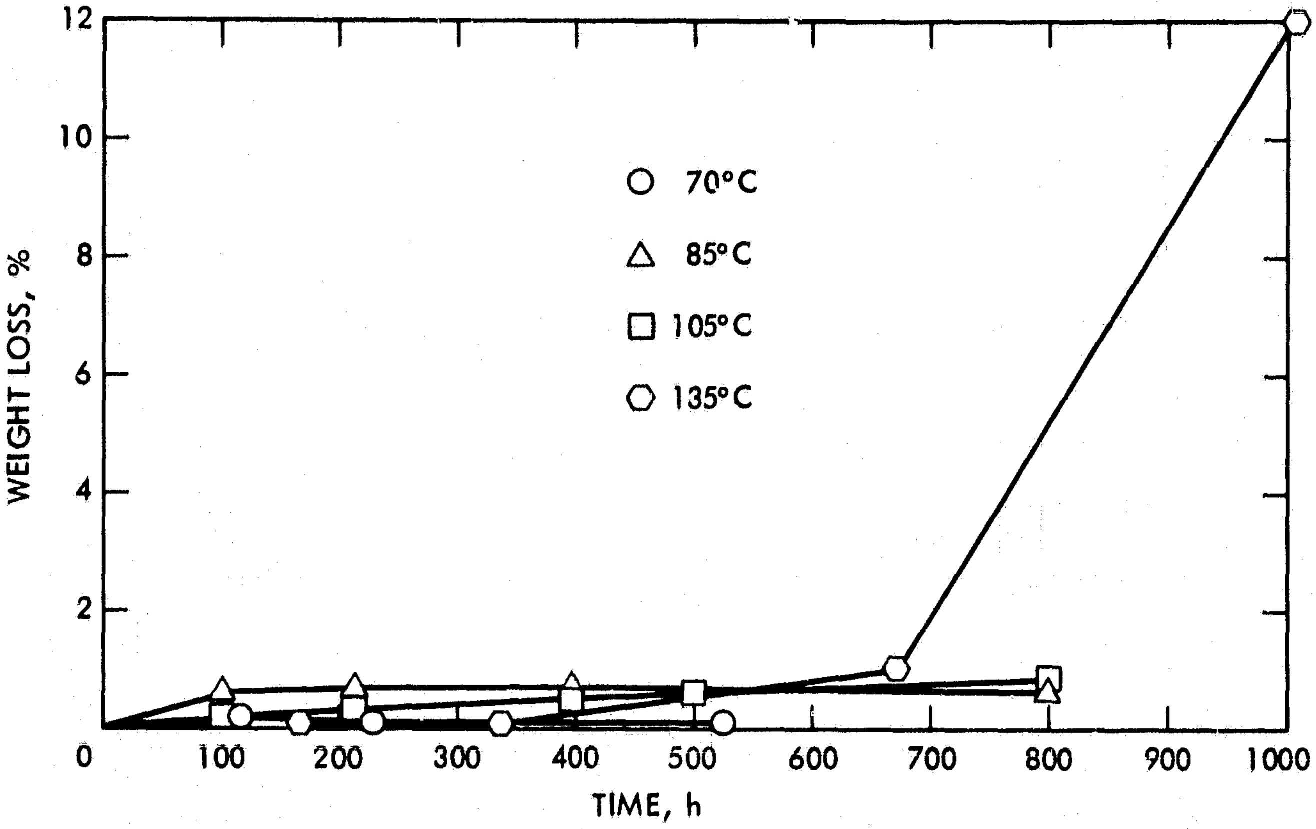

Figure 27. Weight Loss as a Function of Covered Photothermal Aging of EVA at 70°C, 85°C, 105°C, and 135°C

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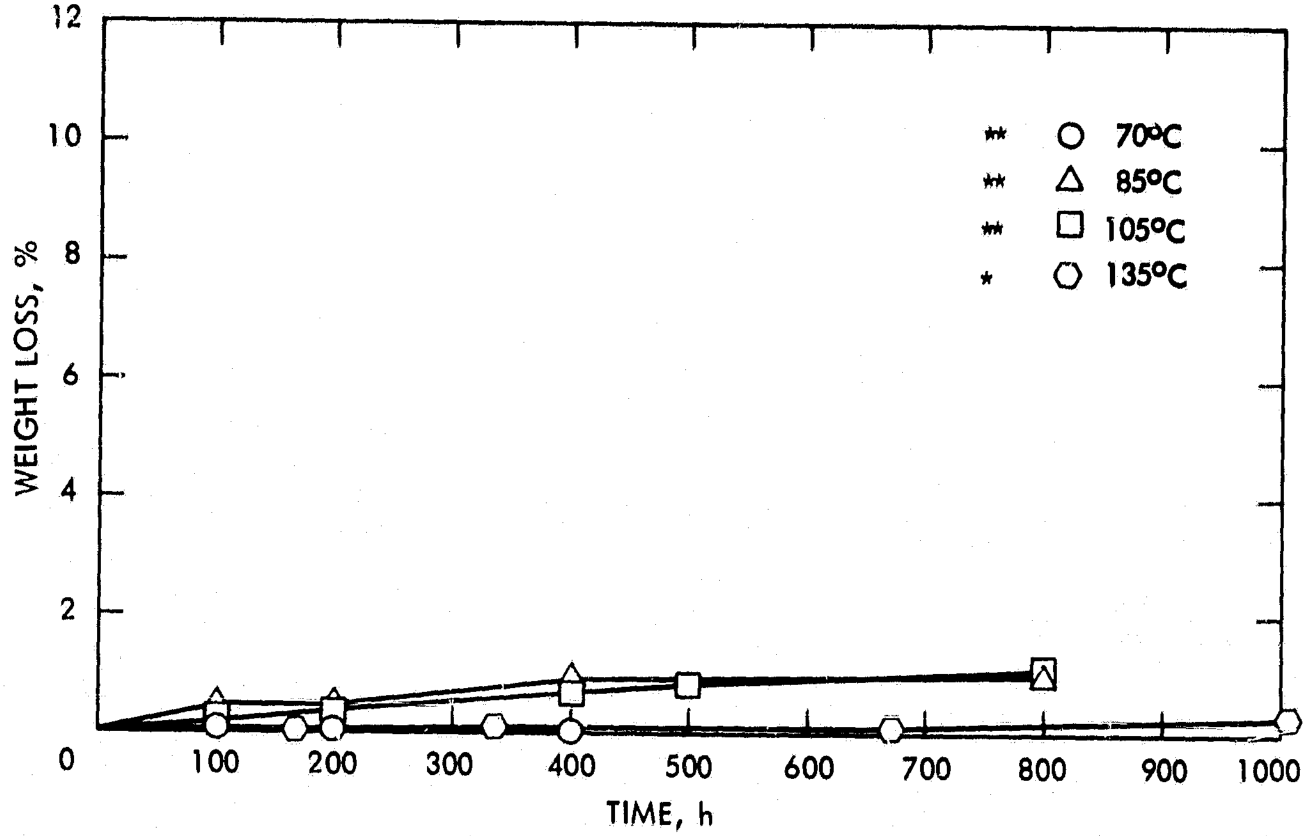

Figure 28. Weight Loss as a Function of Thermal Aging of EVA at 70°C, 85°C, 105°C, and 135°C

D. OTHER PROPERTIES

Table 7. Sol/Gel and Molecular Weight Data as a Function of Open Photothermal Aging of EVA at 30°C, 70°C, 85°C, 105°C, and 135°C

T, °C	TIME OF AGING, h	CROSSLINKING DENSITY, MOL/cm^3	SOL, %	GEL, %	MOL WT (SOL)
30	0	5.62×10^{-6}	30	70	206,000
85	800	4.32×10^{-6}	33	67	118,000
105	200	3.11×10^{-6}	33	67	
	800	5.86×10^{-6}	33	67	91,000
135	84	7.0×10^{-6}			
	168	5.6×10^{-6}			
	336	11.3×10^{-6}	55	45	
	1008	20.4×10^{-6}	22	78	

Table 8. Sol/Gel and Molecular Weight Data as a Function of Covered Photothermal Aging of EVA at 30°C, 70°C, 85°C, 105°C, and 135°C

T, °C	TIME OF AGING, h	CROSSLINKING DENSITY, MOL/cm^3	SOL, %	GEL, %	MOL WT (SOL)
30	0	5.62×10^{-6}	30	70	206,000
85	800	7.8×10^{-6}	29	71	75,000
105	800	10.10×10^{-6}	34	66	44,000
135	168	7.1×10^{-6}	39	61	
	336	33.8×10^{-6}	29	71	
	672	72.8×10^{-6}	26	74	
	1008	39.8×10^{-6}	18	82	

Table 9. Sol/Gel and Molecular Weight Data as a Function of Thermal Aging of EVA at 30°C, 70°C, 85°C, 105°C, and 135°C

T °C	TIME OF AGING, h	CROSSLINKING DENSITY, MOL/cm^3	SOL, %	GEL, %	MOL WT (SOL)
30	0	5.62×10^{-6}	30	70	206,000
85	800	2.29×10^{-6}	35	65	168,000
105	800	1.33×10^{-6}	37	63	174,000
135	168	6.76×10^{-6}	26	74	
	336	5.34×10^{-6}	30	70	
	672	5.59×10^{-6}	30	70	
	1008	6.09×10^{-6}	33	67	

SECTION III

PVB (MONSANTO SAFLEX)

The following figures and tables offer data on optical transmittance (Figures 29 through 33); mechanical properties (Figures 34 through 39, Tables 10 through 12); weight loss (Figures 40 through 42) of PVB (Mansanto Saflex).

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A. OPTICAL TRANSMITTANCE

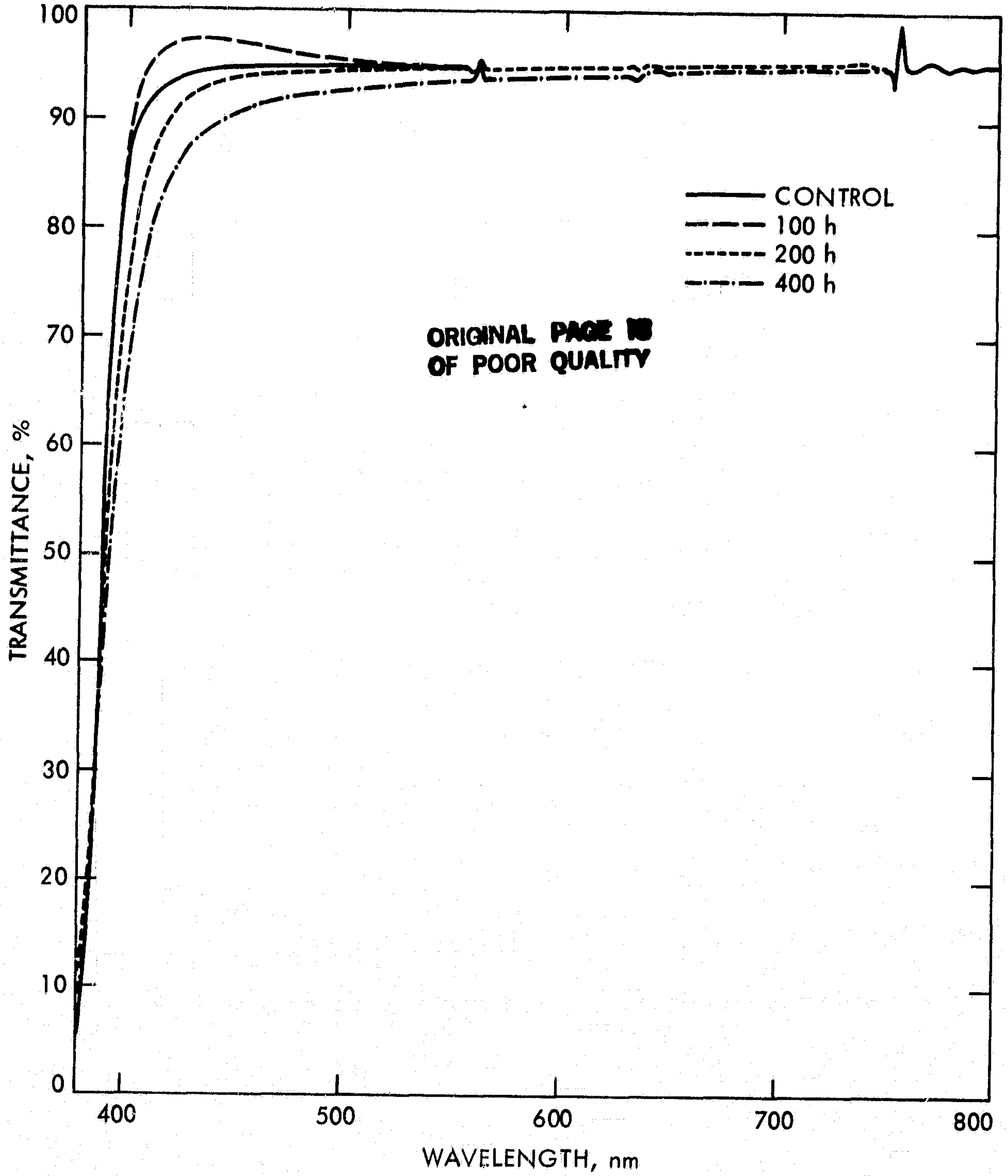

Figure 29. Change in Optical Transmittance as a Function of Open Photothermal Aging of PVB at 70°C

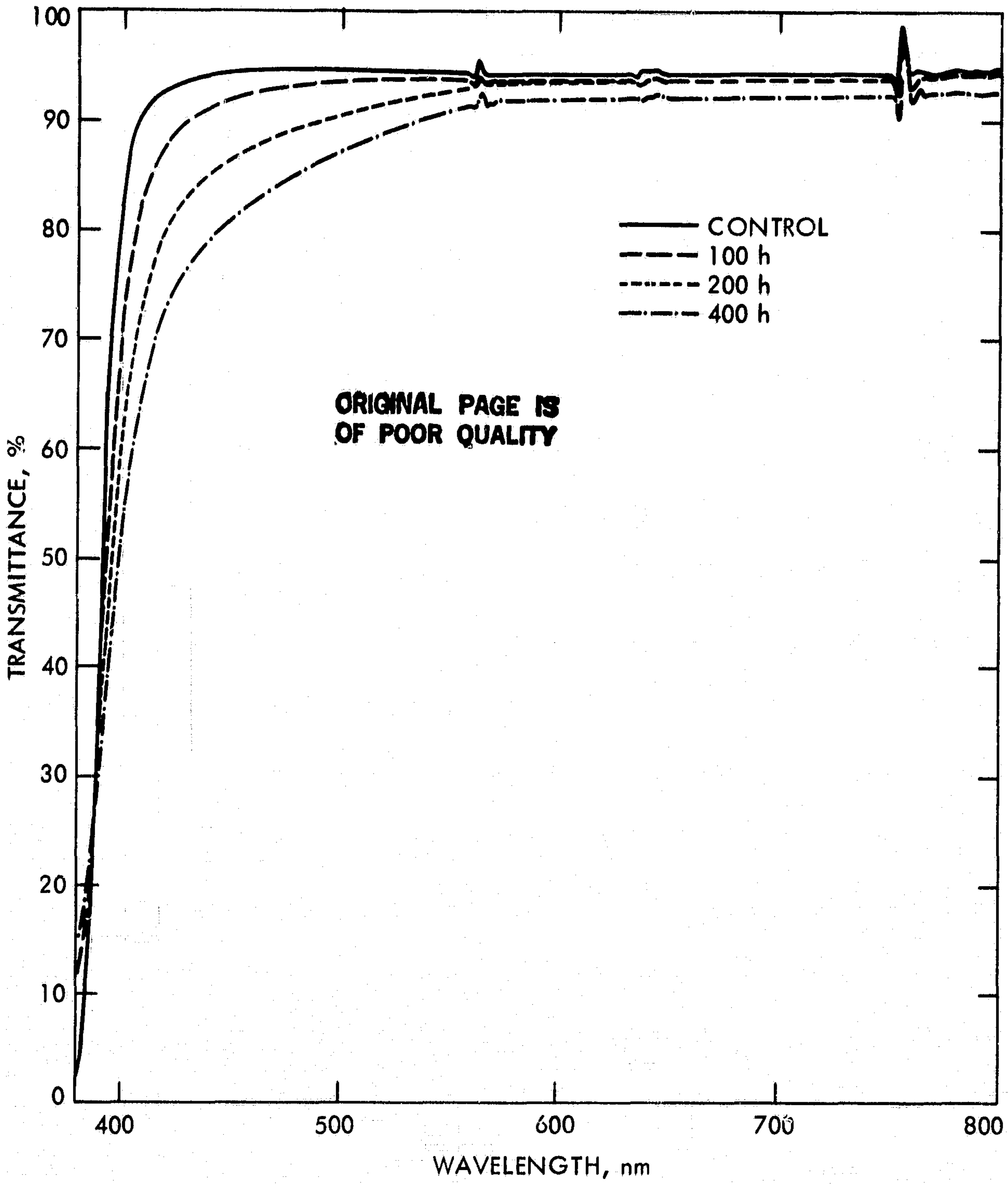

Figure 30. Change in Optical Transmittance as a Function of Covered Photothermal Aging of PVB at 70°C

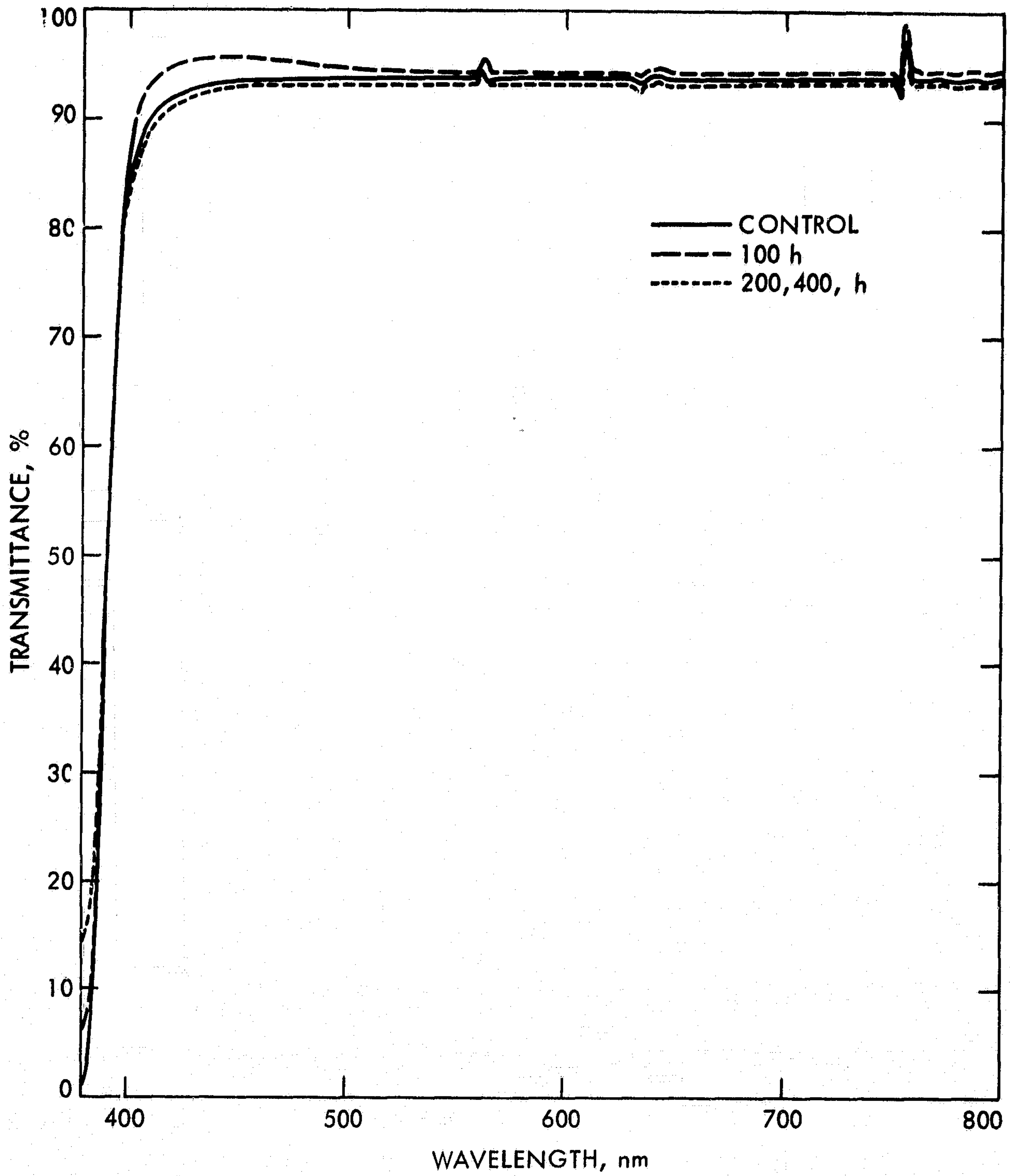

Figure 31. Change in Optical Transmittance as a Function of Thermal Aging of PVB at 70°C

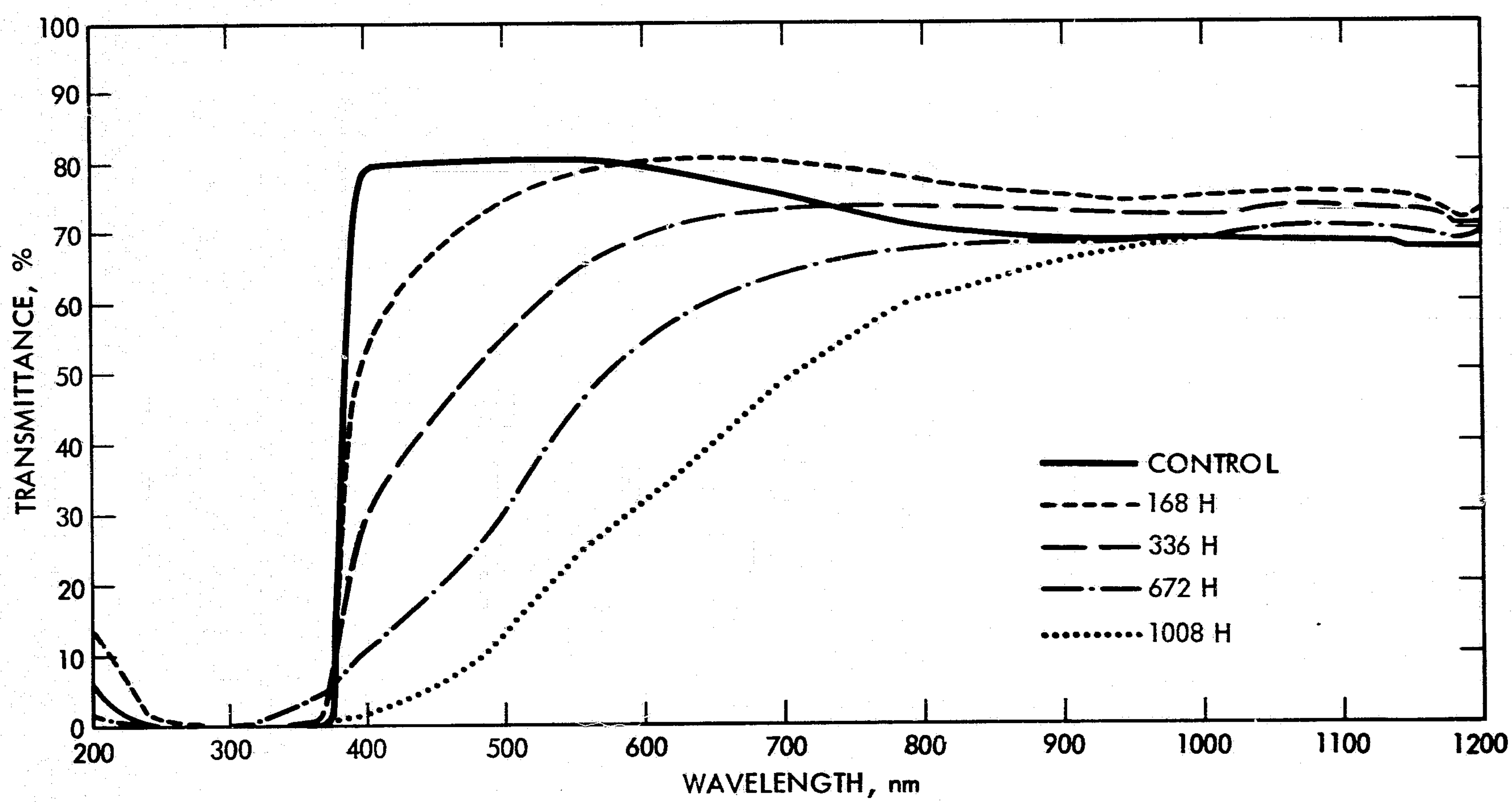

Figure 32. Change in Optical Transmittance as a Function of Covered Photothermal Aging of PVB at 135°C

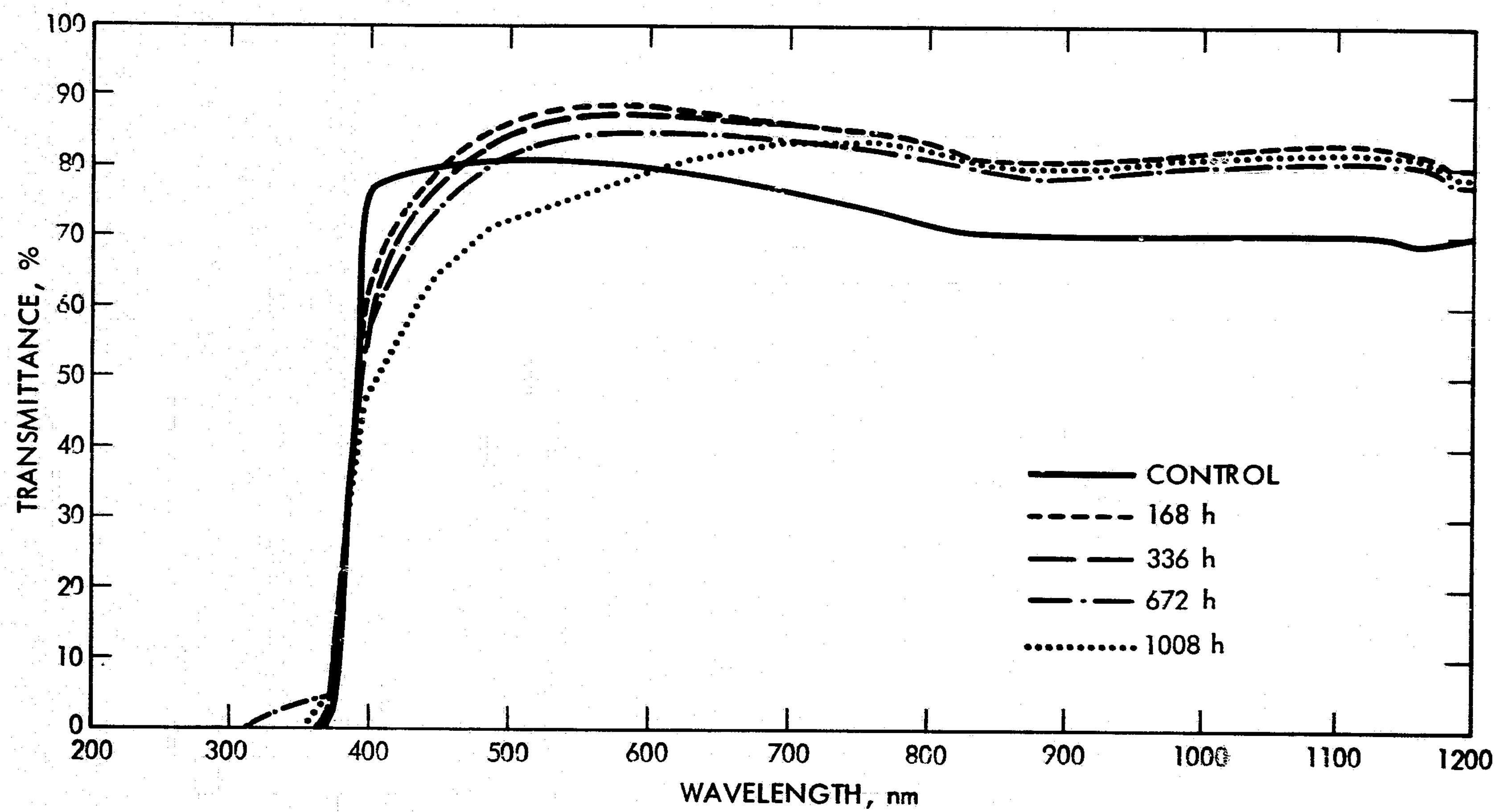

Figure 33. Change in Optical Transmittance as a Function of Thermal Aging of PVB at 135°C

B. MECHANICAL PROPERTIES

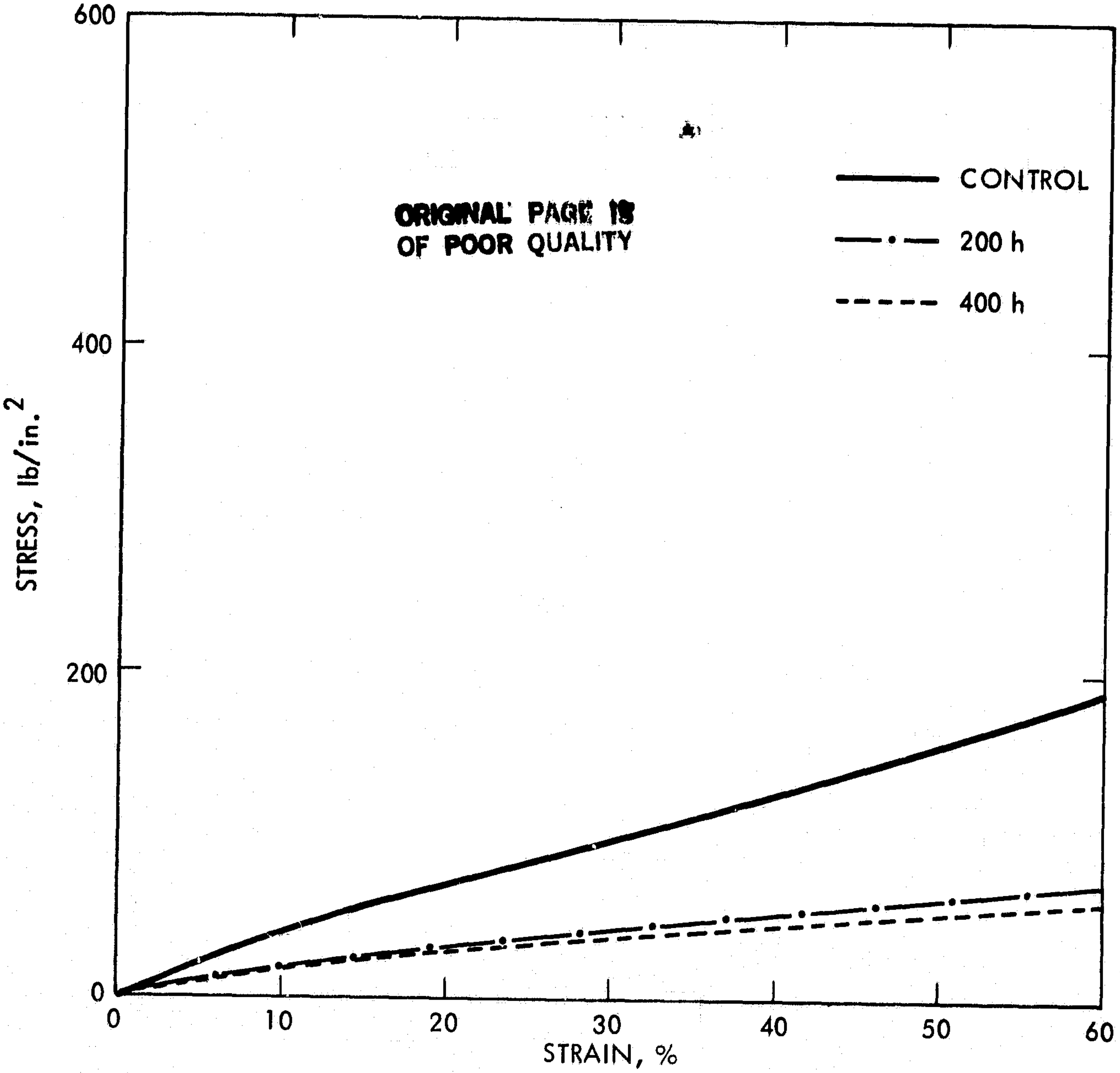

Figure 34. Change in Stress/Strain Response as a Function of Open Photothermal Aging of PVB at 70°C

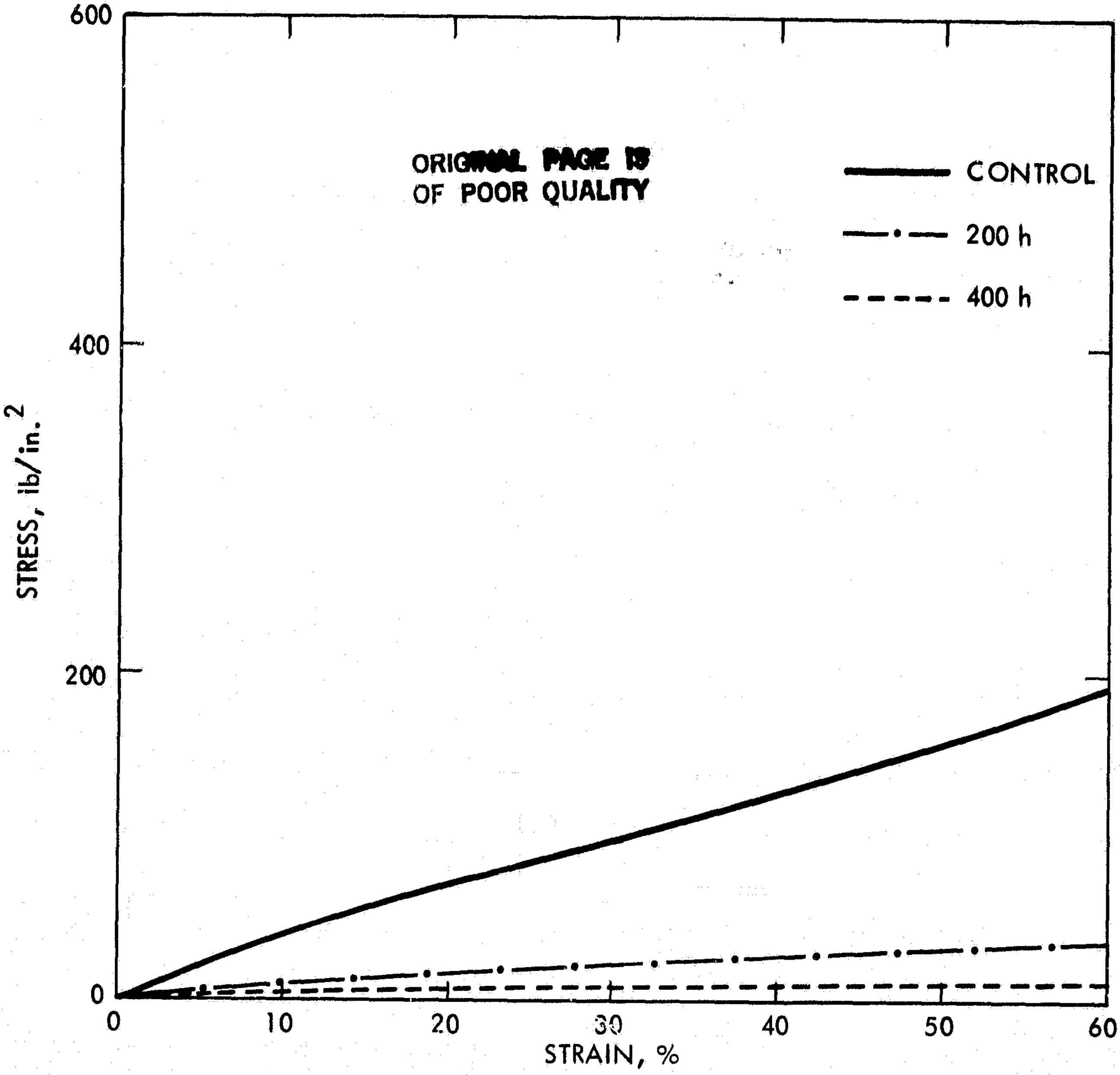

Figure 35. Change in Stress/Strain Response as a Function of Covered Photothermal Aging of PVB at 70°C

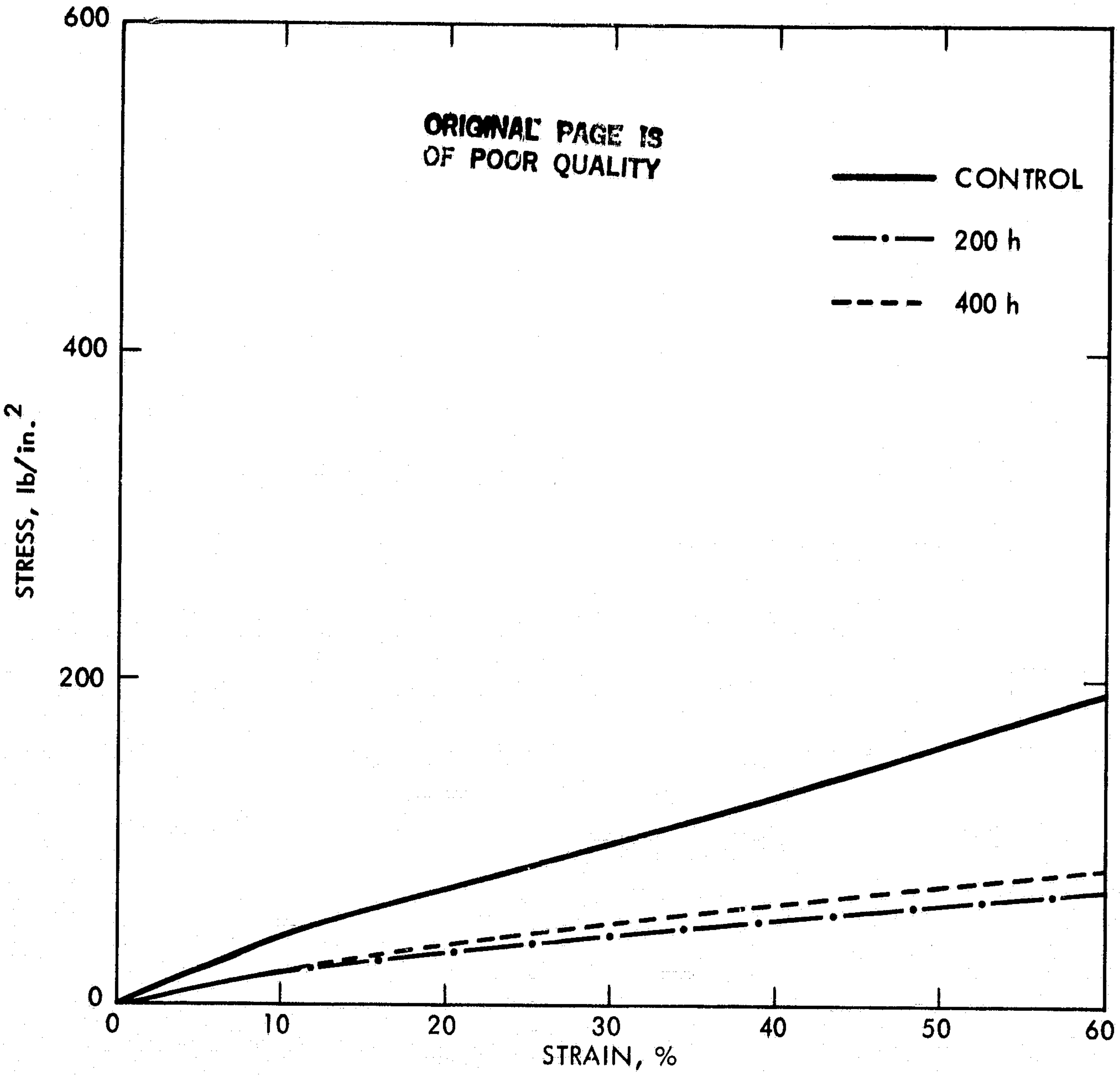

Figure 36. Change in Stress/Strain Response as a Function of Thermal Aging of PVB at 70°C

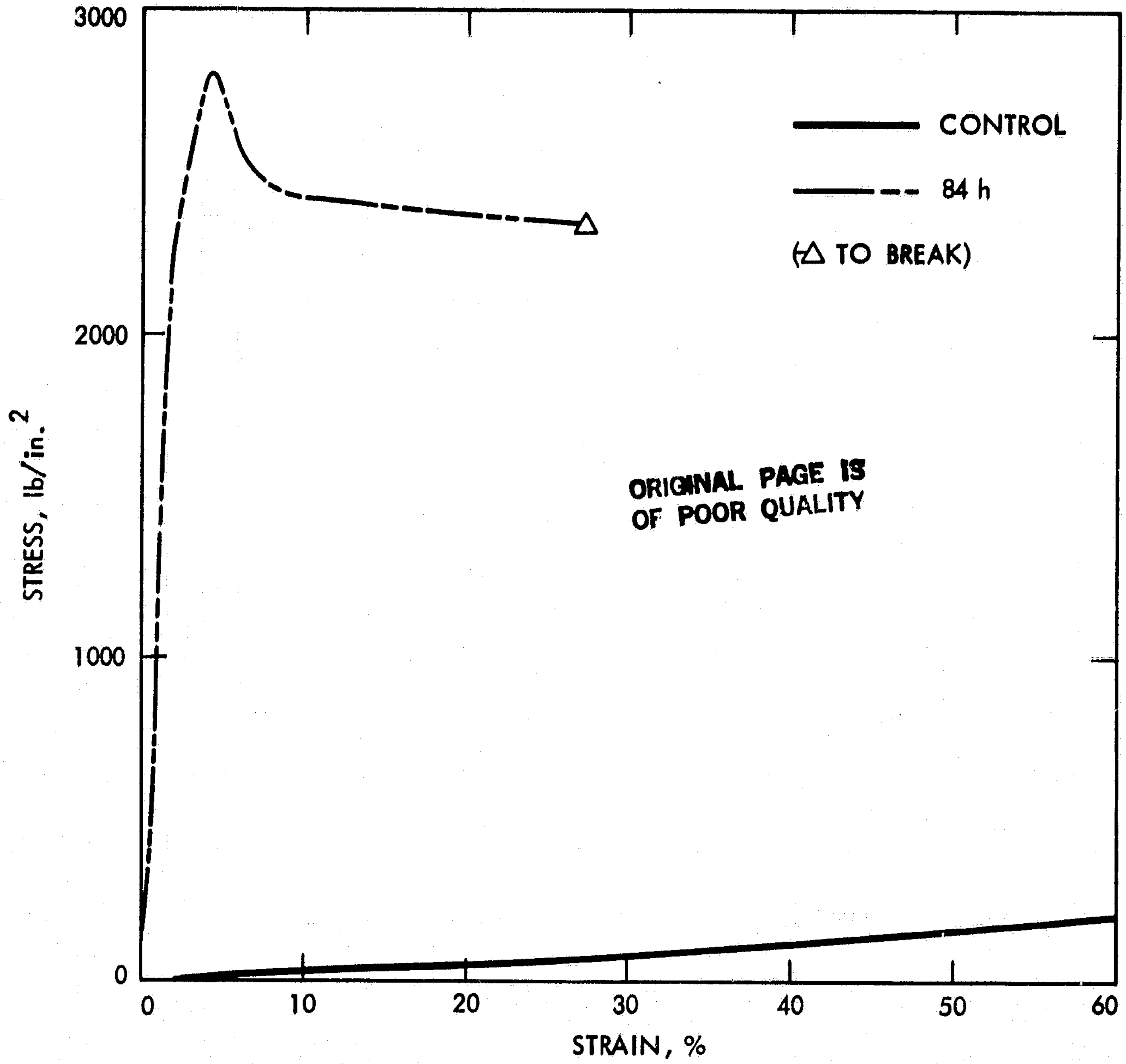

Figure 37. Change in Stress/Strain Response as a Function of Open Photothermal Aging of PVB at 135°C

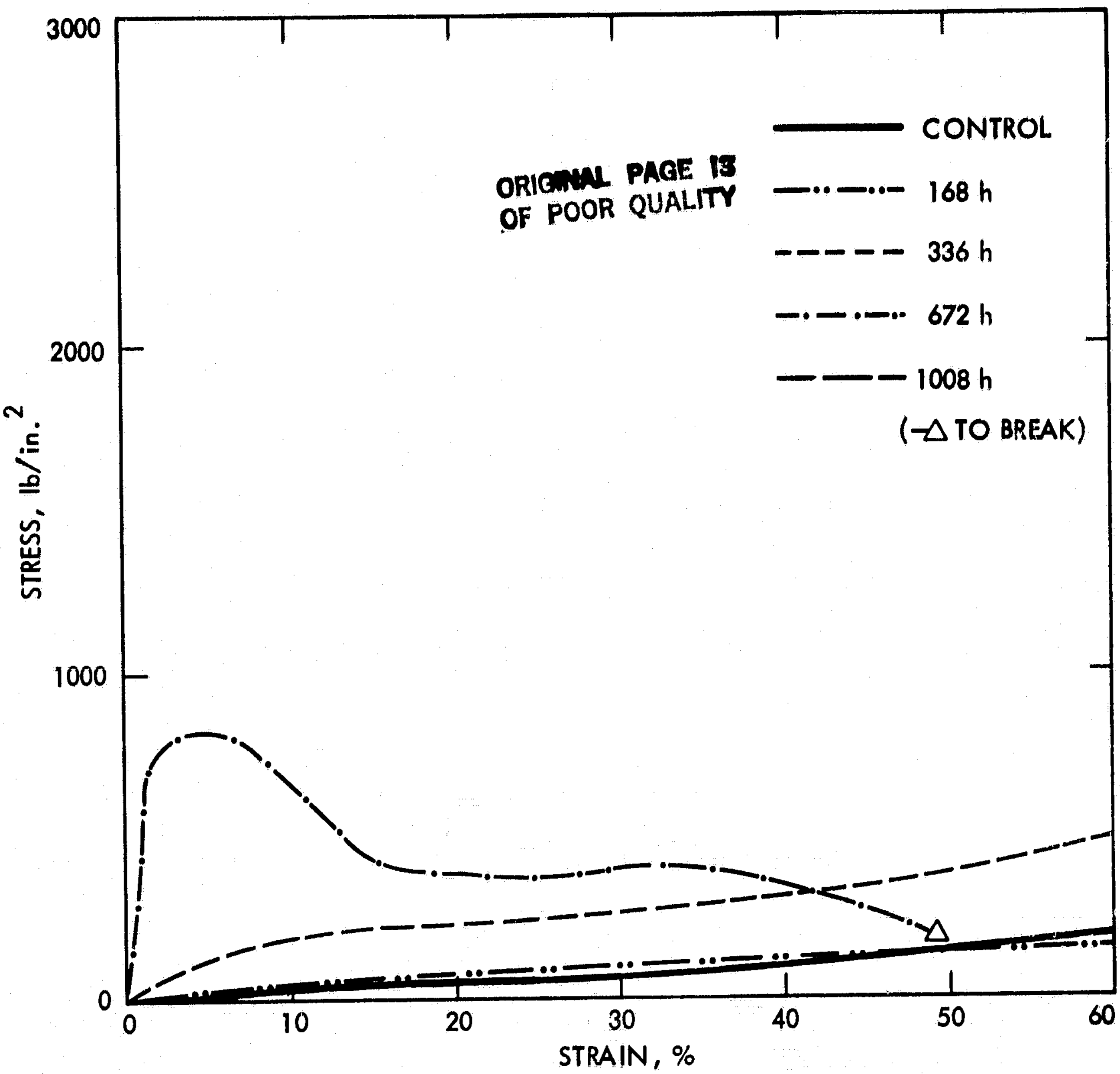

Figure 38. Change in Stress/Strain Response as a Function of Covered Photothermal Aging of PVB at 135°C

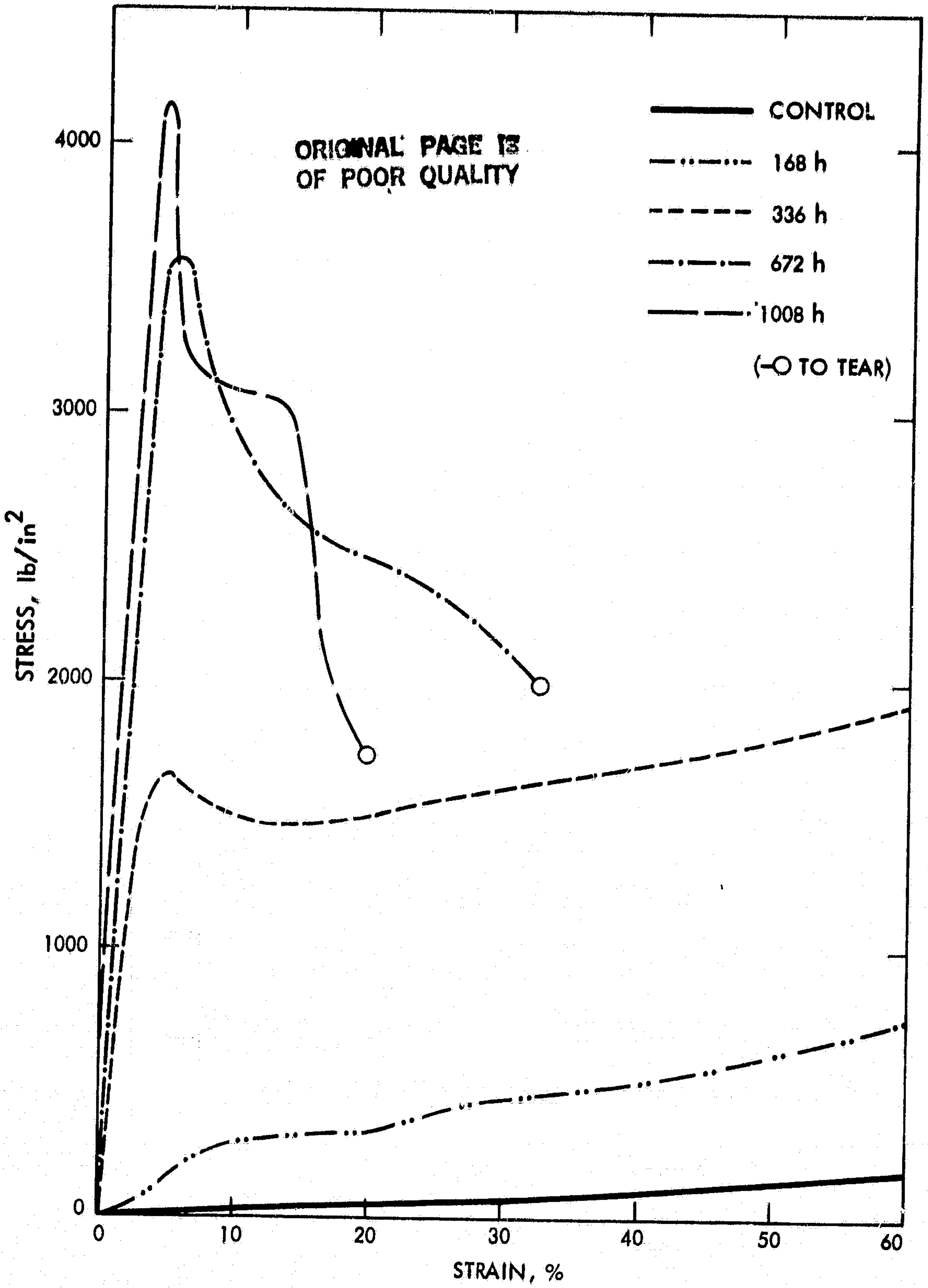

Figure 39. Change in Stress/Strain Response as a Function of Thermal Aging of PVB at 135°C

Table 10. Modulus at 5% Strain as a Function of Open Photothermal Aging of PVB at 30°C, 70°C, and 135°C

TEMPERATURE, °C	TIME OF AGING, h	MODULUS, lb/in.^{2} 5% STRAIN
ROOM TEMP. (30)	0	348
70	400	244
135	84	52,800

Table 11. Modulus at 5% Strain as a Function of Covered Photothermal Aging of PVB at 30°C, 70°C, and 135°C

TEMPERATURE, °C	TIME OF AGING, h	MODULUS, lb/in.^{2} 5% STRAIN
ROOM TEMP. (30)	0	348
70	200 400	100 47
135	168 336 672 1008	638 2610 39,200* 90,000*

* 1% STRAIN

Table 12. Modulus at 5% Strain as a Function of Thermal Aging of PVB at 30°C, 70°C, and 135°C

TEMPERATURE, °C	TIME OF AGING, h	MODULUS, lb/in.^{2} 5% STRAIN
ROOM TEMP. (30)	0	348
70	200	219
	400	238
135	168	3110
	336	32,277
	672	70,500
	1008	71,600

C. WEIGHT LOSS

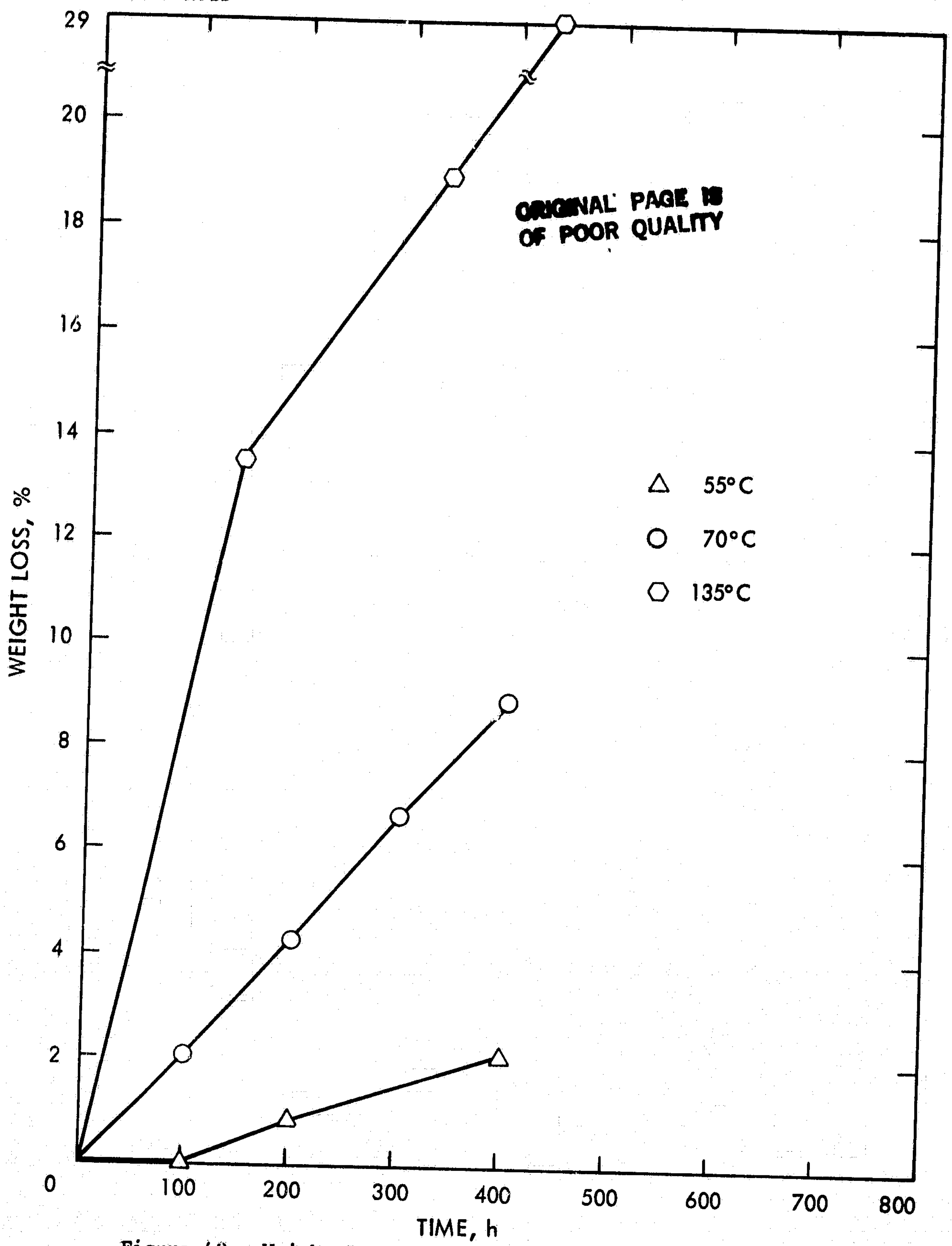

Figure 40. Weight Loss as a Function of Open Photothermal Aging of PVB at 55°C, 70°C, and 135°C

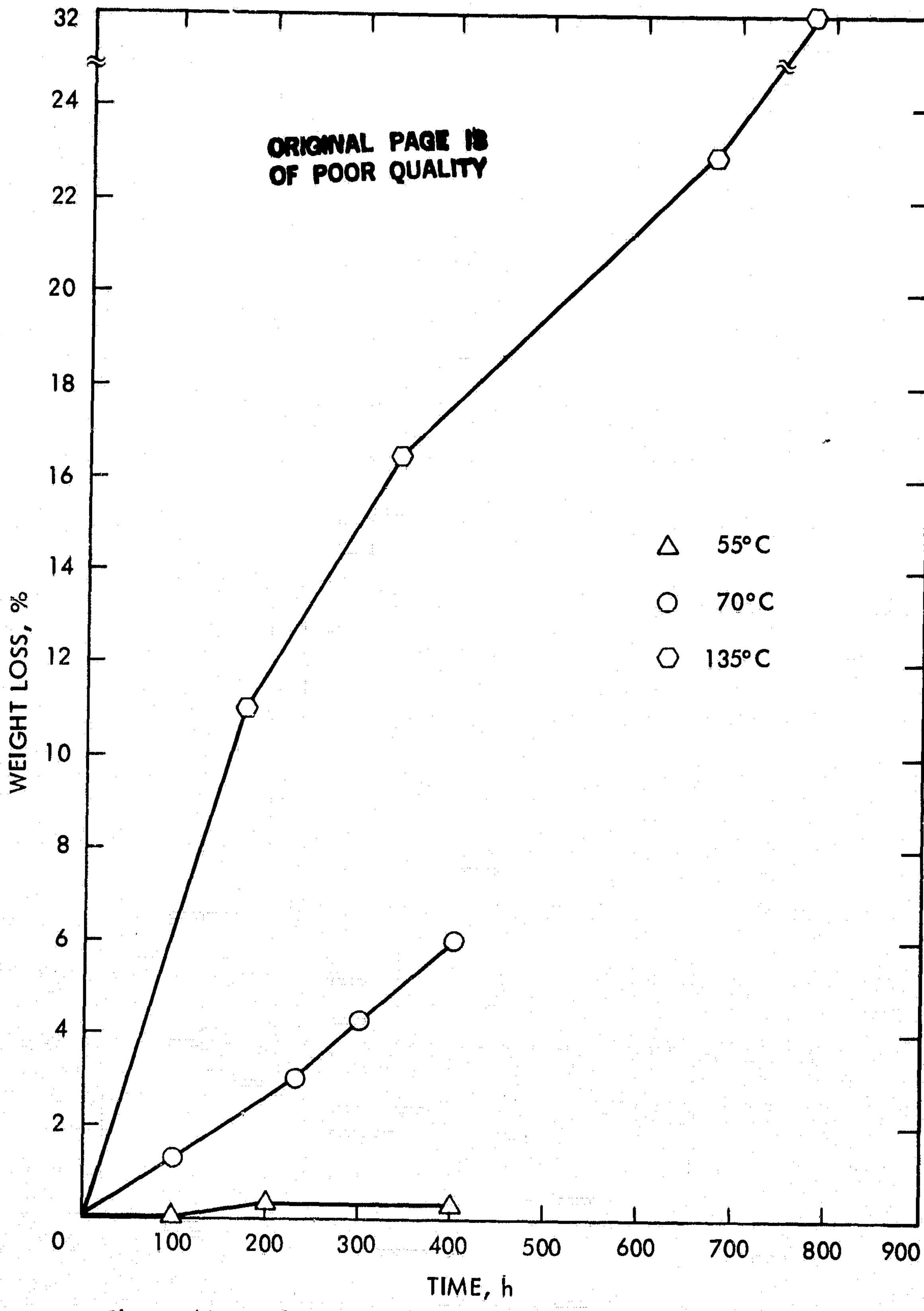

Figure 41. Weight Loss as a Function of Covered Photothermal Aging of PVB at 55°C, 70°C, and 135°C

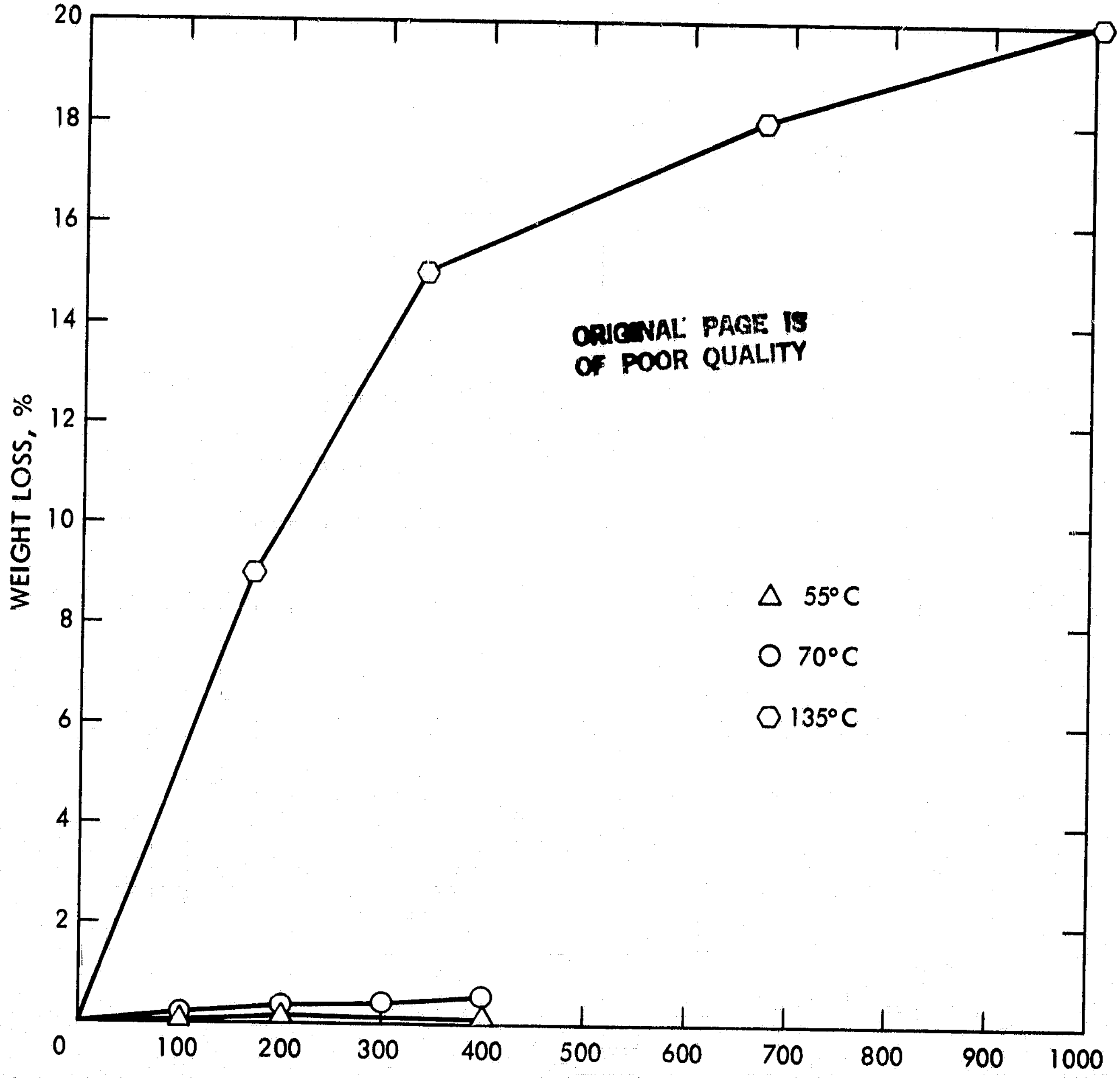

Figure 42. Weight Loss as a Function of Thermal Aging of PVB at 55°C, 70°C, and 135°C

SECTION IV

RTV SILICONE ELASTOMER (GE RTV-615)

The following figures and tables offer data on optical transmittance (Figures 43 through 51); mechanical properties (Figures 52 through 60, Tables 13 through 15); weight loss (Figures 61 through 63); other properties (Tables 16 through 18) of RTV silicone elastomer (GE RTV-615).

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A. OPTICAL TRANSMITTANCE

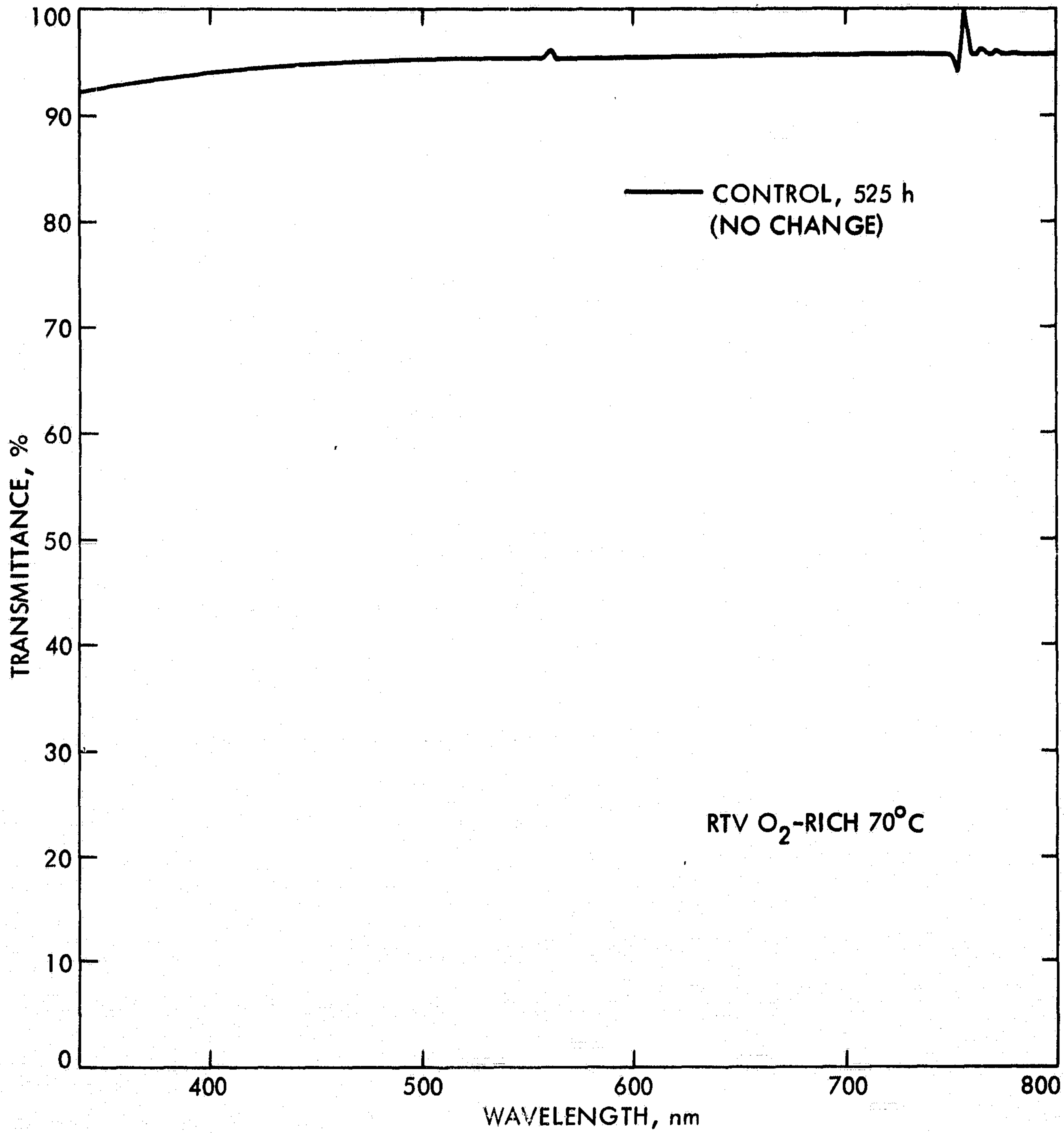

Figure 43. Change in Optical Transmittance as a Function of Open Photothermal Aging of RTV at 70°C

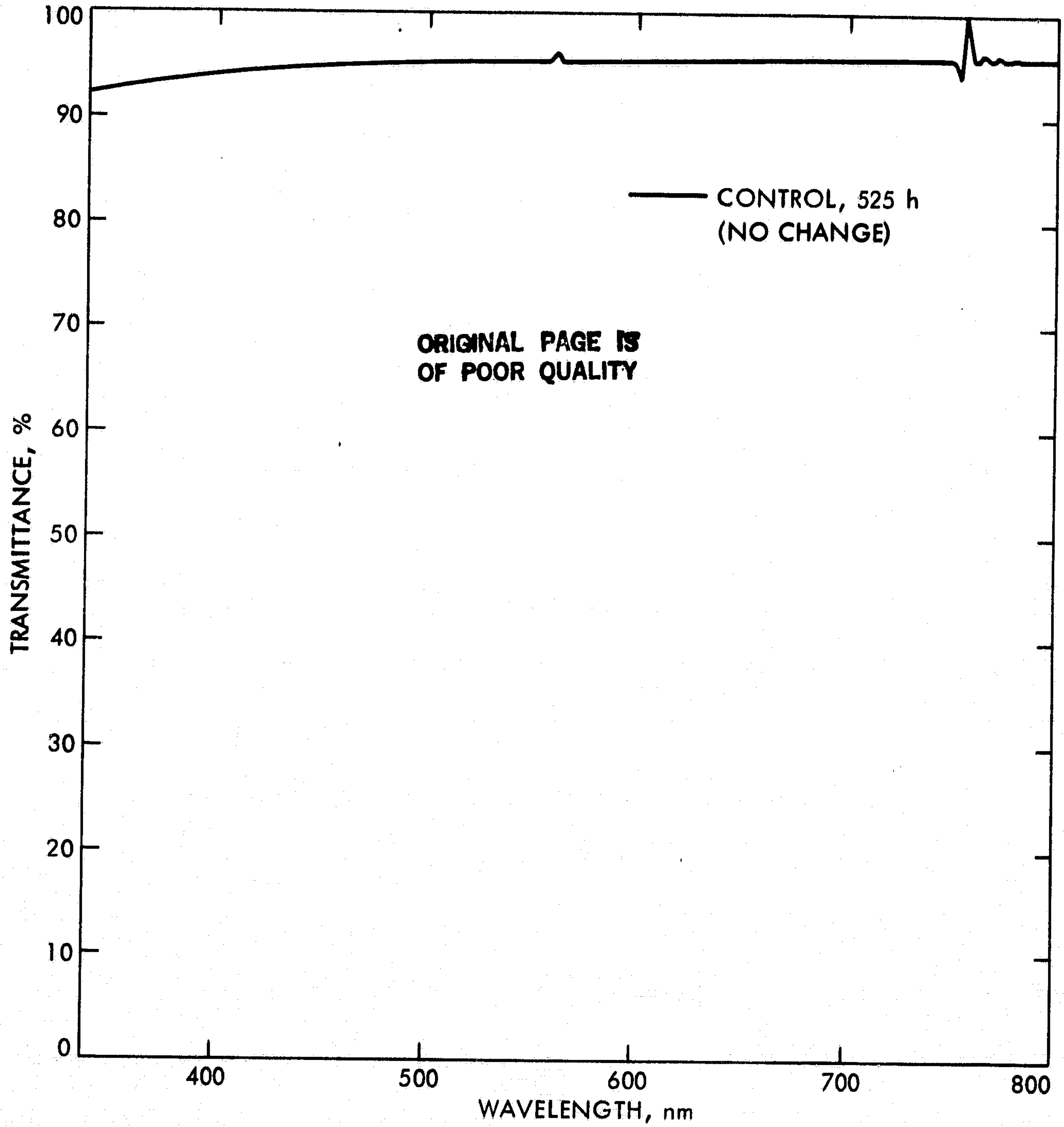

Figure 44. Change in Optical Transmittance as a Function of Covered Photothermal Aging of RTV at 70°C

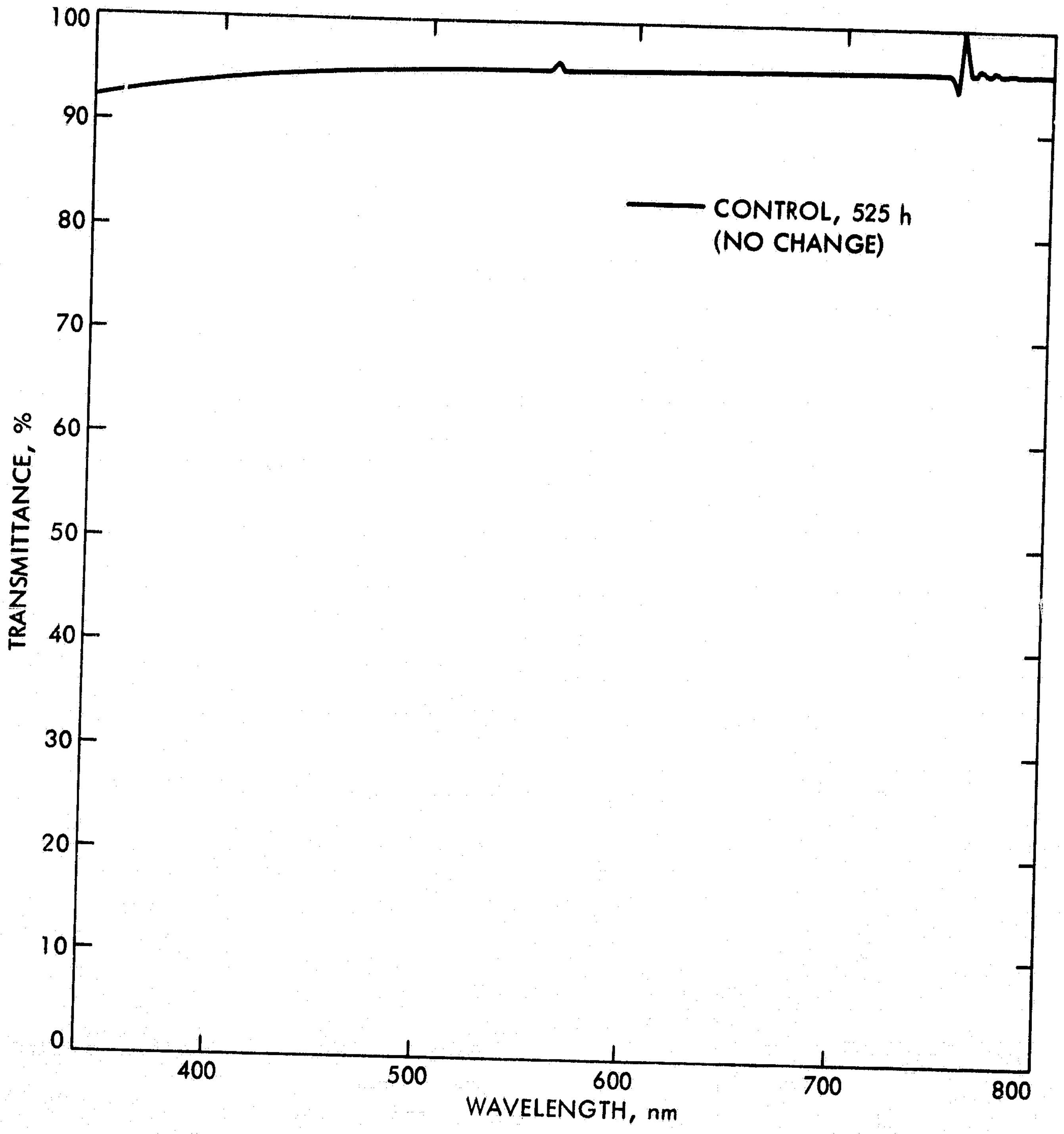

Figure 45. Change in Optical Transmittance as a Function of Thermal Aging of RTV at 70°C

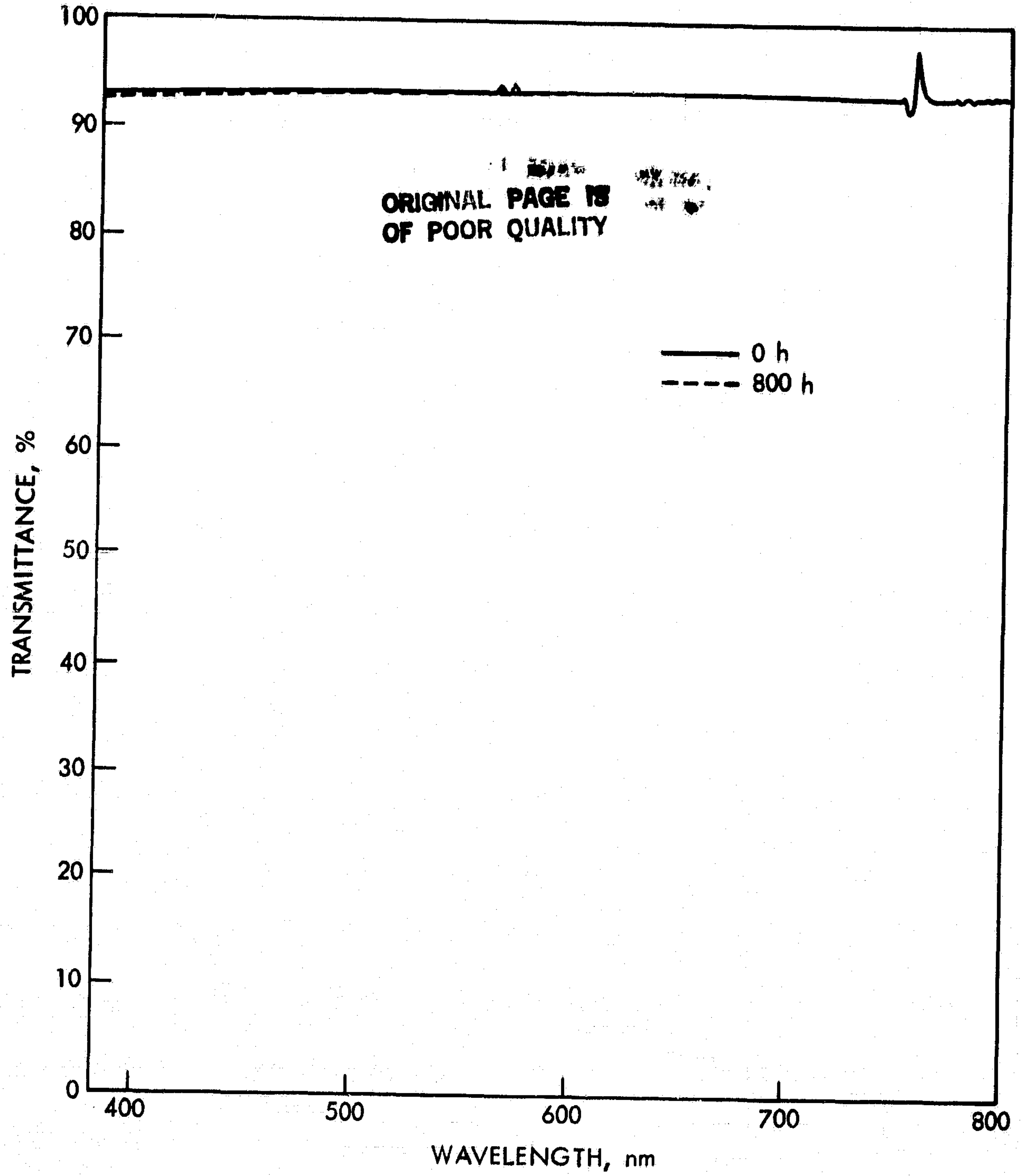

Figure 46. Change in Optical Transmittance as a Function of Open Photothermal Aging of RTV at 85°C

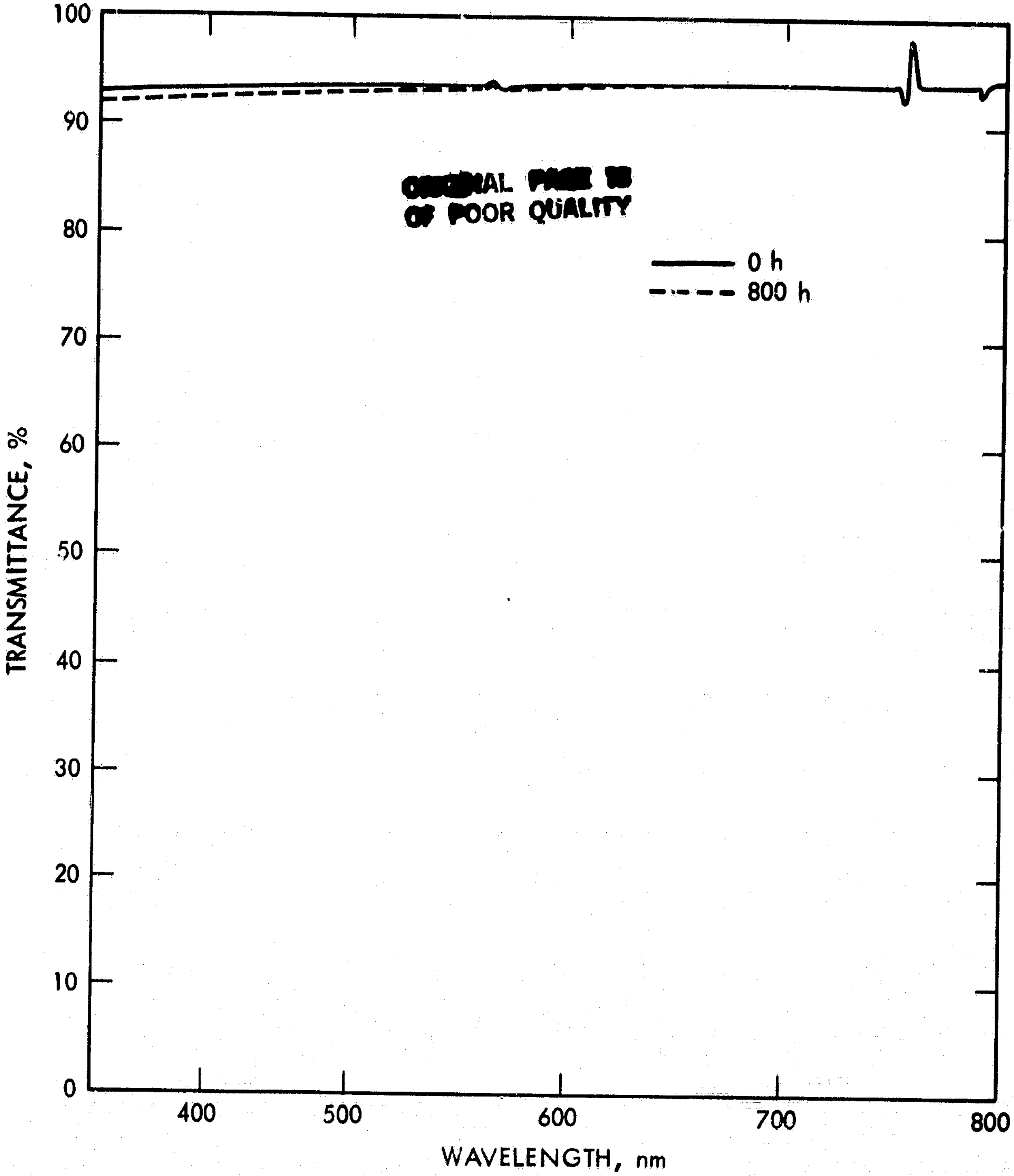

Figure 47. Change in Optical Transmittance as a Function of Covered Photothermal Aging of RTV at 85°C

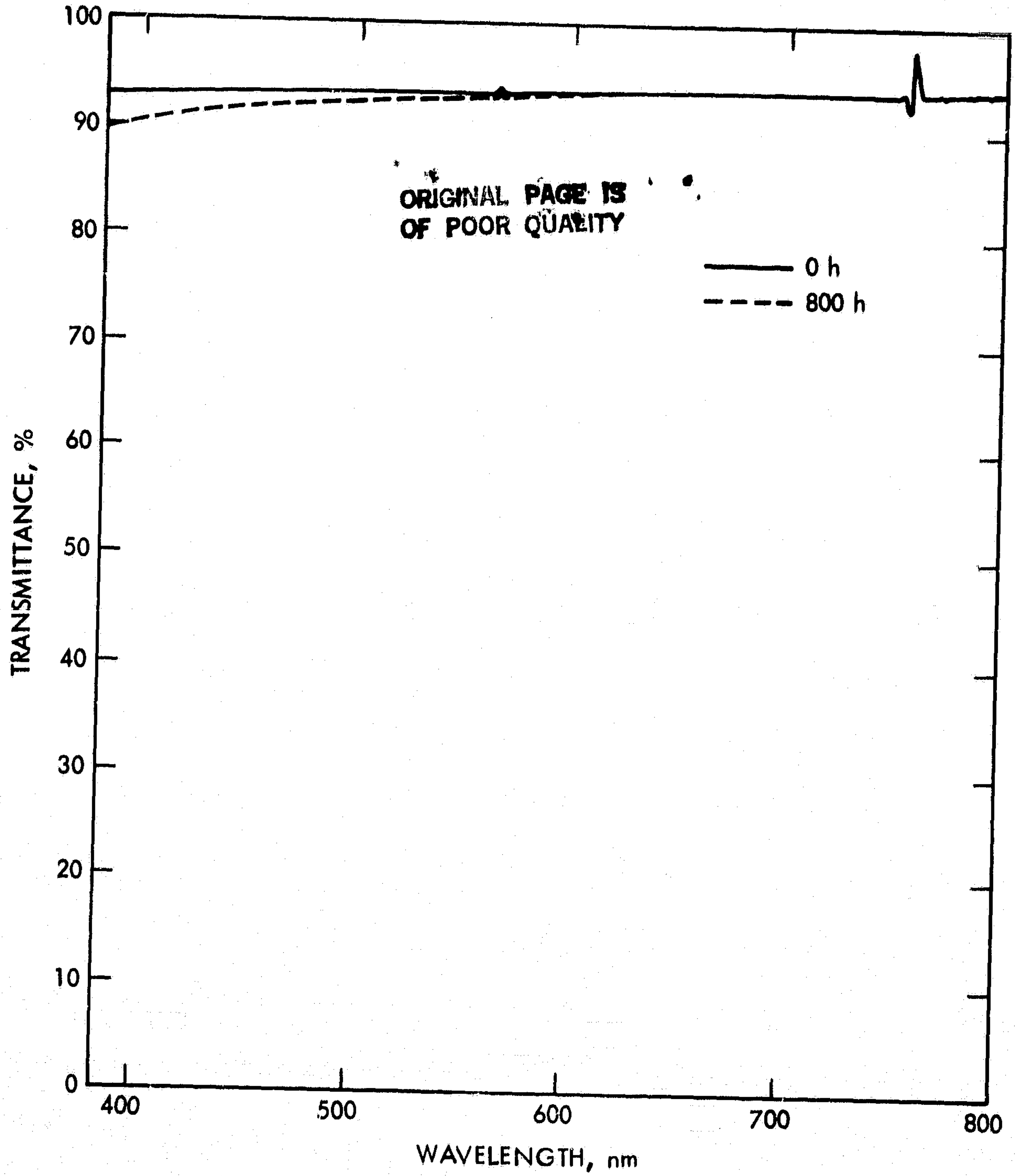

Figure 48. Change in Optical Transmittance as a Function of Thermal Aging of RTV at 85°C

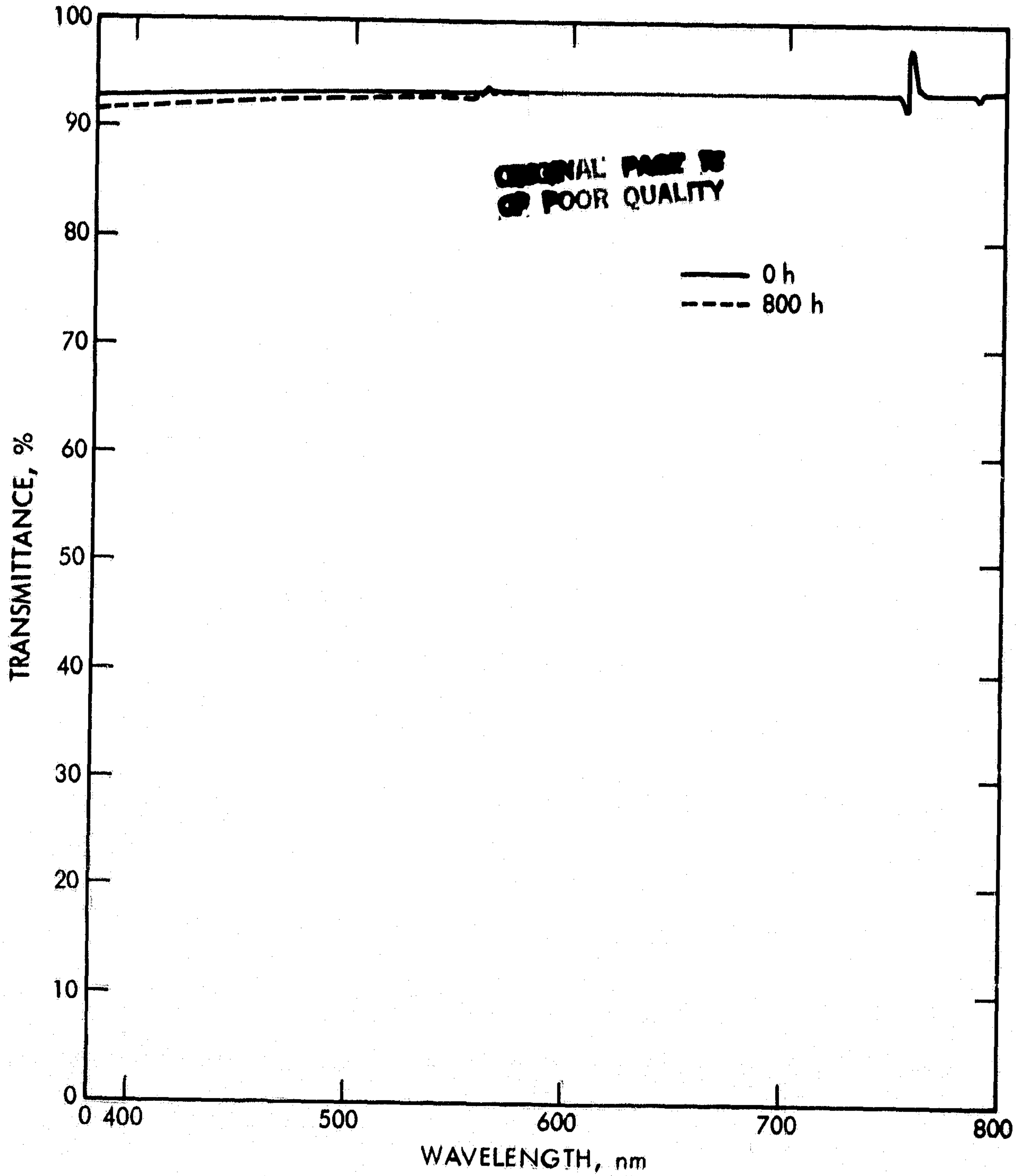

Figure 49. Change in Optical Transmittance as a Function of Open Photothermal Aging of RTV at 105°C

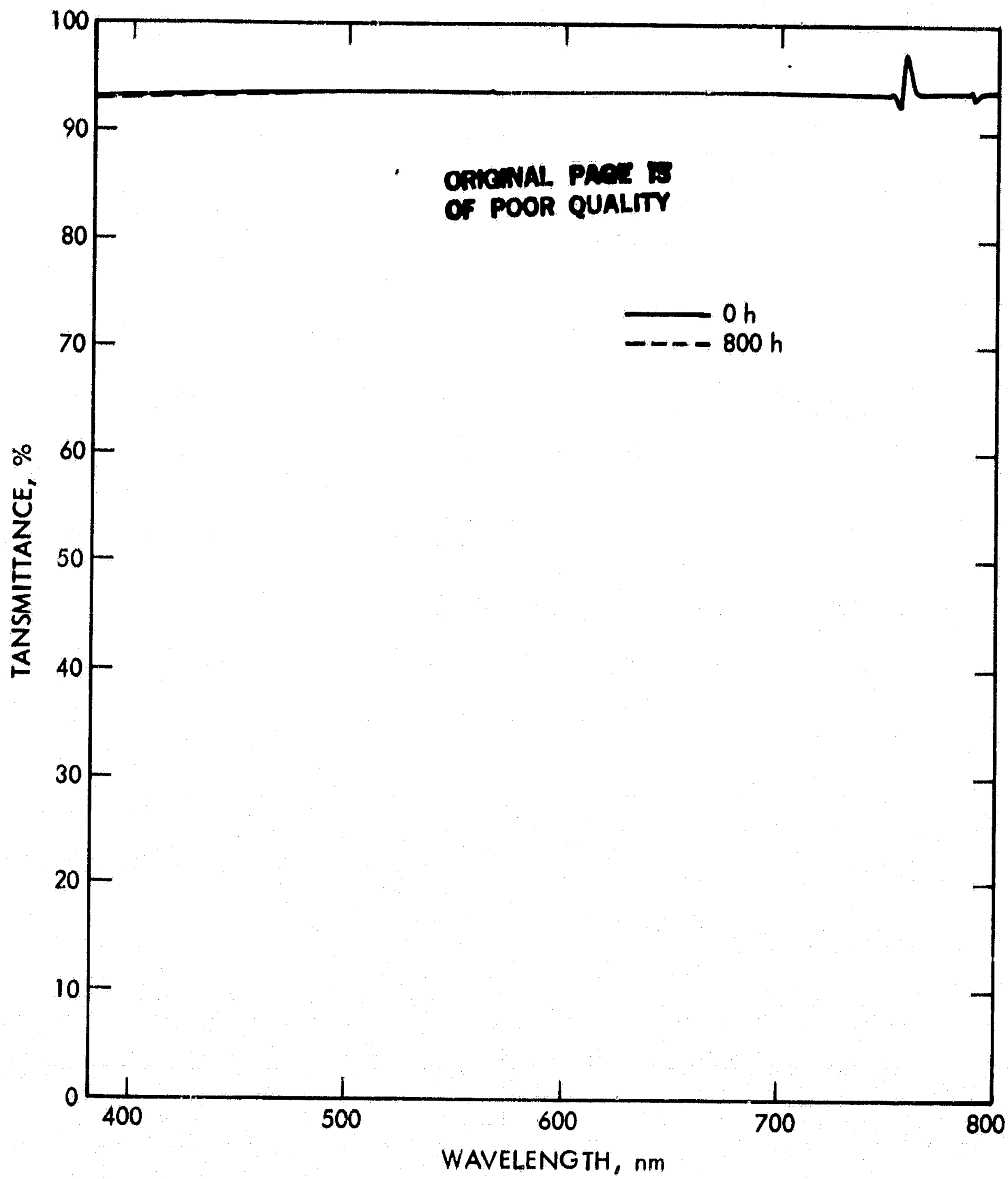

Figure 50. Change in Optical Transmittance as a Function of Covered Photothermal Aging of RTV at 105°C

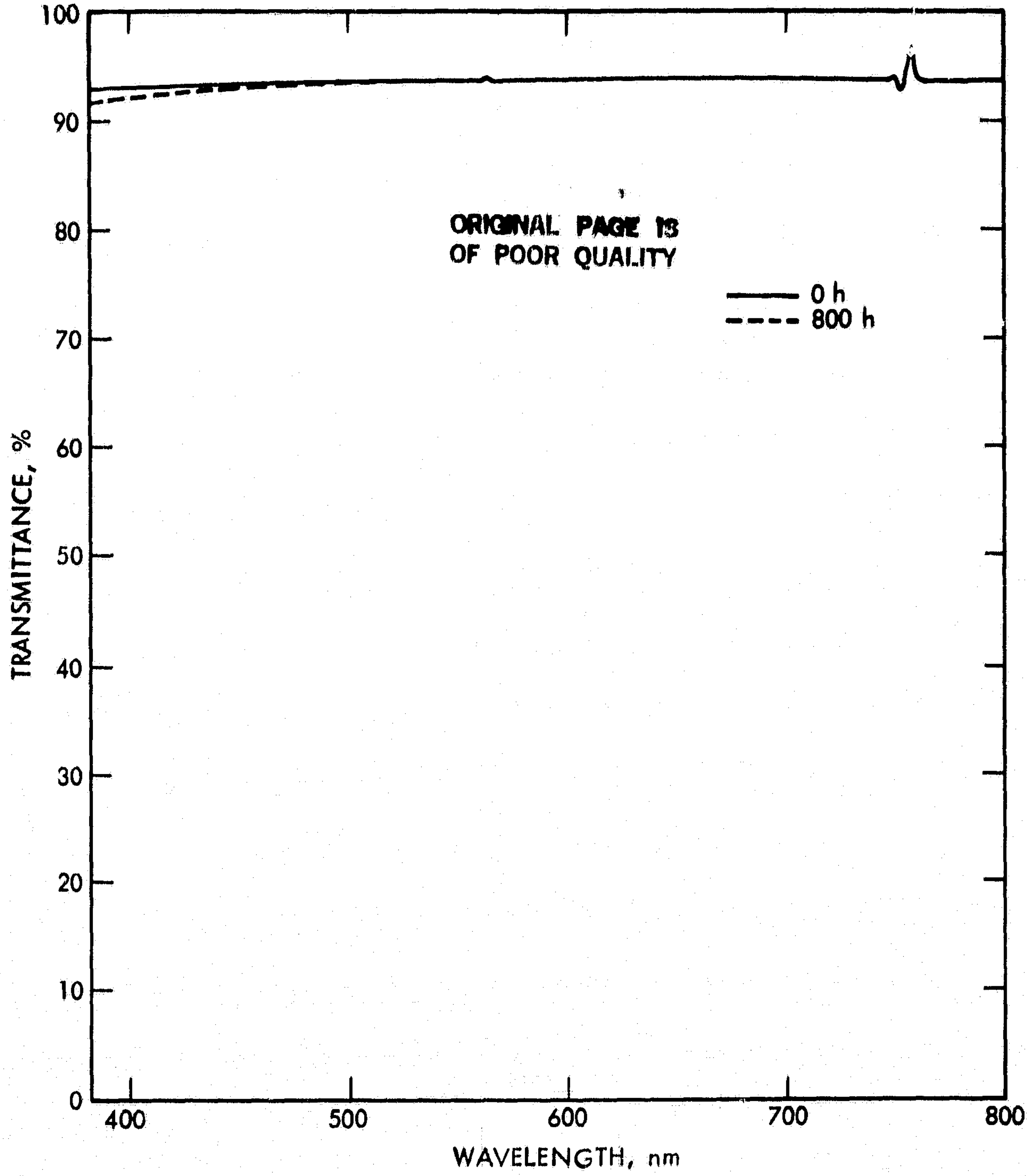

Figure 51. Change in Optical Transmittance as a Function of Thermal Aging of RTV at 105°C

B. MECHANICAL PROPERTIES

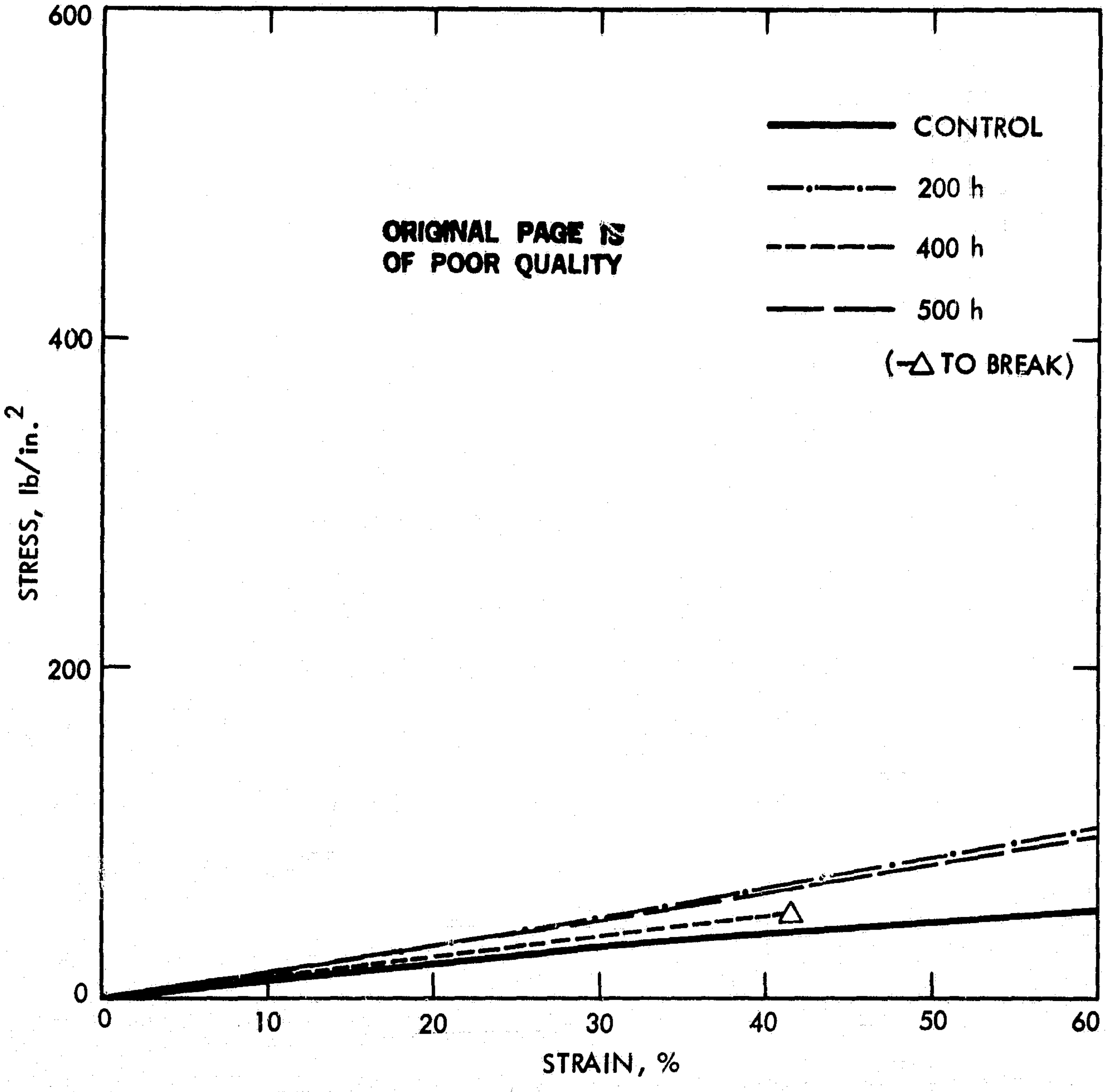

Figure 52. Change in Stress/Strain Response as a Function of Open Photothermal Aging of RTV at 70°C

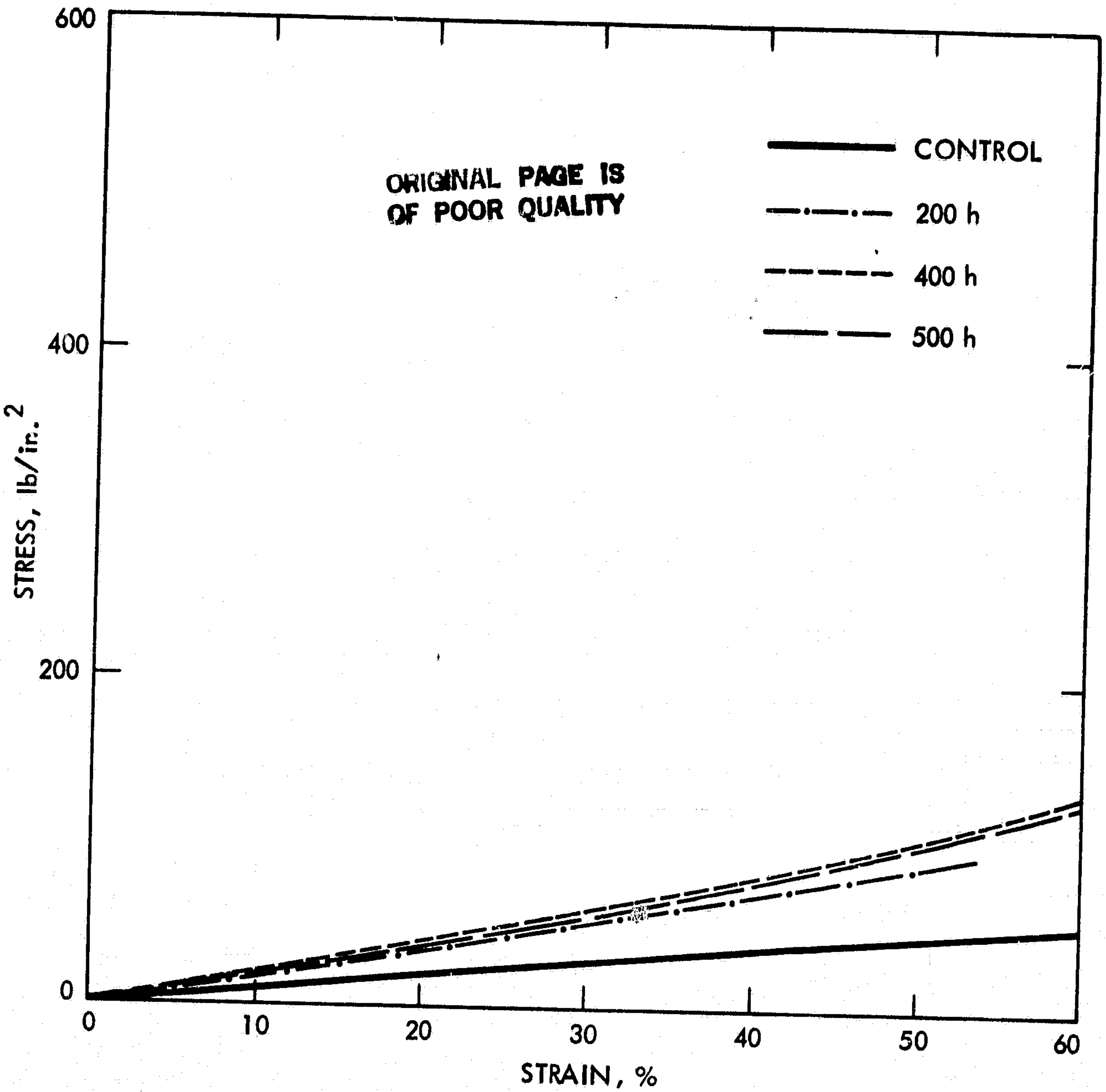

Figure 53. Change in Stress/Strain Response as a Function of Covered Photothermal Aging of RTV at 70°C

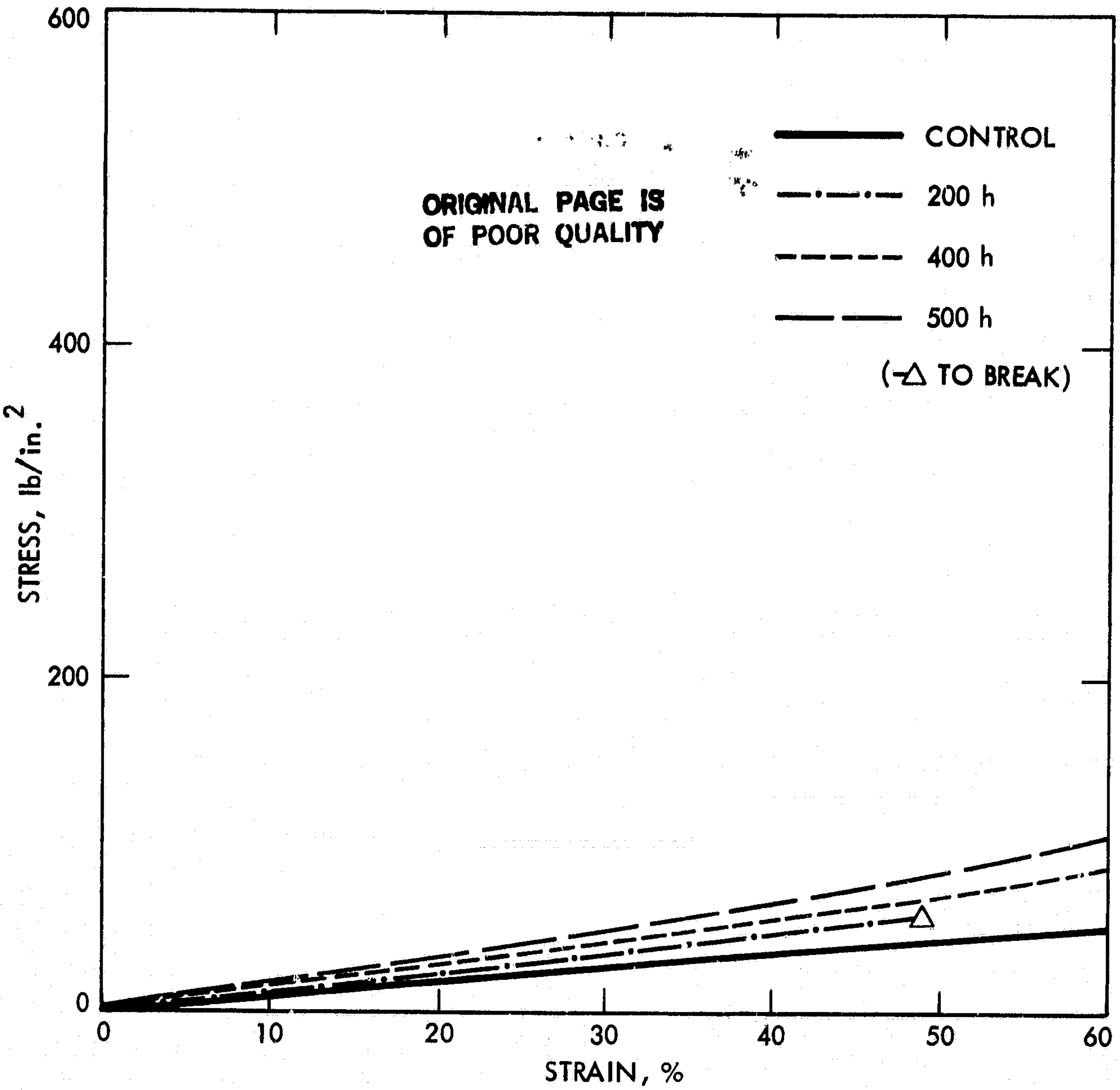

Figure 54. Change in Stress/Strain Response as a Function of Thermal Aging of RTV at 70°C

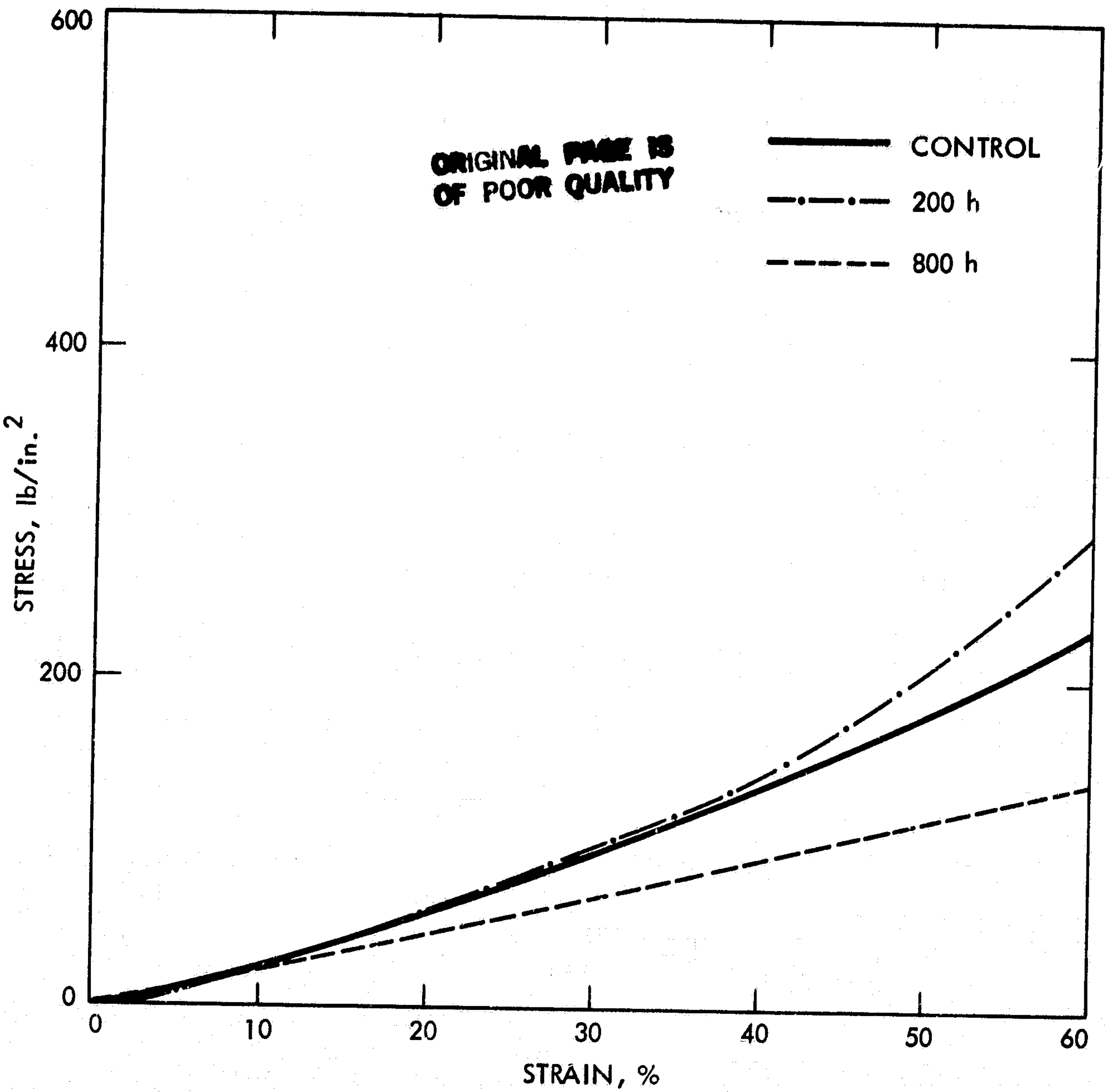

Figure 55. Change in Stress/Strain Response as a Function of Open Photothermal Aging of RTV at 85°C

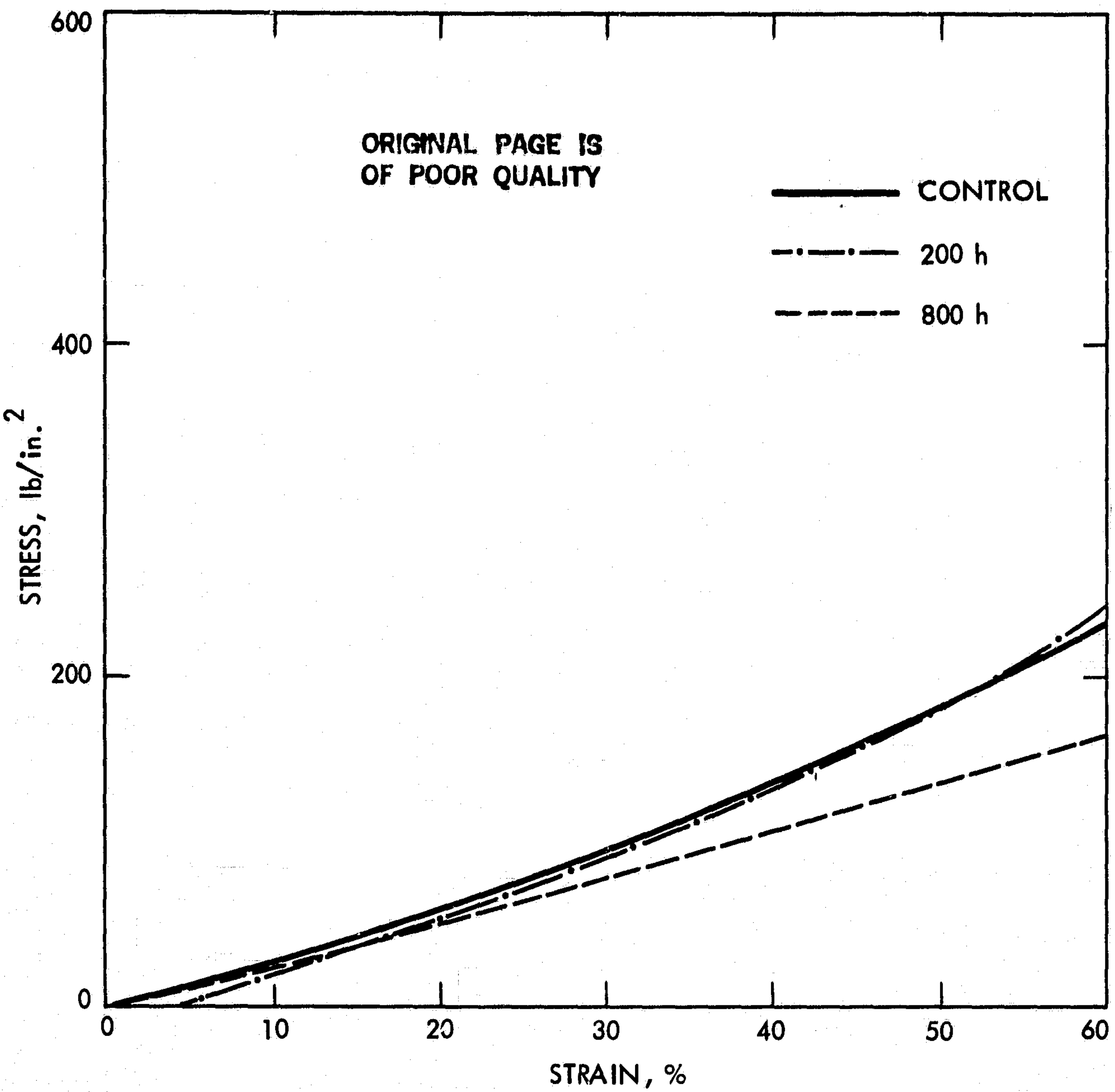

Figure 56. Change in Stress/Strain Response as a Function of Covered Photothermal Aging of RTV at 85°C

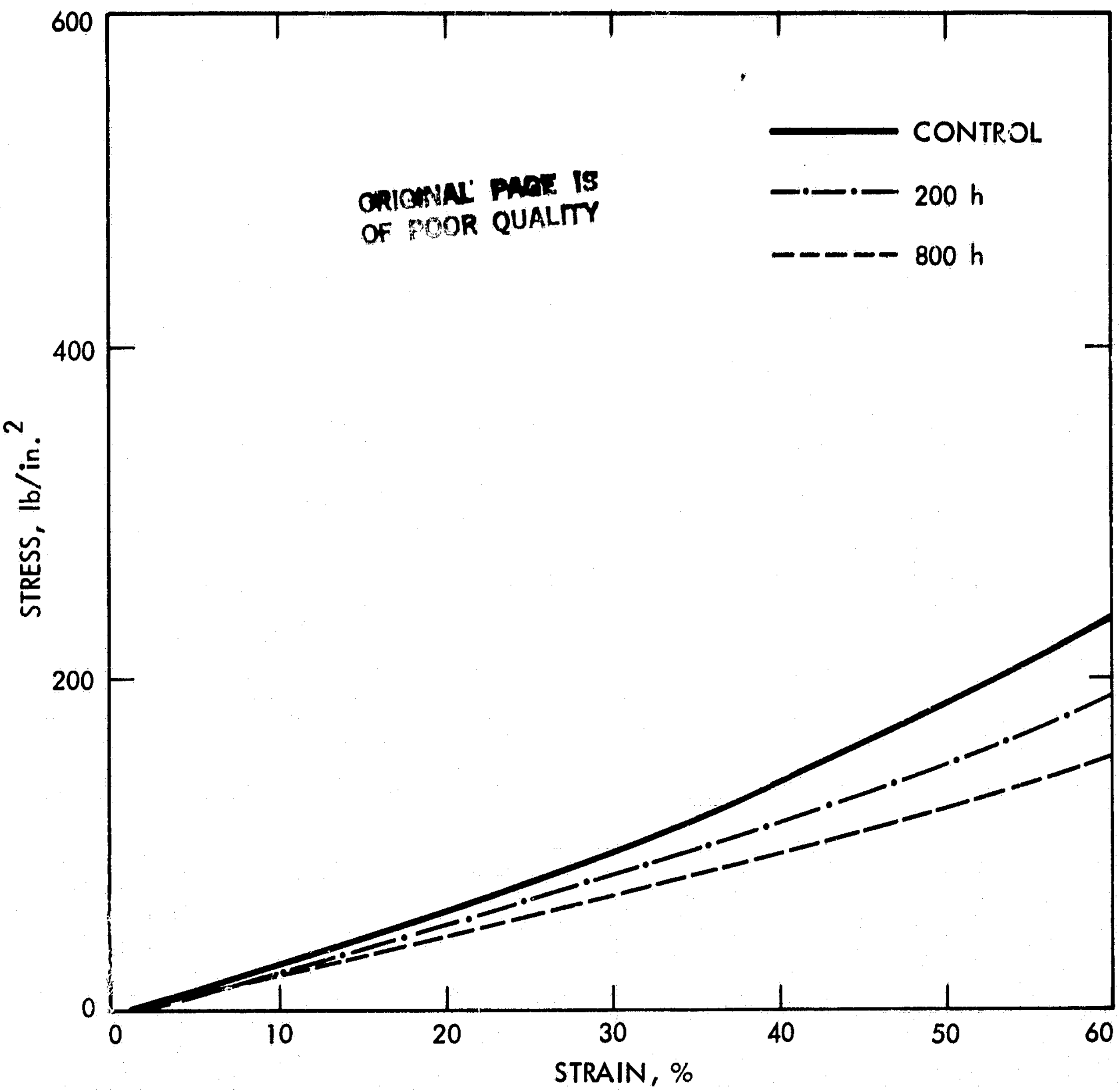

Figure 57. Change in Stress/Strain Response as a Function of Thermal Aging of RTV at 85^{o}C

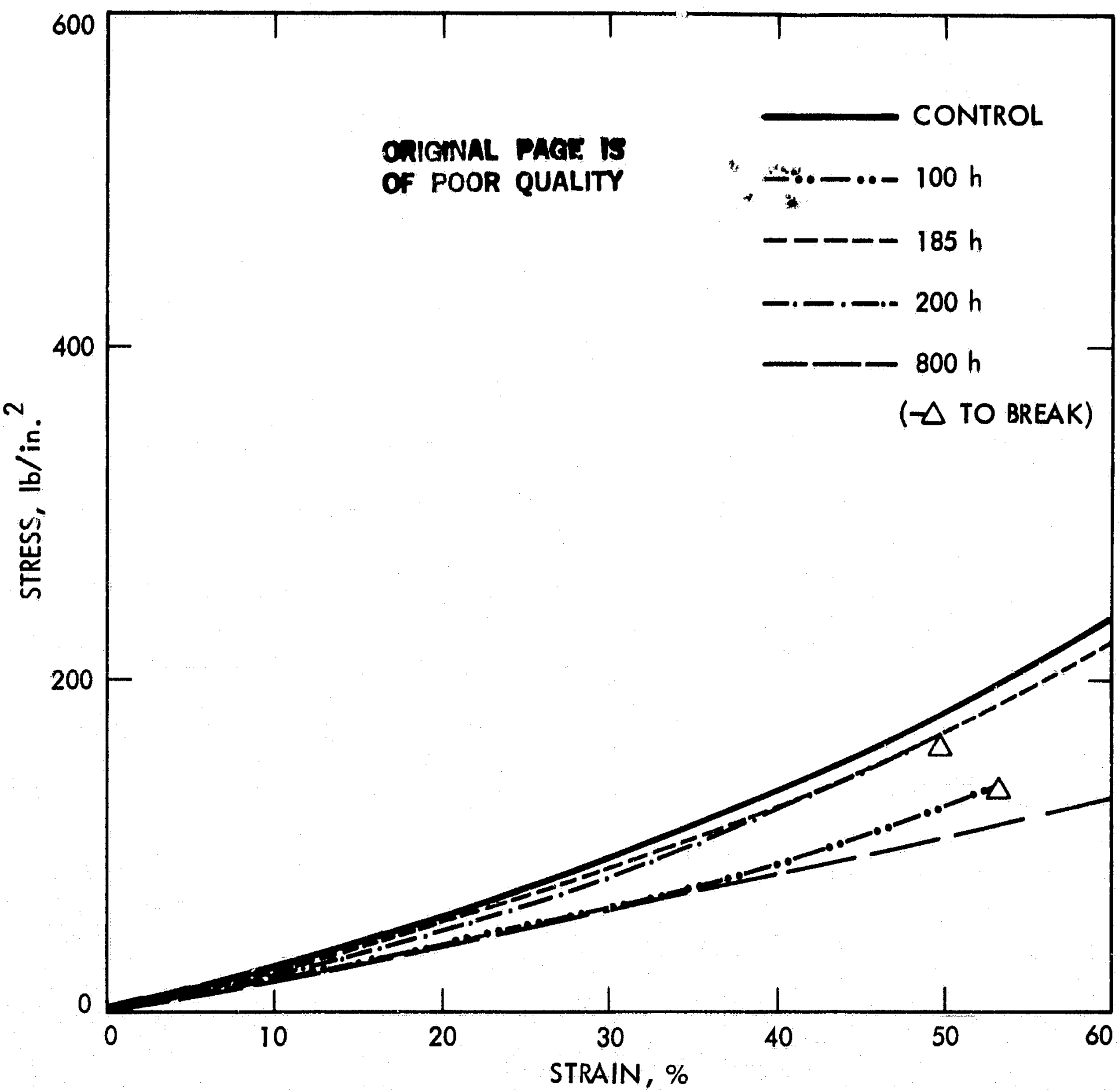

Figure 58. Change in Stress/Strain Response as a Function of Open Photothermal Aging of RTV at 105°C

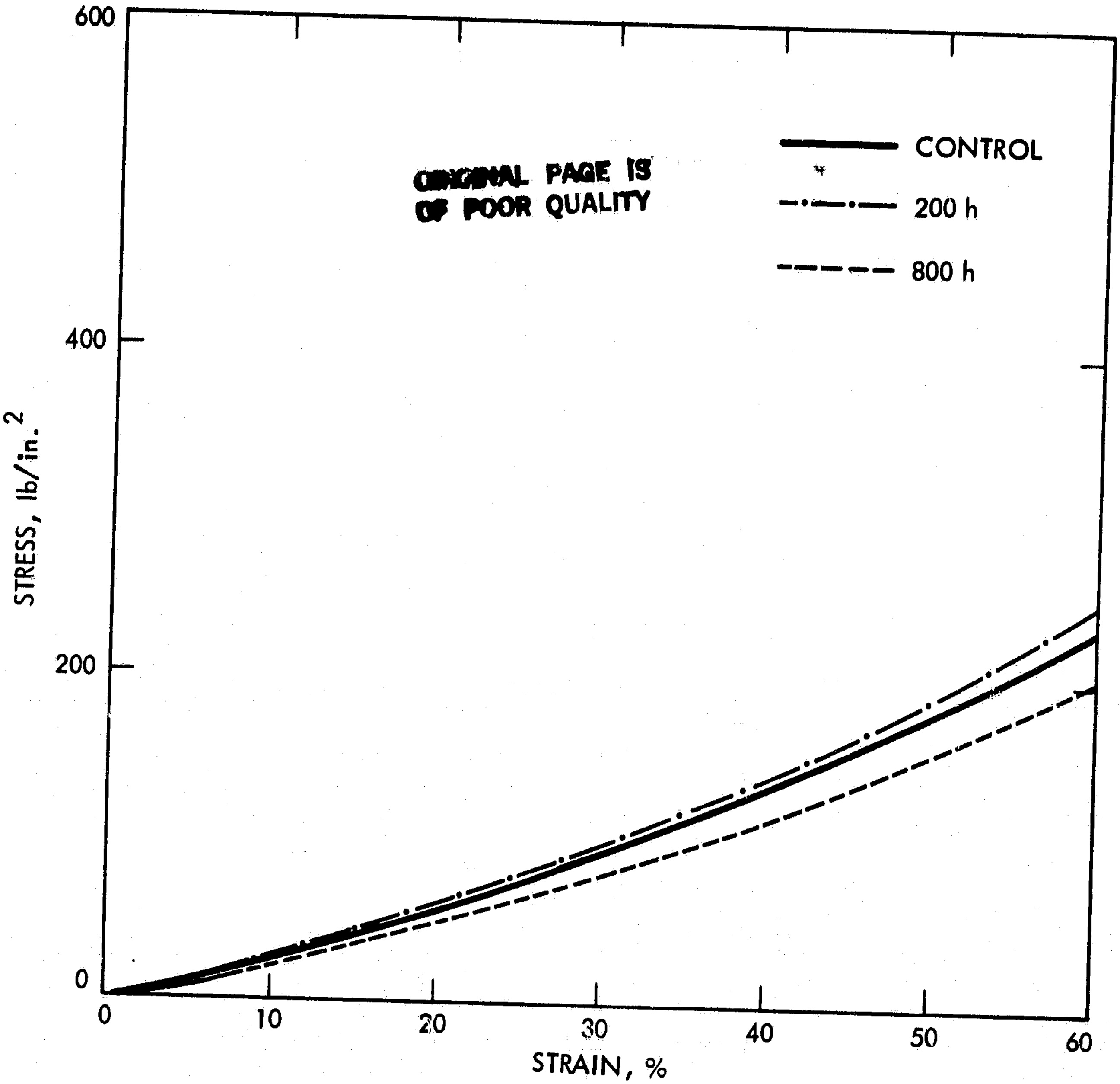

Figure 59. Change in Stress/Strain Response as a Function of Covered Photothermal Aging of RTV at 105°C

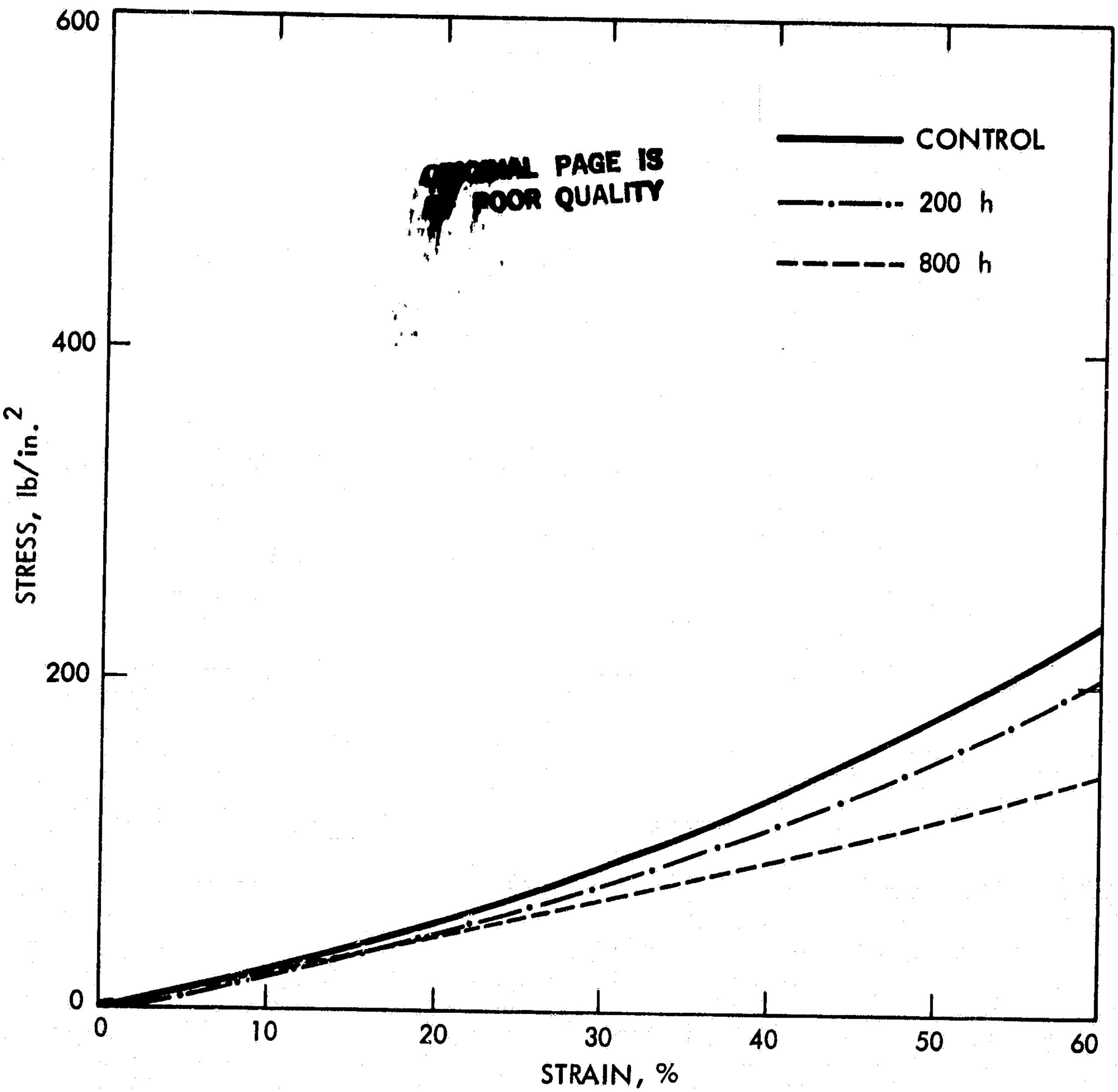

Figure 60. Change in Stress/Strain Response as a Function of Thermal Aging of RTV at 105°C

Table 13. Modulus at 5% Strain as a Function of Open Photothermal Aging of RTV at 30°C, 70°C, 85°C, and 105°C

TEMPERATURE, °C	TIME OF AGING, h	MODULUS, In lb/in.^{2} 5% STRAIN	
		SAMPLE 1	SAMPLE 2
ROOM TEMP. (30)	0	110	322
70	200 400 500	186 141 167	
85	200 800		335 314
105	100 200 800		238 300 285

Table 14. Modulus at 5% Strain as a Function of Covered Photothermal Aging of RTV at 30°C, 70°C, 85°C, and 105°C

TEMPERATURE, °C	TIME OF AGING, h	MODULUS, $lb/in.^2$ 5% STRAIN	
		SAMPLE 1	SAMPLE 2
ROOM TEMP. (30)	0	110	322
70	200 400 500	234 217 234	
85	200 800		308 301
105	200 800		341 312

Table 15. Modulus at 5% Strain as a Function of Thermal Aging of RTV at 30°C, 70°C, 85°C, and 105°C

TEMPERATURE, °C	TIME OF AGING, h	MODULUS, lb/in.^{2} 5% STRAIN	
		SAMPLE 1	SAMPLE 2
ROOM TEMP. (30)	0	110	322
70	200 400 500	158 158 179	
85	200 800		275 270
105	200 800		266 263

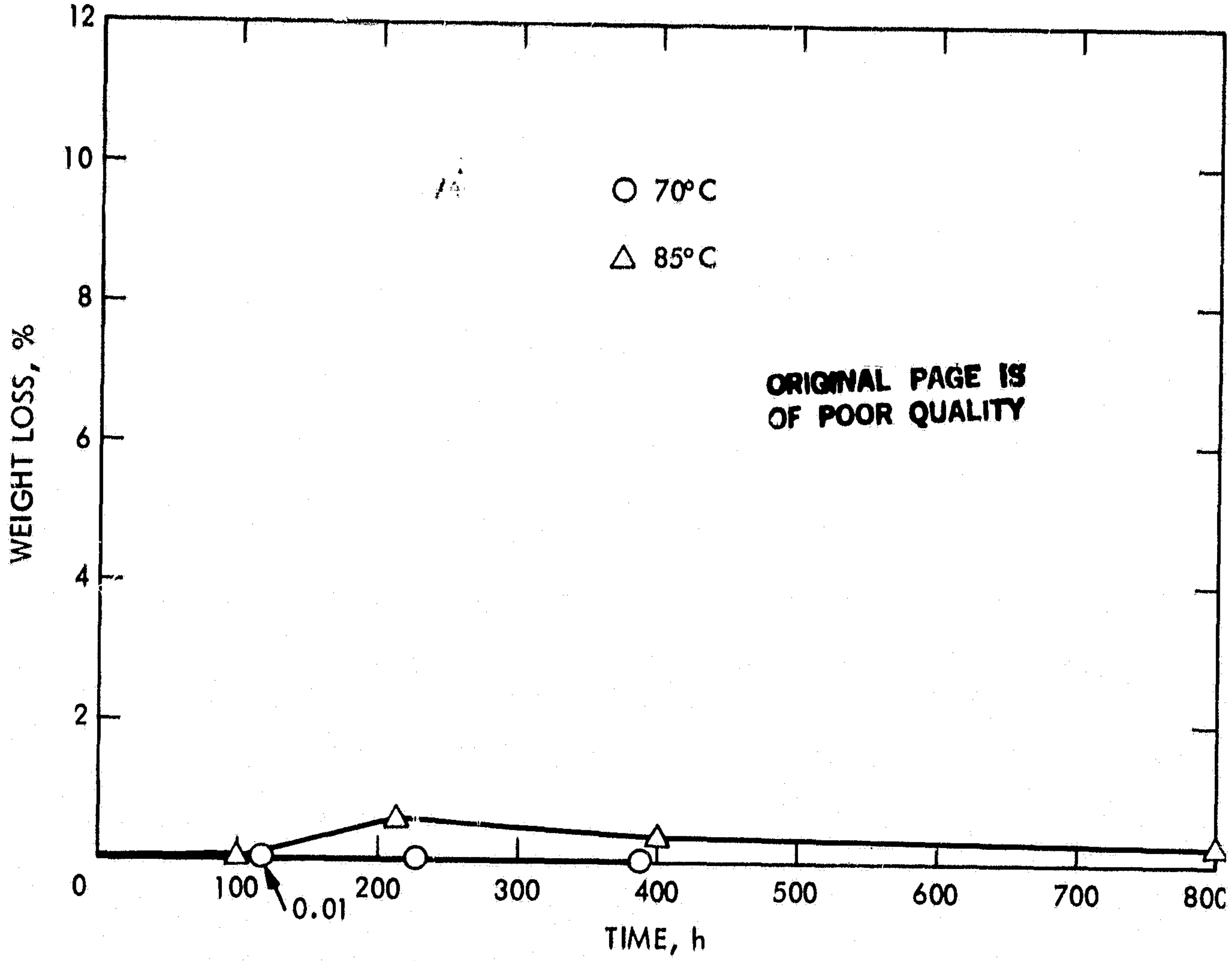

Figure 61. Weight Loss as a Function of Open Photothermal Aging of RTV at 70°C and 85°C

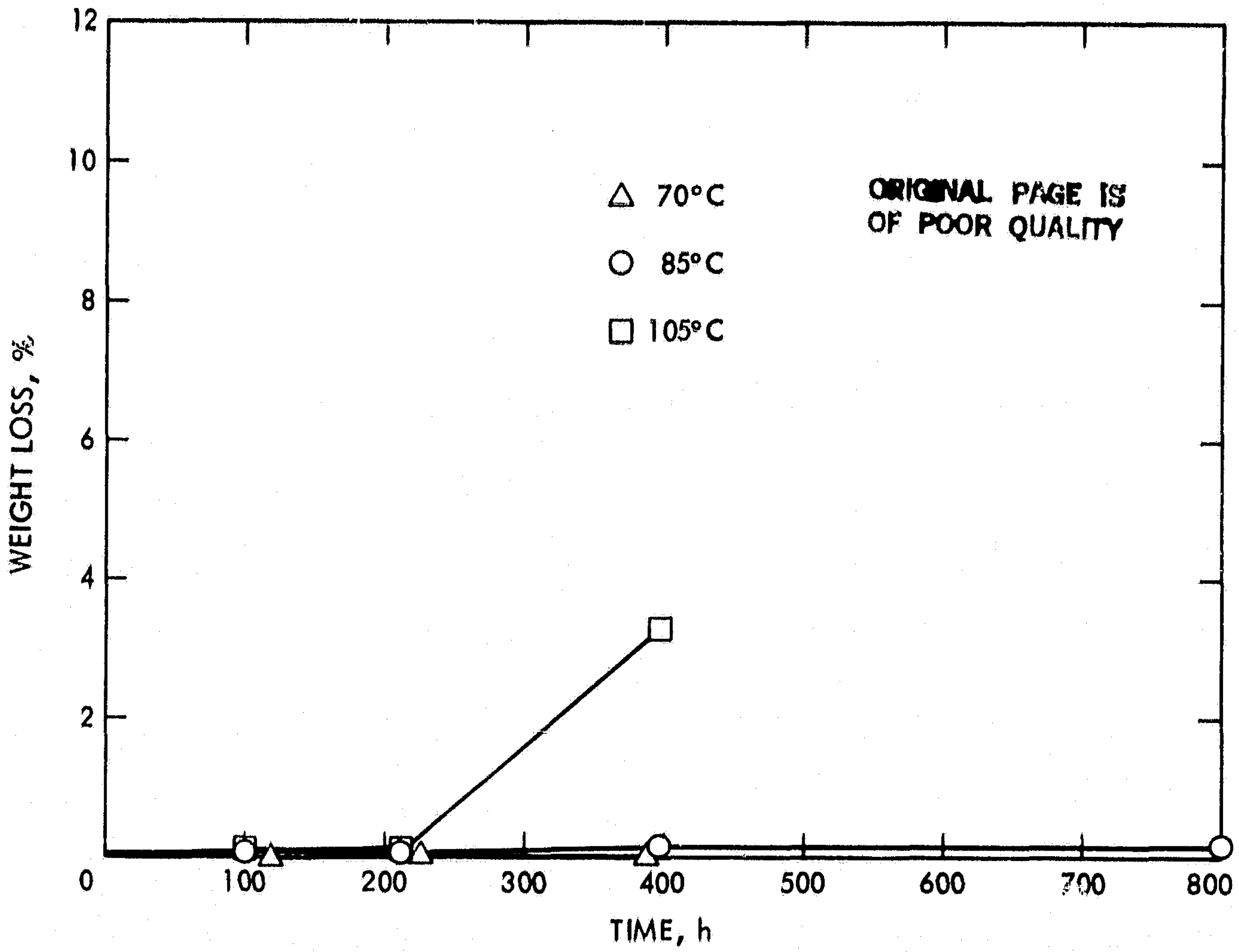

Figure 62. Weight Loss as a Function of Covered Photothermal Aging of RTV at 70°C, 85°C, and 105°C

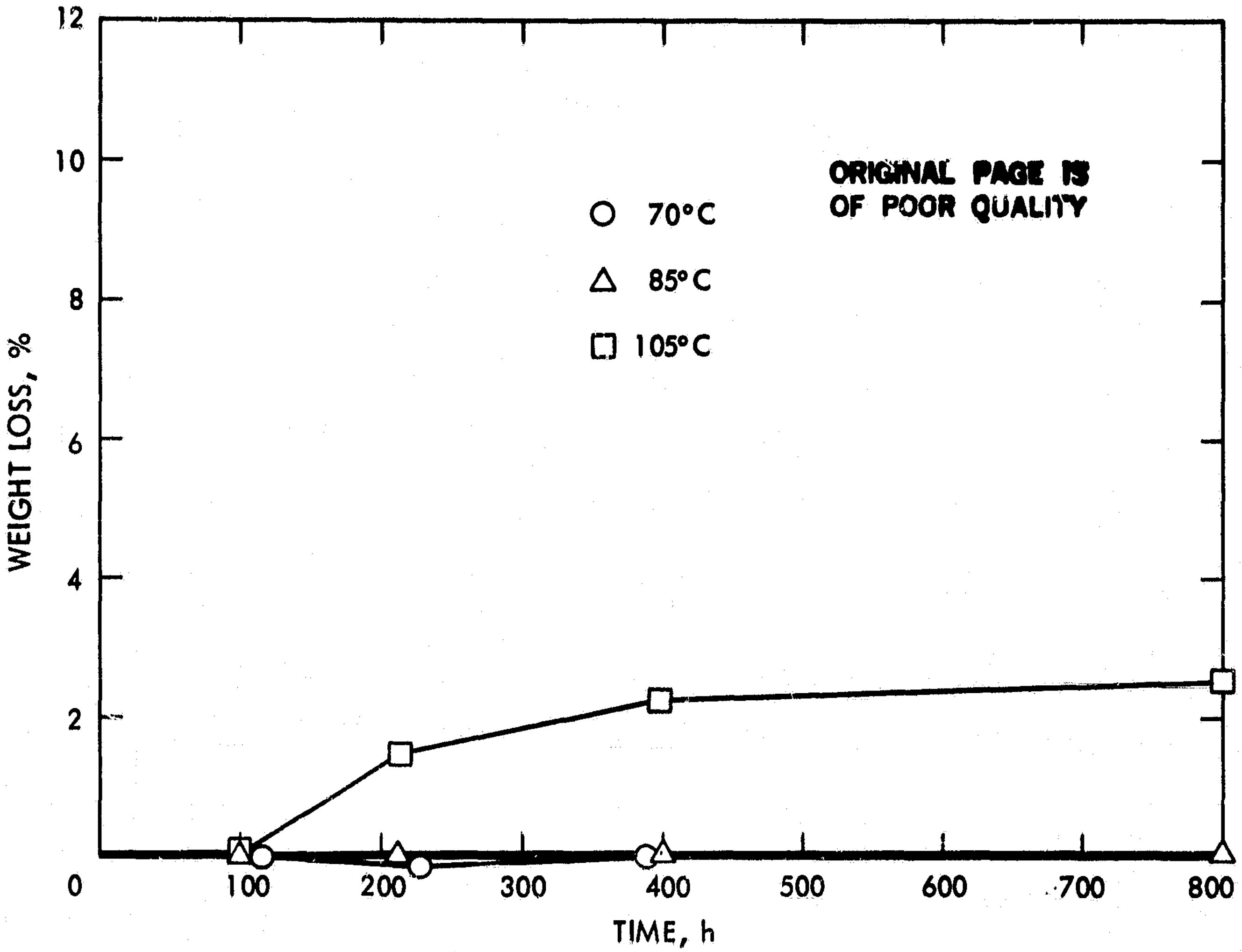

Figure 63. Weight Loss as a Function of Thermal Aging of RTV at 70°C, 85°C, and 105°C

C-2

D. OTHER PROPERTIES

Table 16. Sol/Gel and Molecular Weight Data as a Function of Open Photothermal Aging of RTV at 30°C, 70°C, 85°C, and 105°C

T, °C	TIME OF AGING, h	CROSSLINKING DENSITY, MOL/cm^3		SOL, %		GEL, %		MOL WT (SOL)	
		SAMPLE 1	SAMPLE 2	1	2	1	2	1	2
30	0	2.04×10^{-4}	7.97×10^{-4}		4		96		2000
70	500	2.70×10^{-4}		4		96		2000	
85	800		7.62×10^{-4}		4		96		2000
105	800		7.42×10^{-4}		4		96		2000

Table 17. Sol/Gel and Molecular Weight Data as a Function of Covered Photothermal Aging of RTV at 30°C, 70°C, 85°C, and 105°C

T, °C	TIME OF AGING, h	CROSSLINKING DENSITY, MOL/cm^3		SOL, %		GEL, %		MOL WT (SOL)	
		SAMPLE 1	SAMPLE 2	1	2	1	2	1	2
30	0	2.04×10^{-4}	7.97×10^{-4}		4		96		2000
70	500	4.69×10^{-4}		3		97		2000	
85	800		7.69×10^{-4}		4		96		2000
105	800		8.79×10^{-4}		4		96		2000

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Table 18. Sol/Gel and Molecular Weight Data as a Function of Thermal Aging of RTV at 30°C, 70°C. 85°C, and 105°C

T, °C	TIME OF AGING, h	CROSSLINKING DENSITY, MOL/cm^3		SOL, %		GEL, %		MOL WT (SOL)	
		SAMPLE 1	SAMPLE 2	1	2	1	2	1	2
30	0	2.04×10^{-4}	7.97×10^{-4}		4		96		2000
70	500	2.75×10^{-4}		3.5		96.5		2000	
85	800		5.83×10^{-4}		4		96		2000
105	800		6.08×10^{-4}		3.5		96.5		2000

SECTION V

EMA (SPRINGBORN A-13404)

The following figures and tables offer data on mechanical properties (Figures 64 and 65, Tables 19 and 20); weight loss (Figures 66 through 68); other properties (Tables 21 through 23) of EMA (Springborn A-13404).

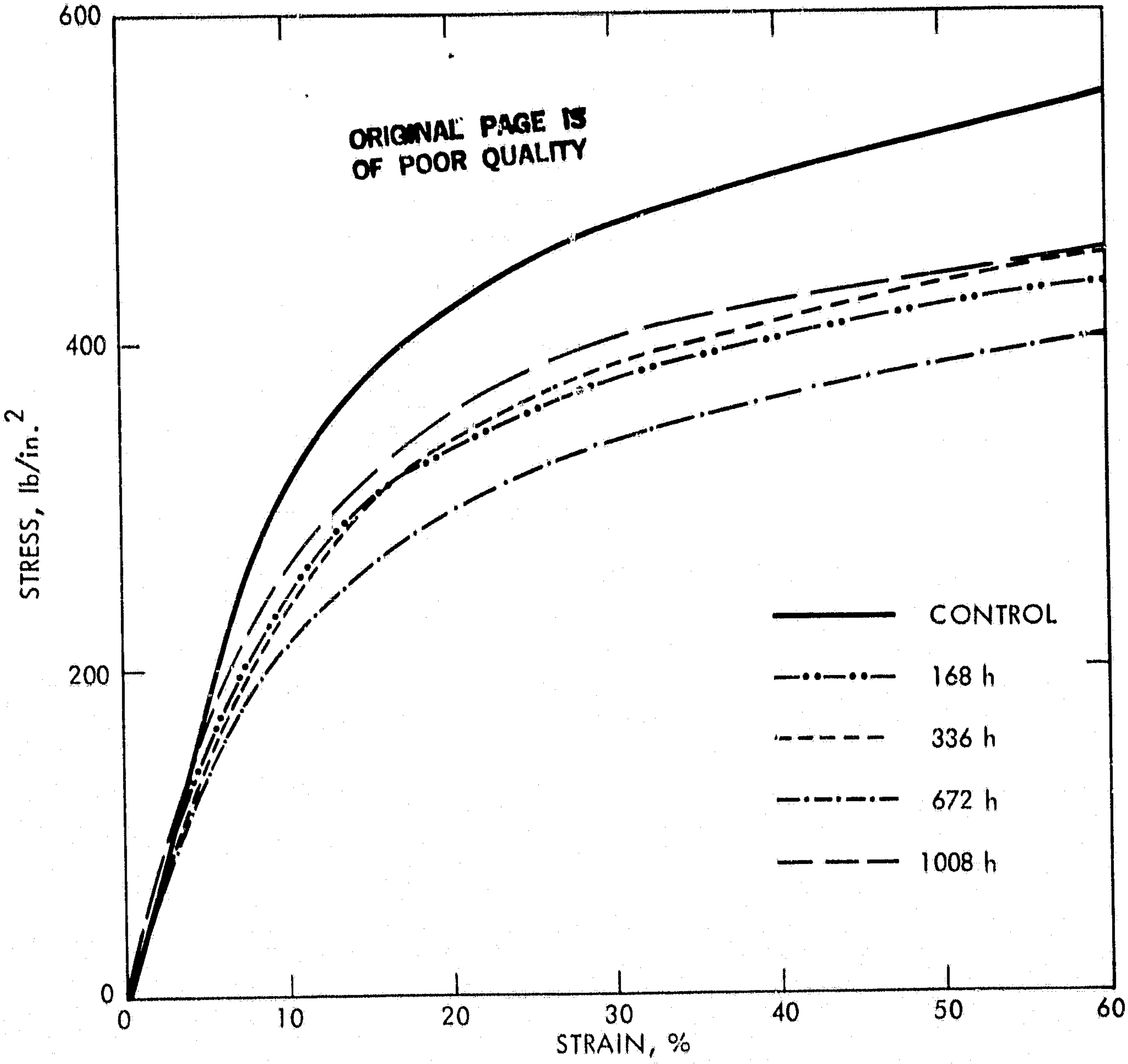

Figure 64. Change in Stress/Strain Response as a Function of Covered Photothermal Aging of EMA at 135°C

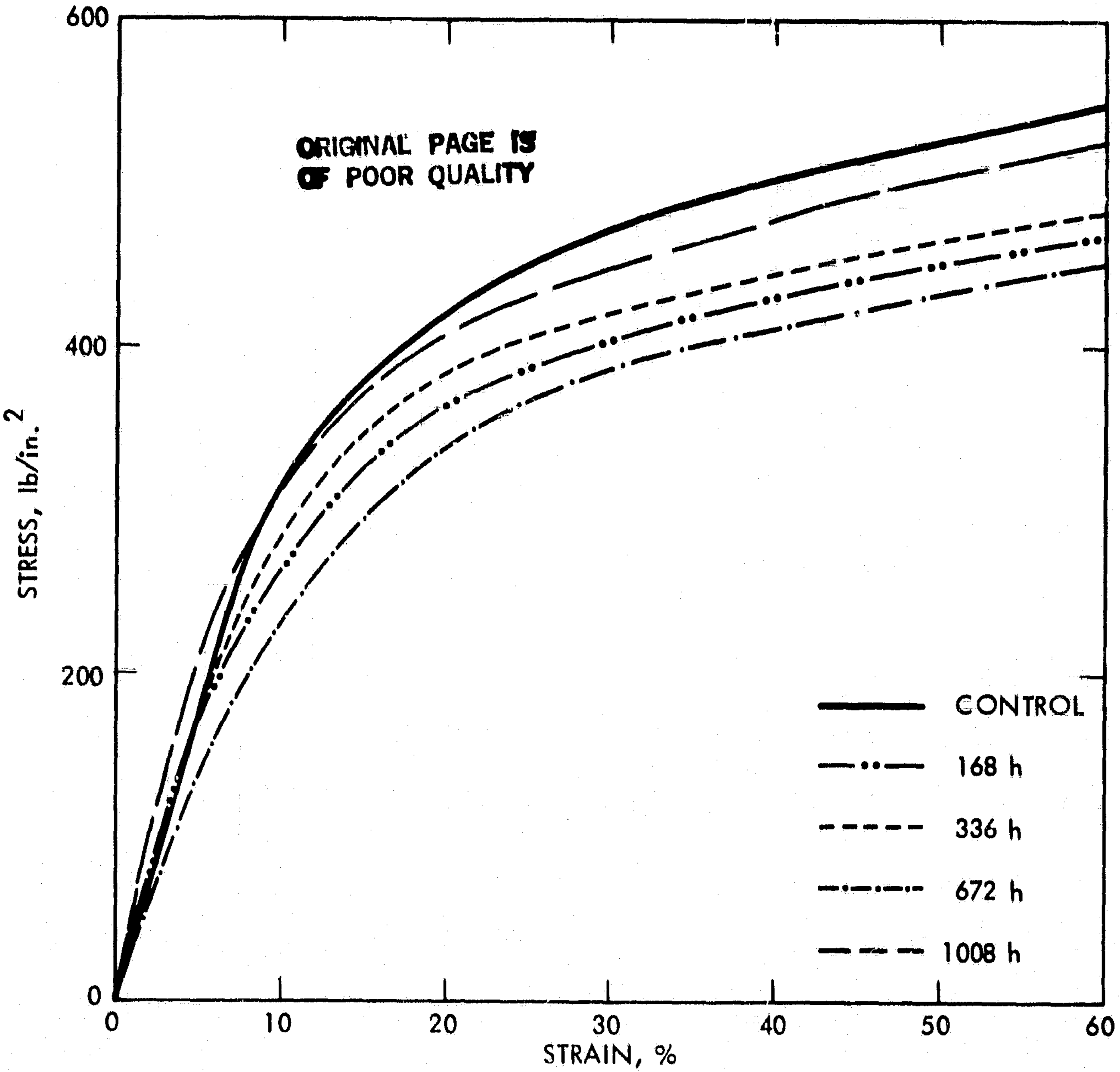

Figure 65. Change in Stress/Strain Response as a Function of Thermal Aging of EMA at 135°C

Table 19. Modulus at 5% Strain as a Function of Covered Photothermal Aging of EMA at 30°C and 135°C

TEMPERATURE, °C	TIME OF AGING, h	MODULUS, LB/in.^{2} 5% STRAIN
ROOM TEMP. (30)	0	3548
135	168 336 672	3016 2871 2552

Table 20. Modulus at 5% Strain as a Function of Thermal Aging of EMA at 30°C and 135°C

TEMPERATURE, °C	TIME OF AGING, h	MODULUS, lb/in.^{2} 5% STRAIN
ROOM TEMP. (30)	0	3548
135 *	168	3398
	336	3530
	672	2736
	1008	4231

* IN A COVERED CONFIGURATION (SANDWICH)

B. WEIGHT LOSS

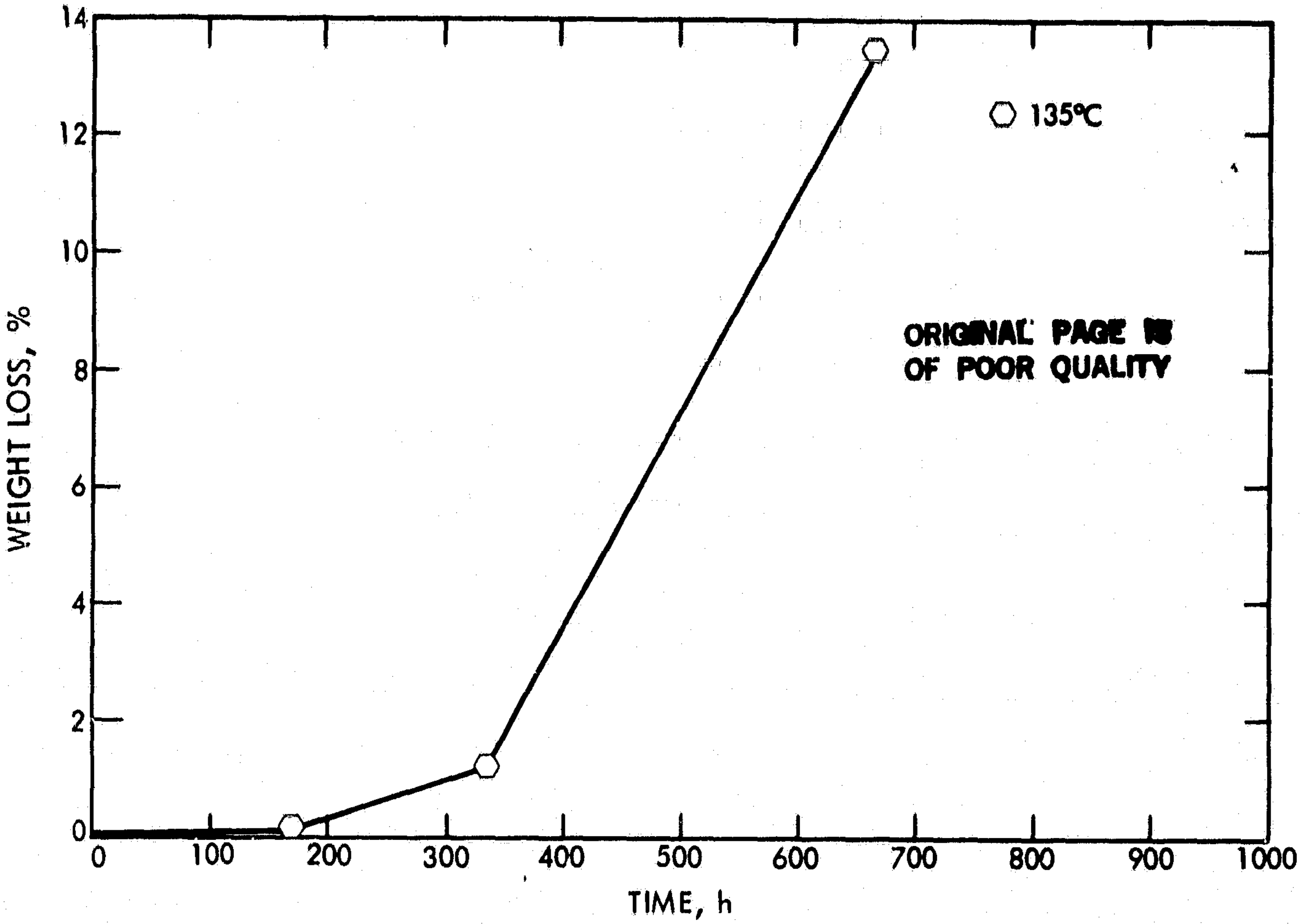

Figure 66. Weight Loss as a Function of Open Photothermal Aging of EMA at 135°C

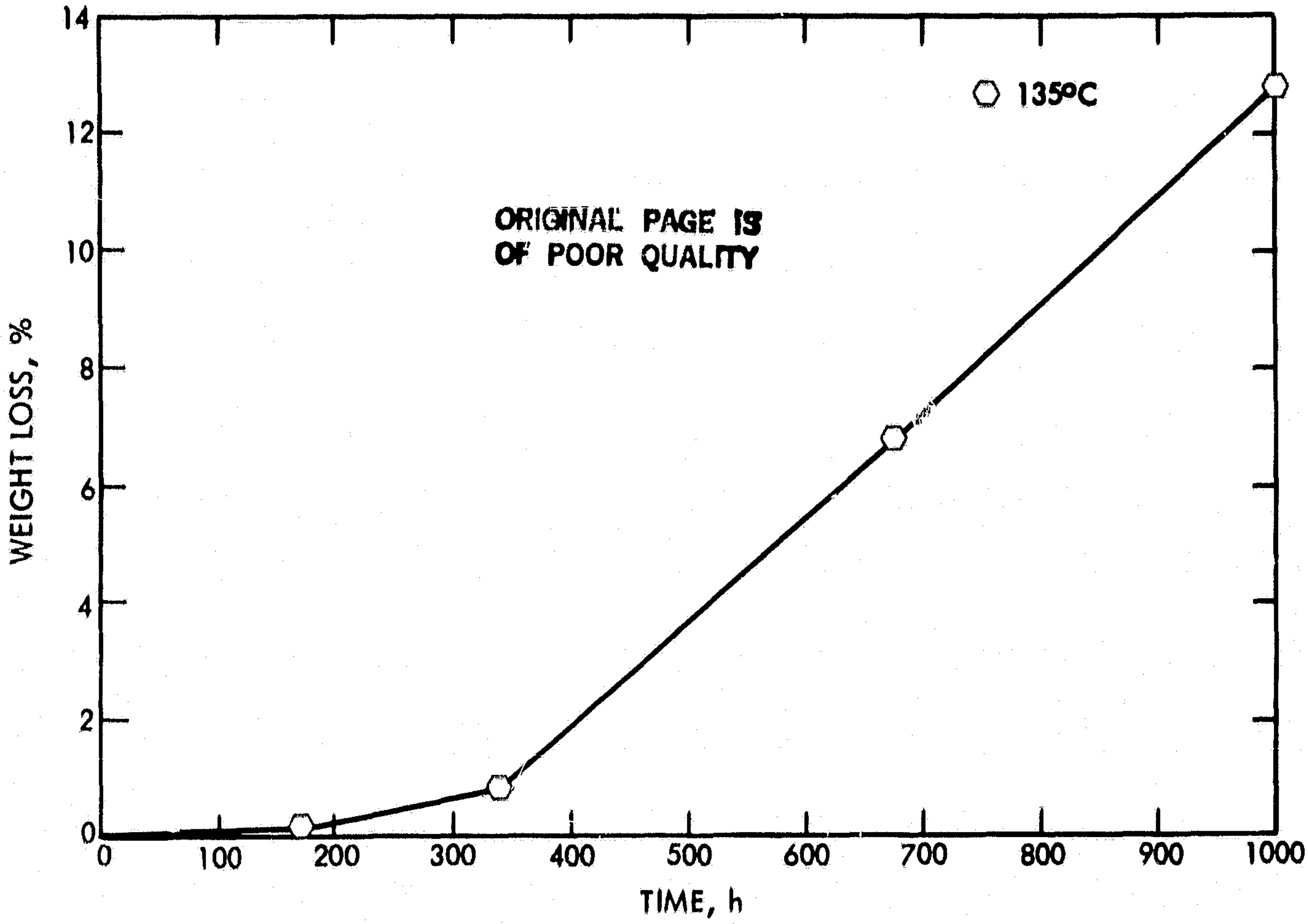

Figure 67. Weight Loss as a Function of Covered Photothermal Aging of EMA at 135°C

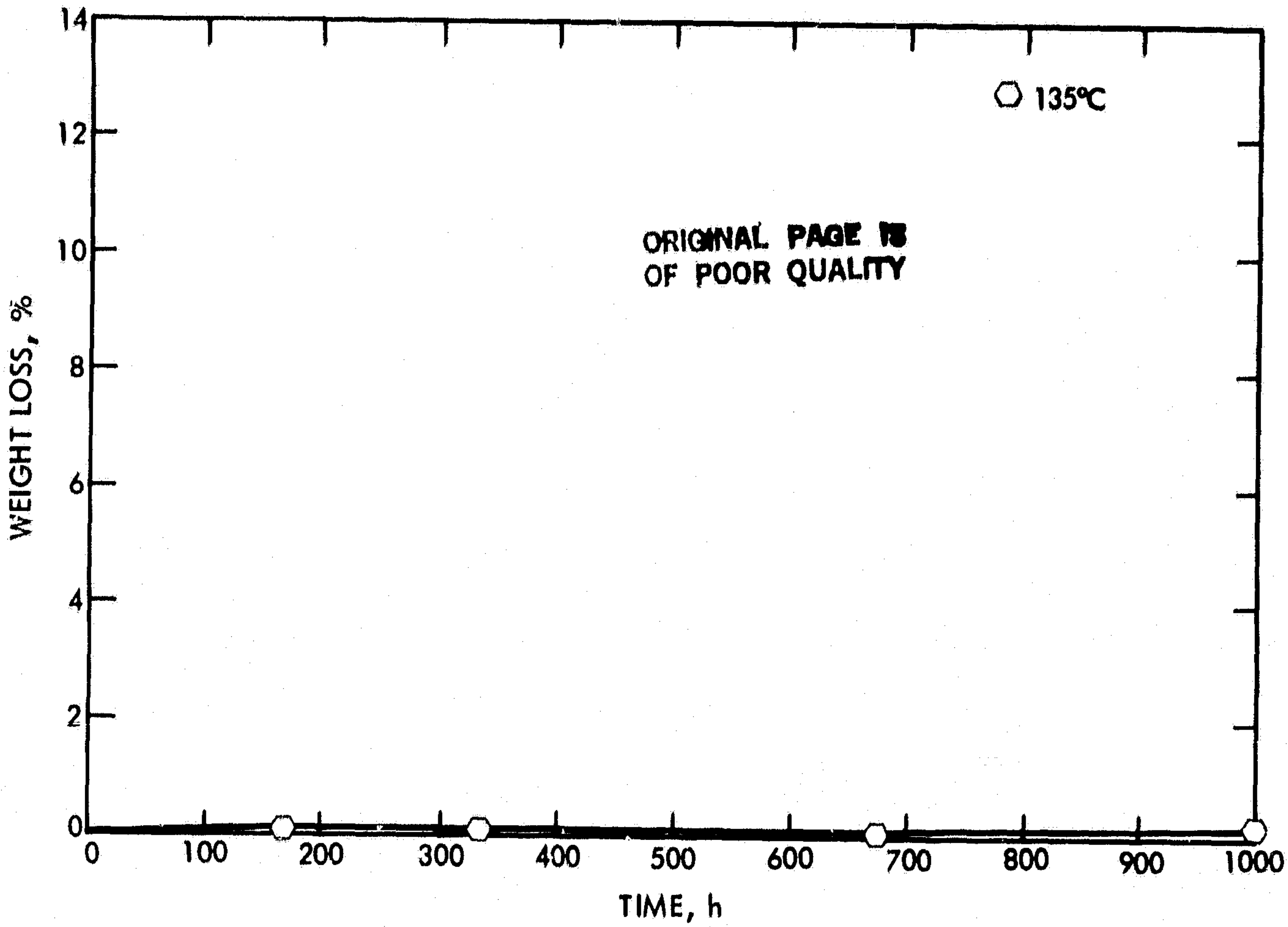

Figure 68. Weight Loss as a Function of Thermal Aging of EMA at 135°C in a Covered (Sandwich) Configuration

C. OTHER PROPERTIES

Table 21. Sol/Gel and Molecular Weight Data as a Function of Open Photothermal Aging of EMA at 30°C and 135°C

T, °C	TIME OF AGING, h	CROSSLINKING DENSITY, MOL/cm^3	SOL, %	GEL, %
30	0	2.0×10^{-4}	15	85
135	84	3.5×10^{-4}	10	90
	168	3.42×10^{-4}	11	89
	336	3.55×10^{-4}	12	88
	672	2.77×10^{-4}	18	82

Table 22. Sol/Gel and Molecular Weight Data as a Function of Covered Photothermal Aging of EMA at 30°C and 135°C

T, °C	TIME OF AGING, h	CROSSLINKING DENSITY, MOL/cm^3	SOL, %	GEL, %
30	0	2.0×10^{-4}	15	85
135	168	1.0×10^{-4}	22	78
	336	0.8×10^{-4}	26	74
	672	1.0×10^{-4}	32	68
	1008	2.3×10^{-4}	20	80

Table 23. Sol/Gel and Molecular Weight Data as a Function of Thermal Aging of EMA at 30°C and 135°C

T, °C	TIME OF AGING, h	CROSSLINKING DENSITY, MOL/cm^3	SOL, %	GEL, %
30	0	2.0×10^{-4}	15	85
135 *	168	3.61×10^{-4}	10	90
	336	3.53×10^{-4}	10	90
	672	3.74×10^{-4}	10	90
	1008	3.63×10^{-4}	11	89

* IN A CLOSED (SANDWICH) CONFIGURATION

SECTION VI

PnBA (SPRINGBORN A-13870)

The following figures and tables offer data on mechanical properties (Figures 69 through 71, Tables 24 through 26); weight loss (Figures 72 and 73); other properties (Tables 27 through 29) of PnBA (Springborn A-13870).

A. MECHANICAL PROPERTIES

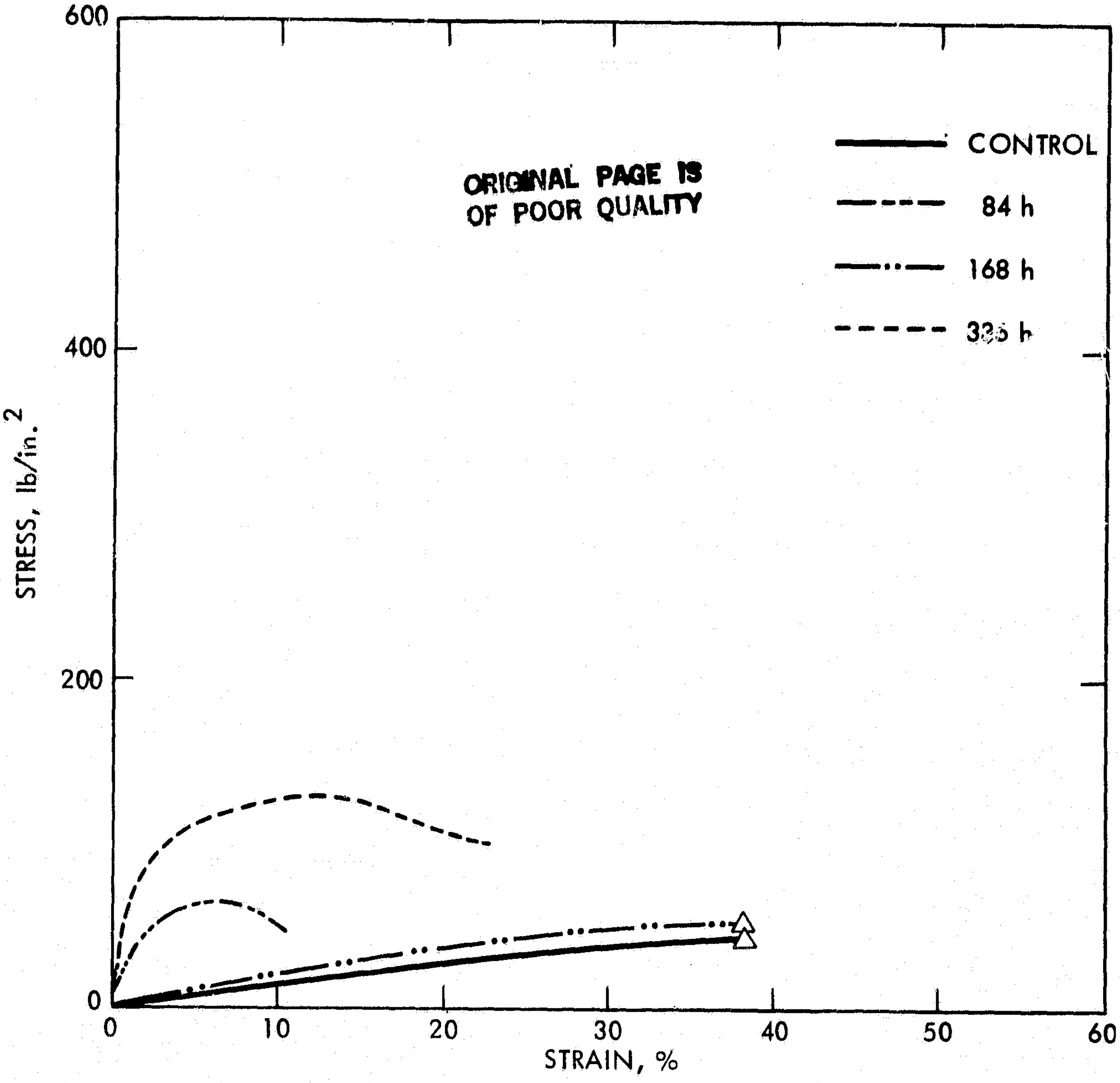

Figure 69. Change in Stress/Strain Response as a Function of Open Photothermal Aging of PnBA at 135°C

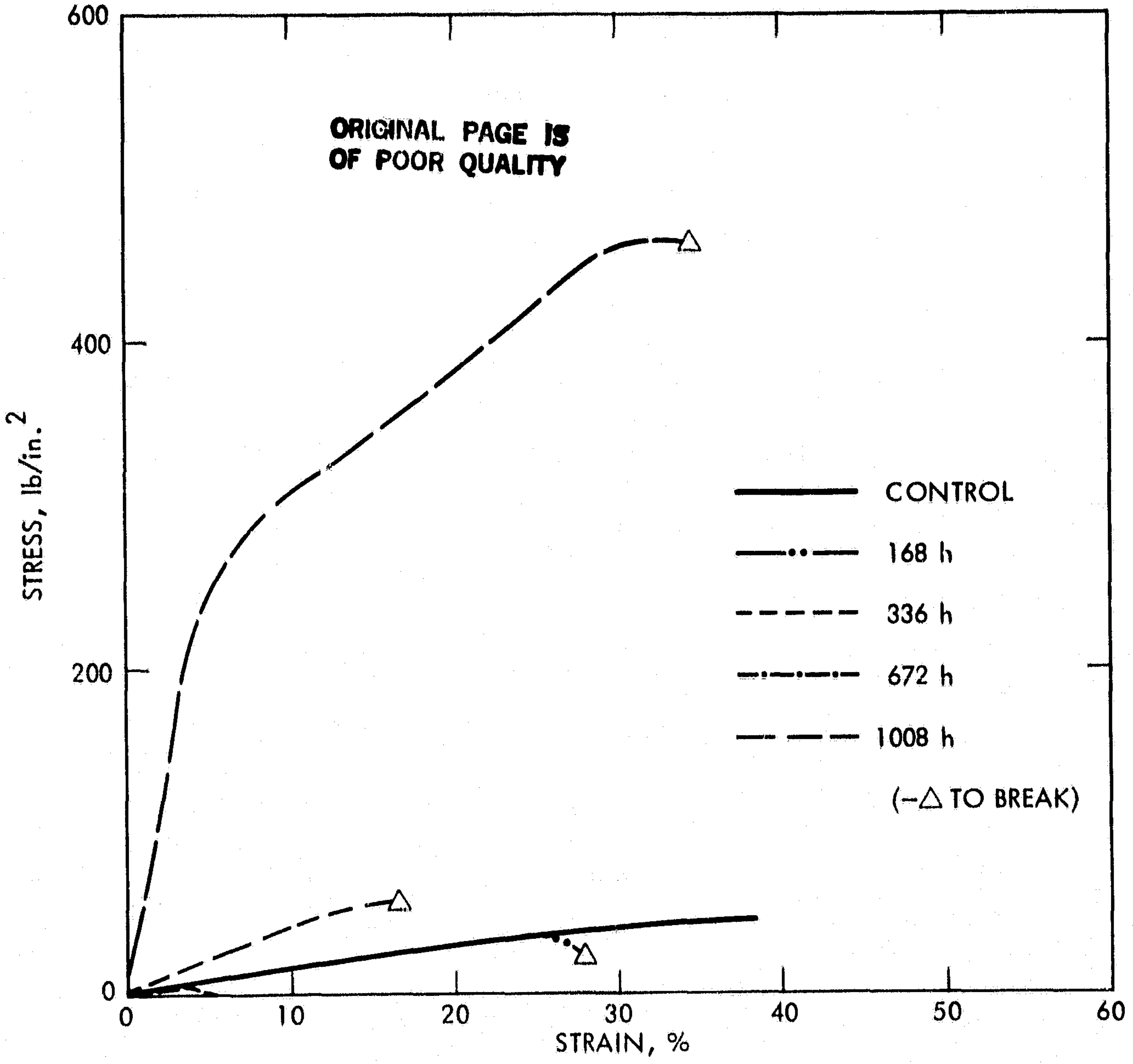

Figure 70. Change in Stress/Strain Response as a Function of Covered Photothermal Aging of PnBA at 135°C

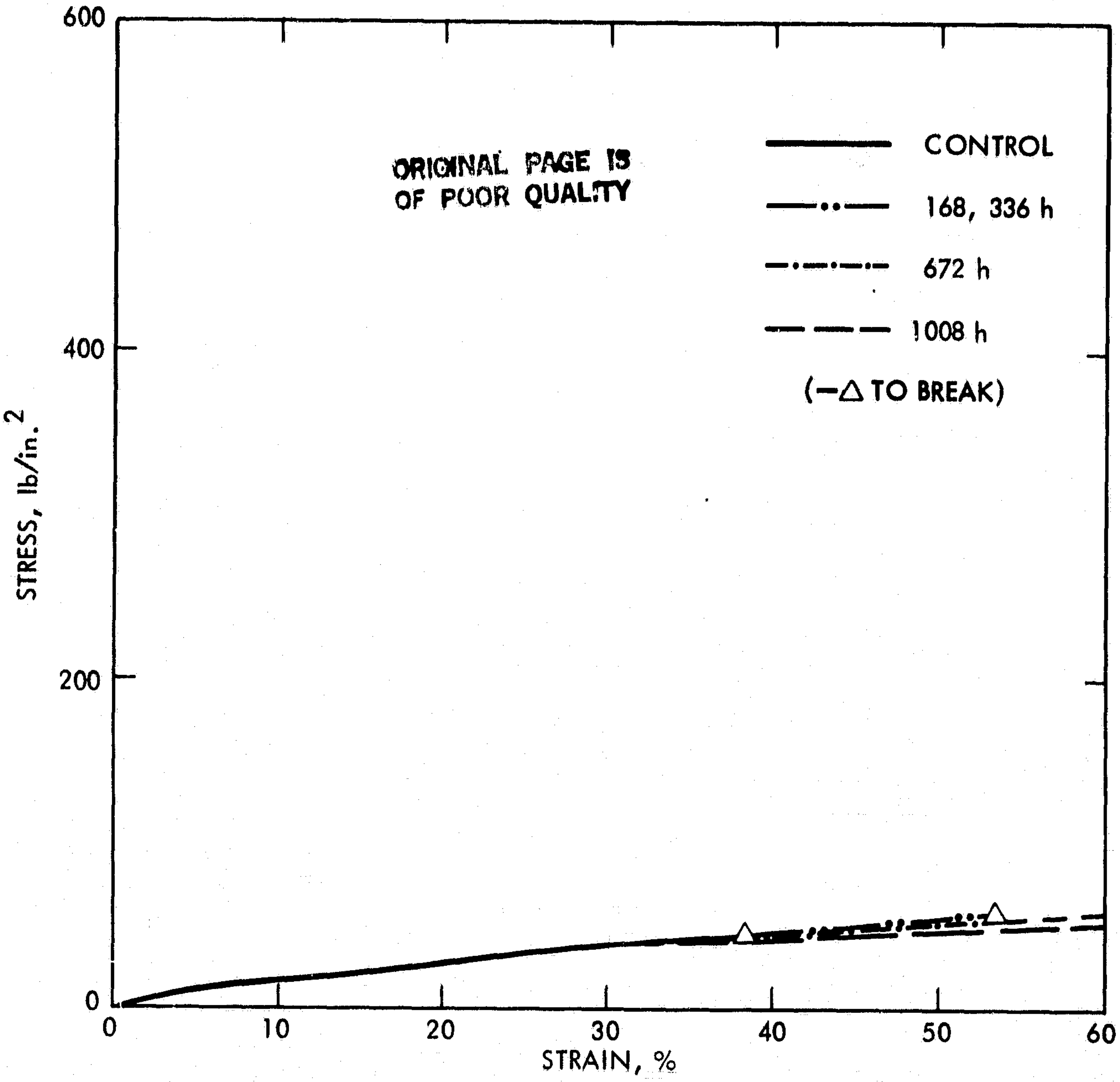

Figure 71. Change in Stress/Strain Response as a Function of Thermal Aging of PnBA at 135°C

Table 24. Modulus at 5% Strain as a Function of Open Photothermal Aging of PnBA at 30°C and 135°C

TEMPERATURE, °C	TIME OF AGING, h	MODULUS, $lb/in.^2$ 5% STRAIN
ROOM TEMP. (30)	0	175
135	84 168 336	281 1250 2175

Table 25. Modulus at 5% Strain as a Function of Covered Photothermal Aging of PnBA at 30°C and 135°C

TEMPERATURE, °C	TIME OF AGING, h	MODULUS, lb/in.^{2} 5% STRAIN
ROOM TEMP. (30)	0	175
135	168 336 672 1008	155 4915 450 350

Table 26. Modulus at 5% Strain as a Function of Thermal Aging of PnBA at 30°C and 135°C

TEMPERATURE, °C	TIME OF AGING, h	MODULUS, lb/in.^{2} 5% STRAIN
ROOM TEMP. (30)	0	175
135 *	168	169
	336	174
	672	181
	1008	171

* IN A COVERED (SANDWICH) CONFIGURATION

B. WEIGHT LOSS

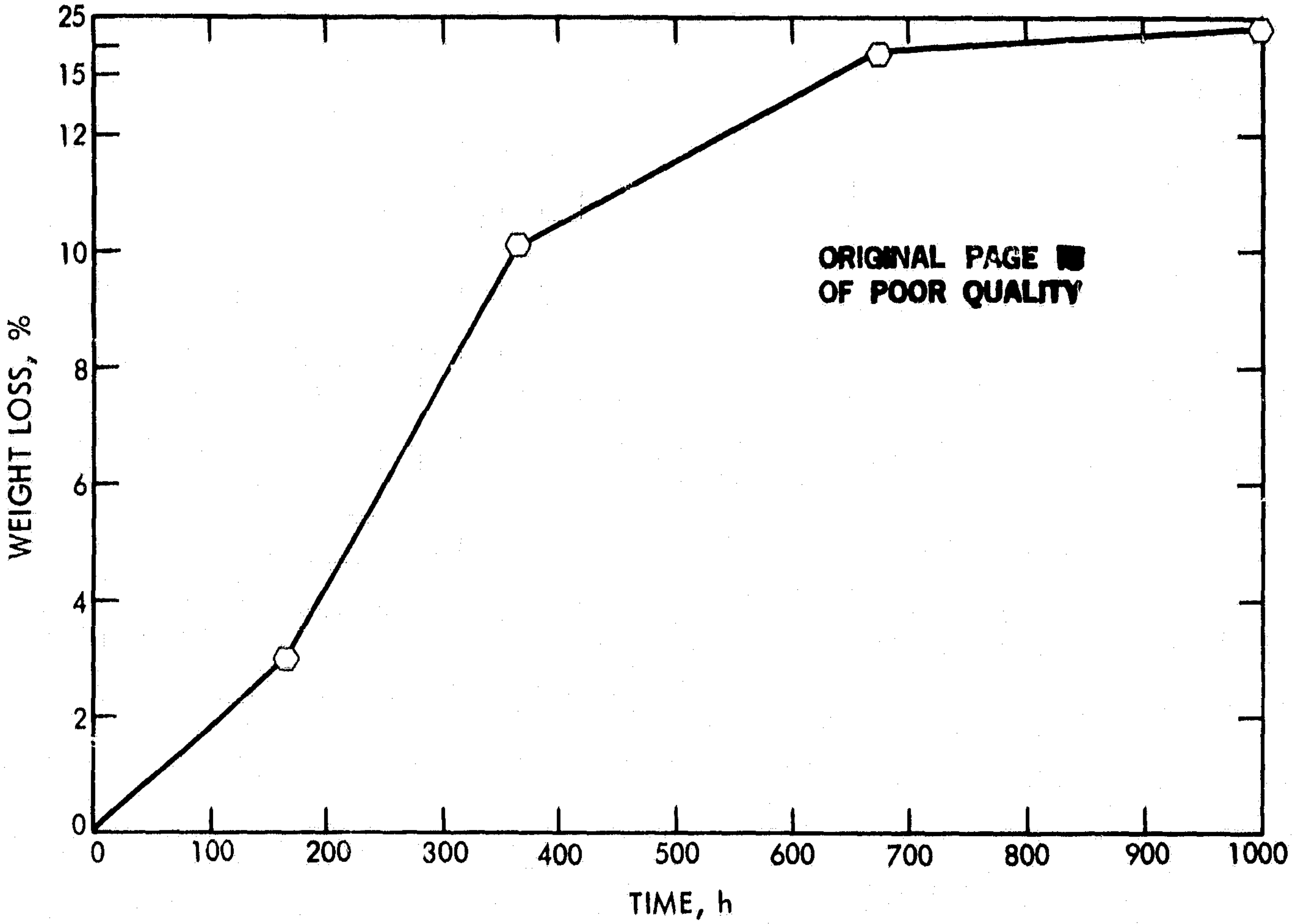

Figure 72. Weight Loss as a Function of Covered Photothermal Aging of PnBA at 135°C

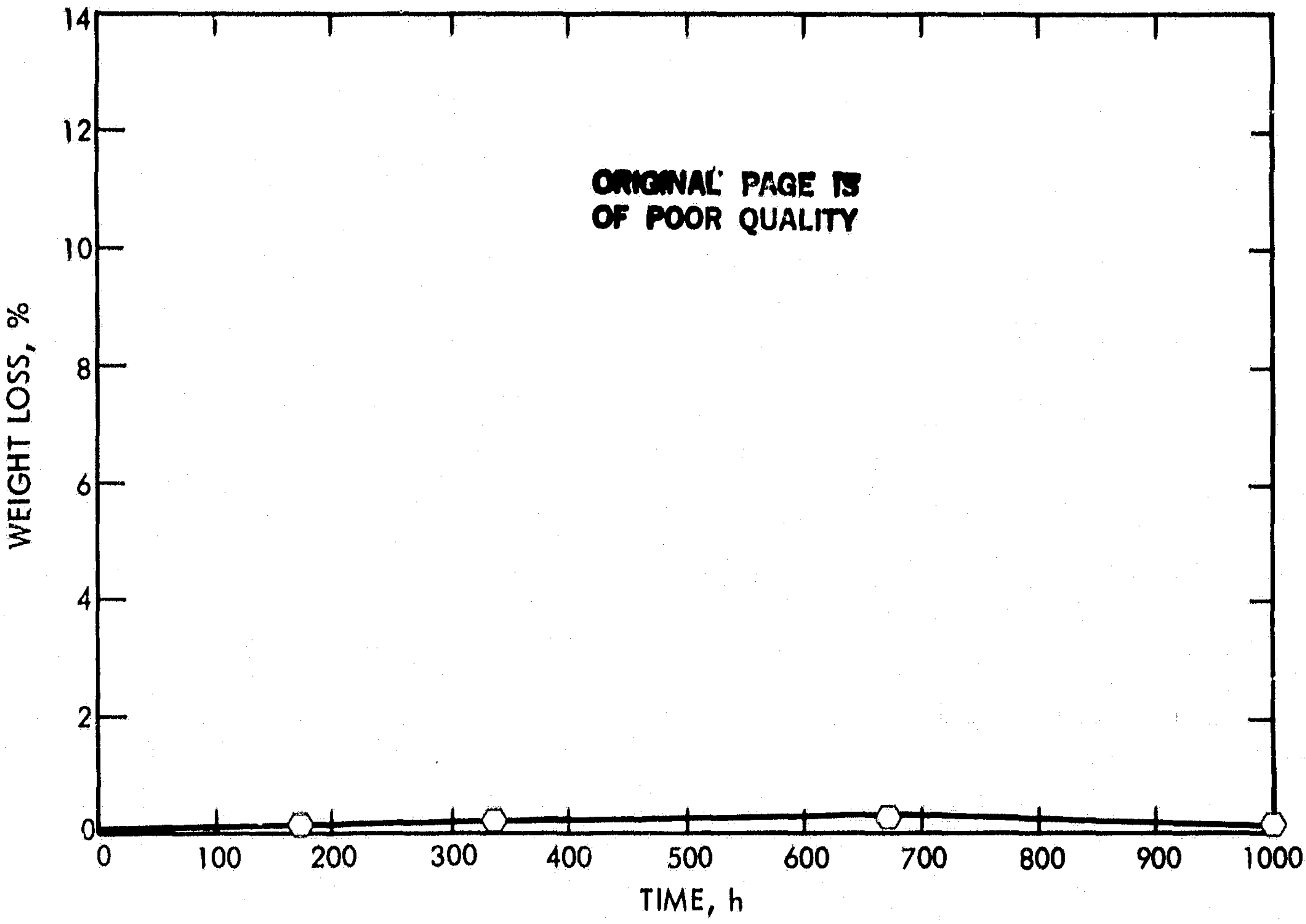

Figure 73. Weight Loss as a Function of Thermal Aging of PnBA at 135°C in a Covered (Sandwich) Configuration

OTHER PROPERTIES

Table 27. Sol/Gel and Molecular Weight Data as a Function of Open Photothermal Aging of PnBA at 30°C and 135°C

T, °C	TIME OF AGING, h	CROSSLINKING DENSITY, MOL/cm^3	SOL, %	GEL, %
30	0	4.34×10^{-4}	15	85
135	84	6.61×10^{-4}	6	94
	168	7.69×10^{-4}	6	94
	336	8.14×10^{-4}	5	95
	672	9.83×10^{-4}	3	97

Table 28. Sol/Gel and Molecular Weight Data as a Function of Covered Photothermal Aging of PnBA at 30°C and 135°C

T, °C	TIME OF AGING, h	CROSSLINKING DENSITY, MOL/cm^3	SOL, %	GEL, %
	0	4.34×10^{-4}	15	85
135	168	4.79×10^{-4}	11	89
	336	27.12×10^{-4}	1	99
	672	7.08×10^{-4}	6	94
	1008	14.13×10^{-4}	6	94

Table 29. Sol/Gel and Molecular Weight Data as a Function of Thermal Aging of PnBA at 30°C and 135°C

T, °C	TIME OF AGING, h	CROSSLINKING DENSITY, MOL/cm^3	SOL, %	GEL, %
30	0	4.34×10^{-4}	15	85
135*	168	4.28×10^{-4}	16	84
	336	4.29×10^{-4}	16	84
	672	4.18×10^{-4}	16	84
	1008	4.37×10^{-4}	15	85

* IN A CLOSED (SANDWICH) CONFIGURATION

SECTION VII

POLYURETHANE (H.J. QUINN -- DEVELOPMENT ASSOCIATES Z-2591)

The following figures and tables offer data on optical transmittance (Figures 74 through 76); mechanical properties (Figures 77 through 80, Tables 30 through 32); weight loss (Figures 81 thrugh 83); other properties (Tables 33 through 35) of polyurethane (H.J. Quinn Co. -- Development Associates Z-2591).

A. OPTICAL TRANSMITTANCE

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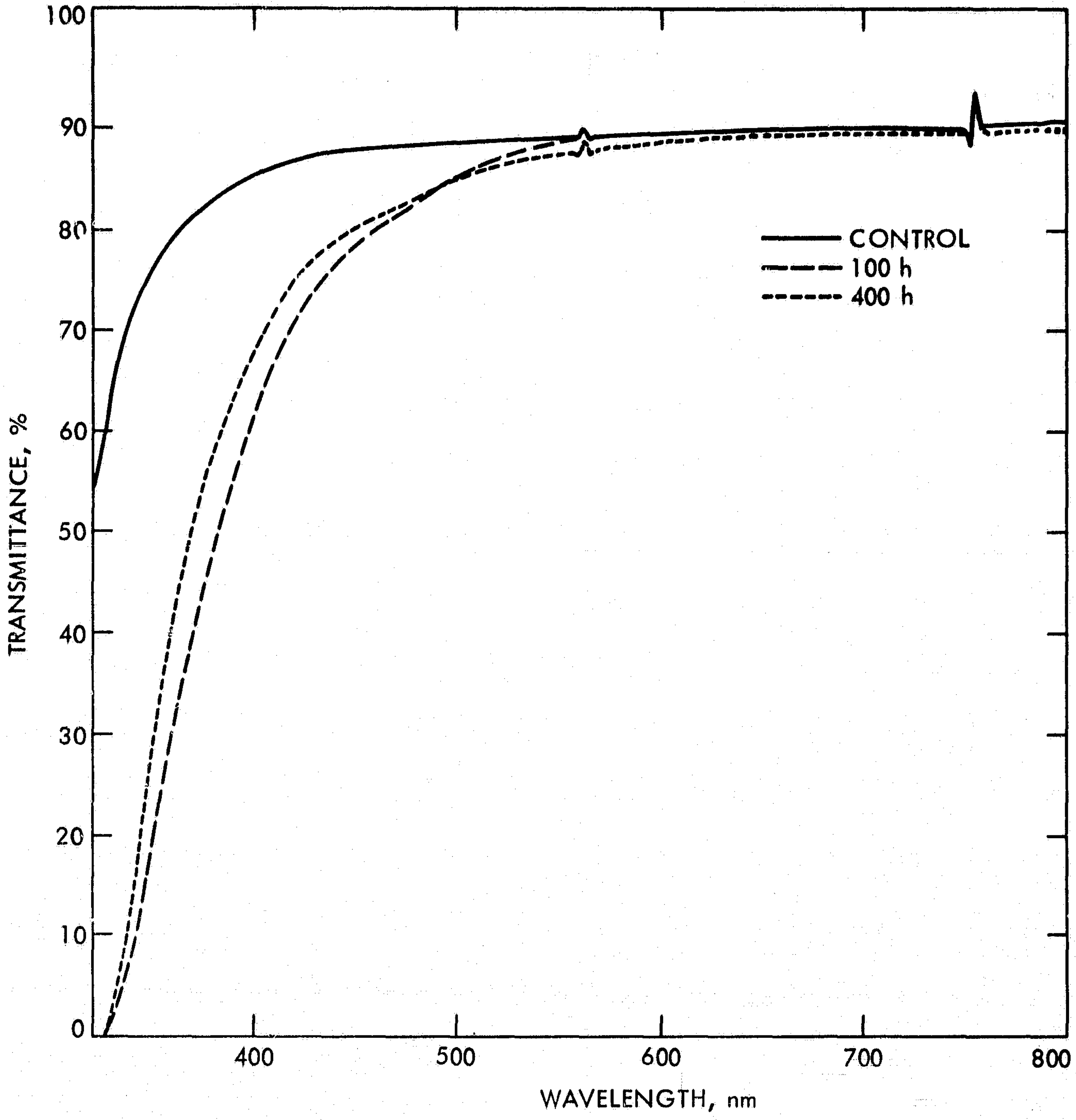

Figure 74. Change in Optical Transmittance as a Function of Open Photothermal Aging of Polyurethane at 70°C

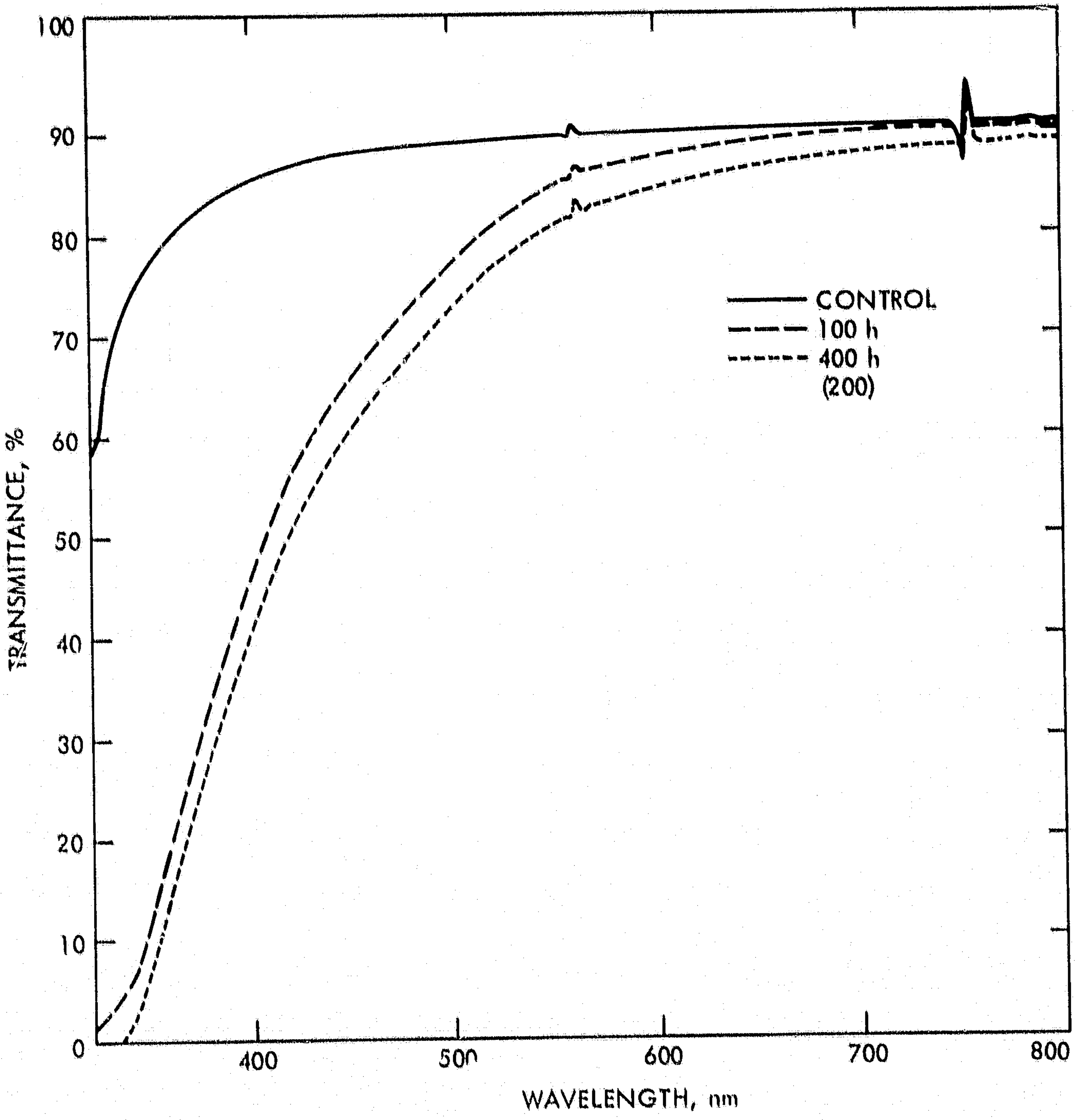

Figure 75. Change in Optical Transmittance as a Function of Covered Photothermal Aging of Polyurethane at 70°C

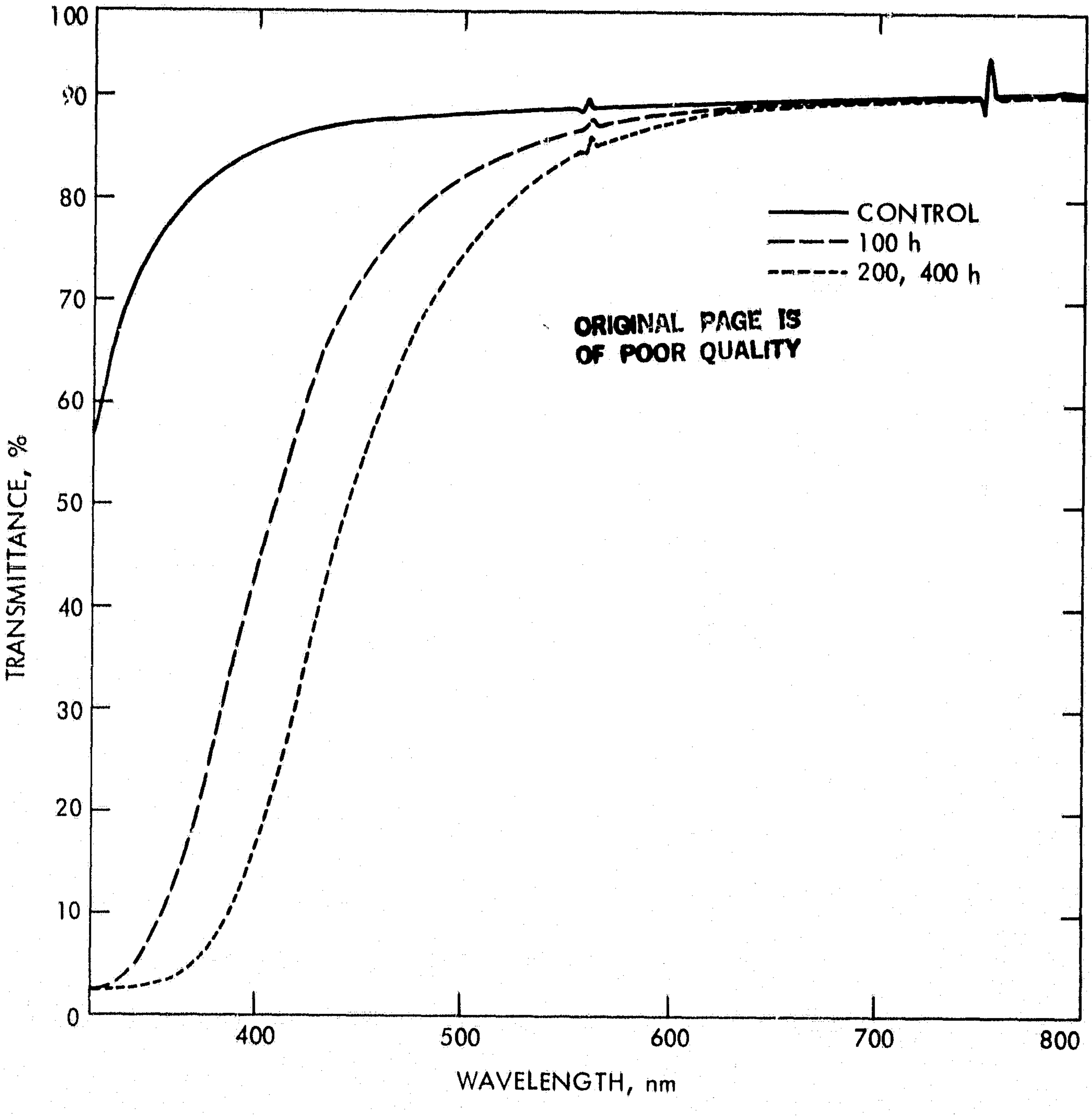

Figure 76. Change in Optical Transmittance as a Function of Thermal Aging of Polyurethane at 70°C

B. MECHANICAL PROPERTIES

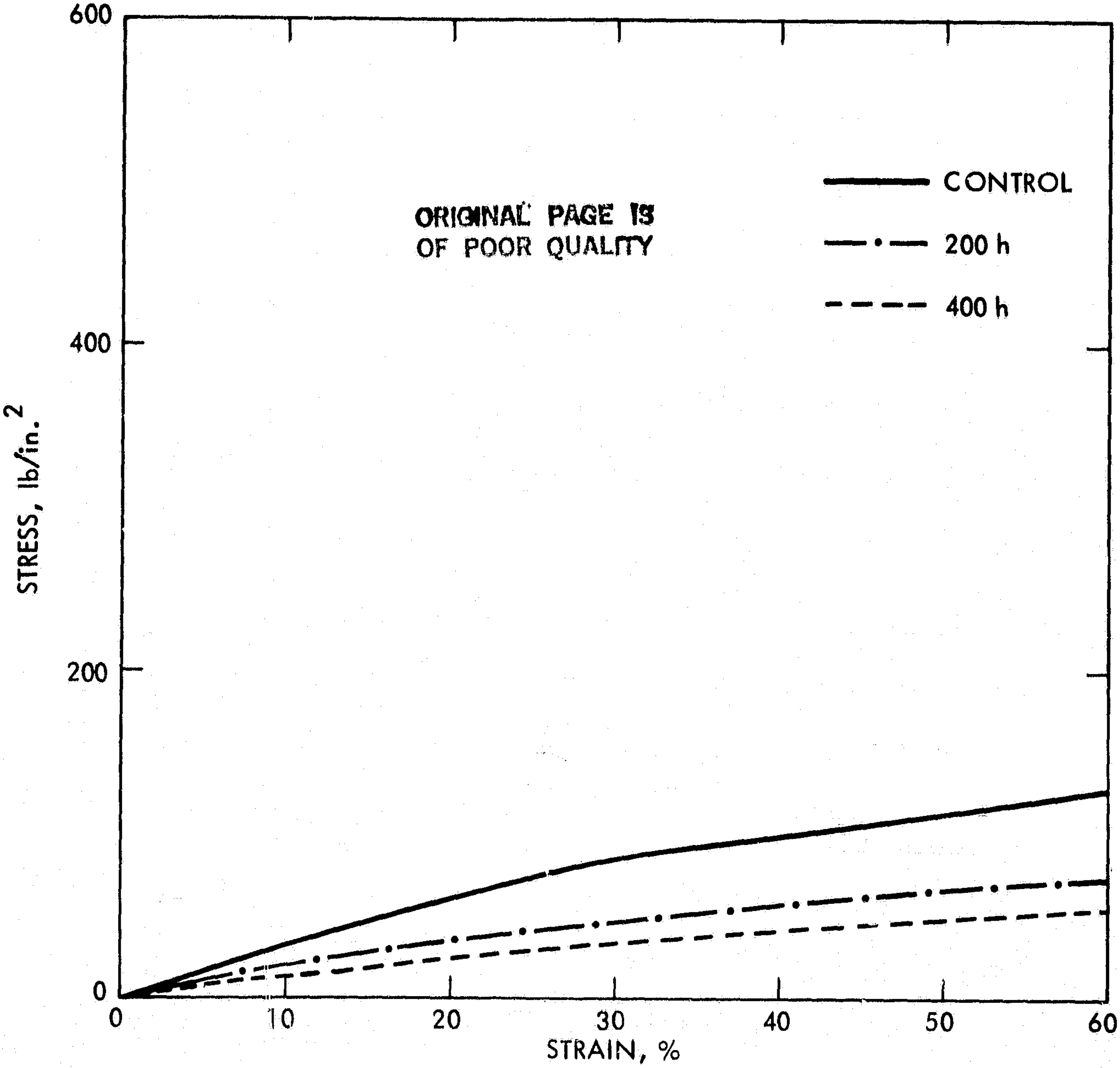

Figure 77. Change in Stress/Strain Response as a Function of Open Photothermal Aging of Polyurethane at 70°C

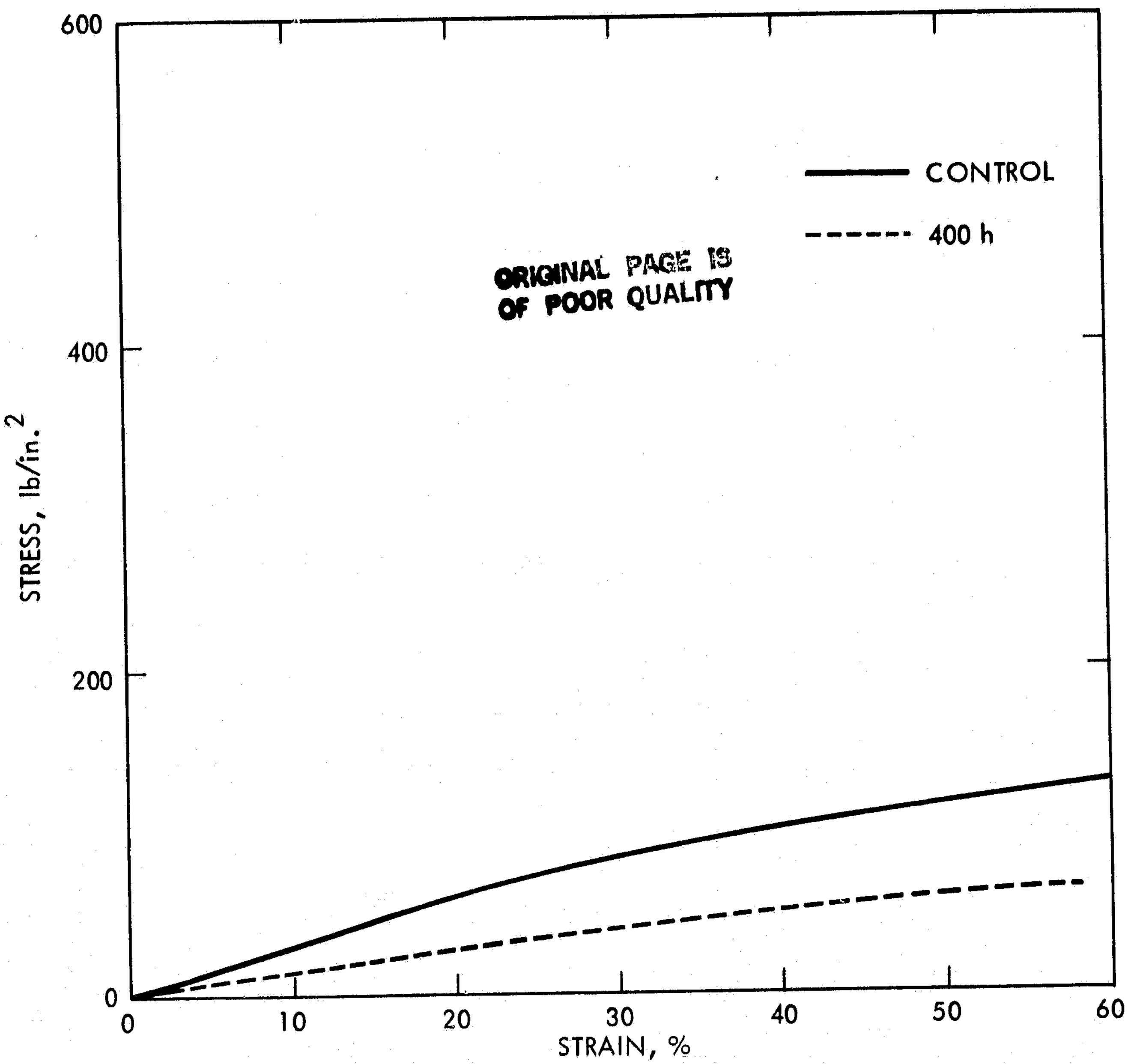

Figure 78. Change in Stress/Strain Response as a Function of Covered Photothermal Aging of Polyurethane at 70°C

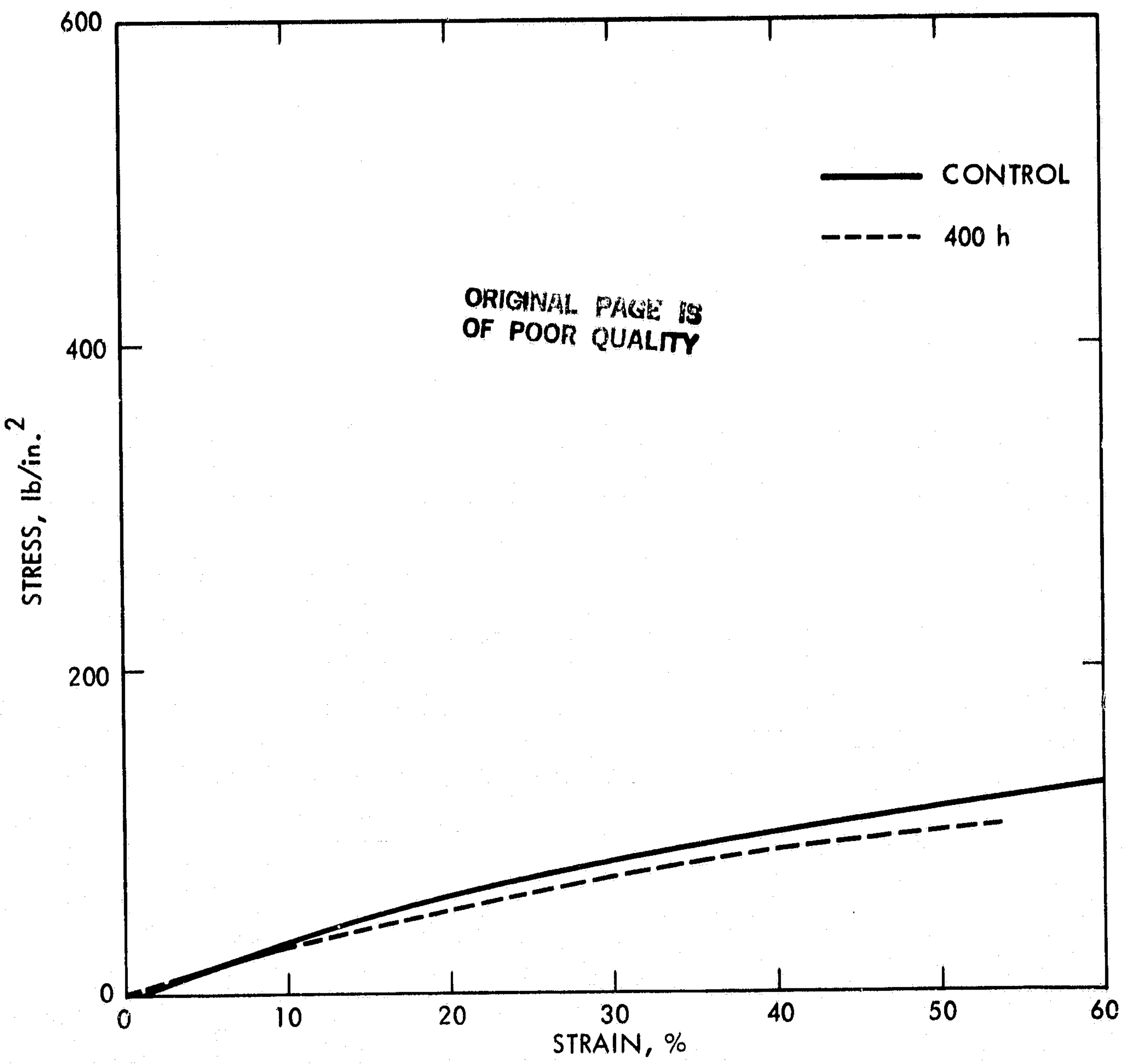

Figure 79. Change in Stress/Strain Response as a Function of Thermal Aging of Polyurethane at 70°C

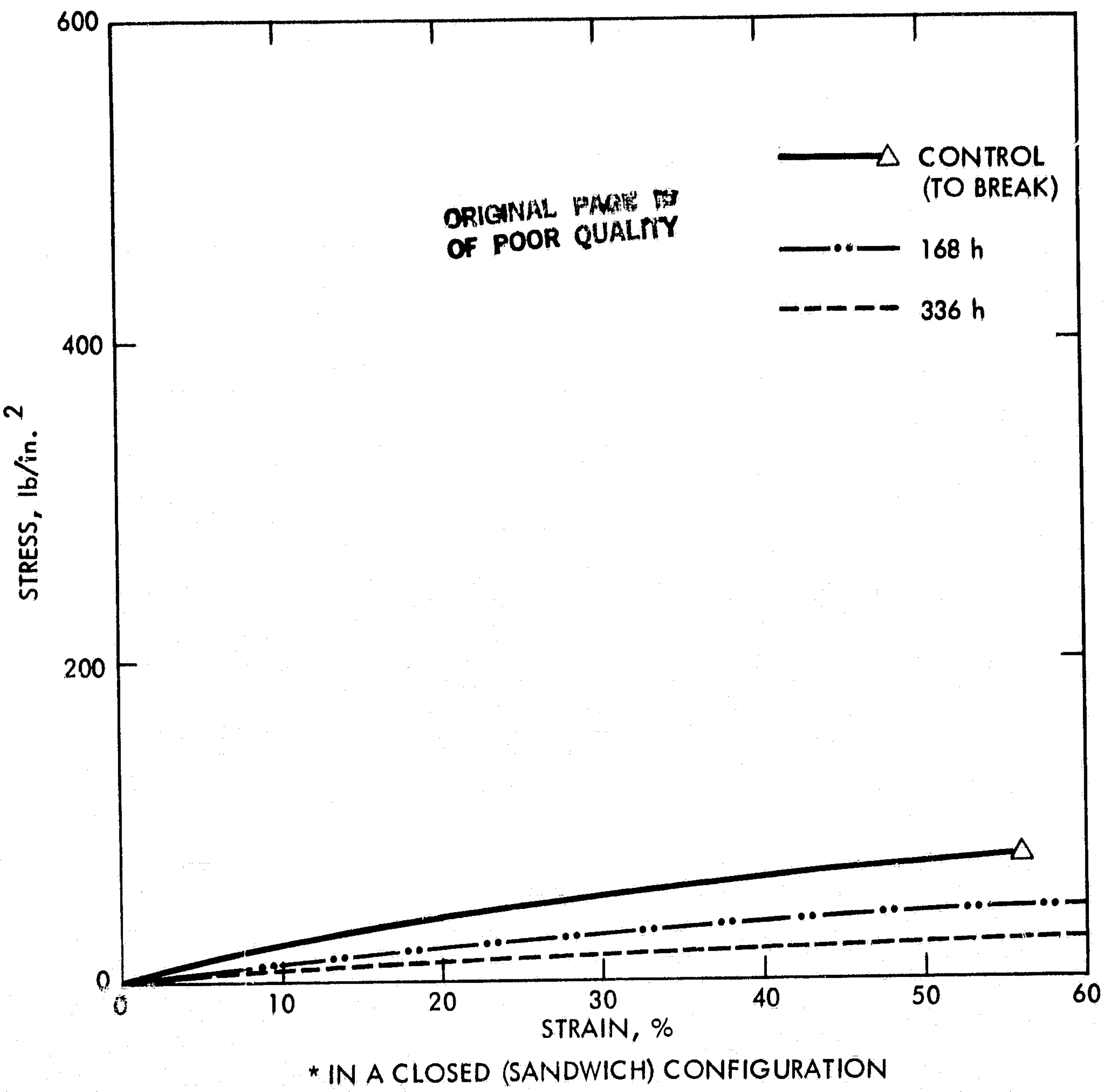

Figure 80. Change in Stress/Strain Response as a Function of Thermal Aging of Polyurethane at 135°C in a Closed (Sandwich) Configuration

Table 30. Modulus at 5% Strain as a Function of Open Photothermal Aging of Polyurethane at 30°C and 70°C

TEMPERATURE, °C	TIME OF AGING, h	MODULUS, lb/in.^{2} 5% STRAIN
ROOM TEMP. (30)	0	380
70*	200 400	205 118

* PU (QUINN)

Table 31. Modulus at 5% Strain as a Function of Covered Photothermal Aging of Polyurethane at 30°C and 70°C

TEMPERATURE, °C	TIME OF AGING, h	MODULUS, $lb/in.^2$ 5% STRAIN
ROOM TEMP. (30)	0	380
70*	200 400	153 154
135**	168 336	73 FLOW

* PU (QUINN)
** PU (DEVELOPMENT ASSOCIATES Z-2591)

Table 32. Modulus at 5% Strain as a Function of Thermal Aging of Polyurethane at 30°C and 70°C

TEMPERATURE, °C	TIME OF AGING, h	MODULUS, lb/in.^{2} 5% STRAIN
ROOM TEMP. (30)	0	380
70*	400	300
135**♦	168 336	101 54

* PU (QUINN)
** PU (DEVELOPMENT ASSOCIATES Z-2591)
♦ IN A COVERED (SANDWICH) CONFIGURATION

C. WEIGHT LOSS

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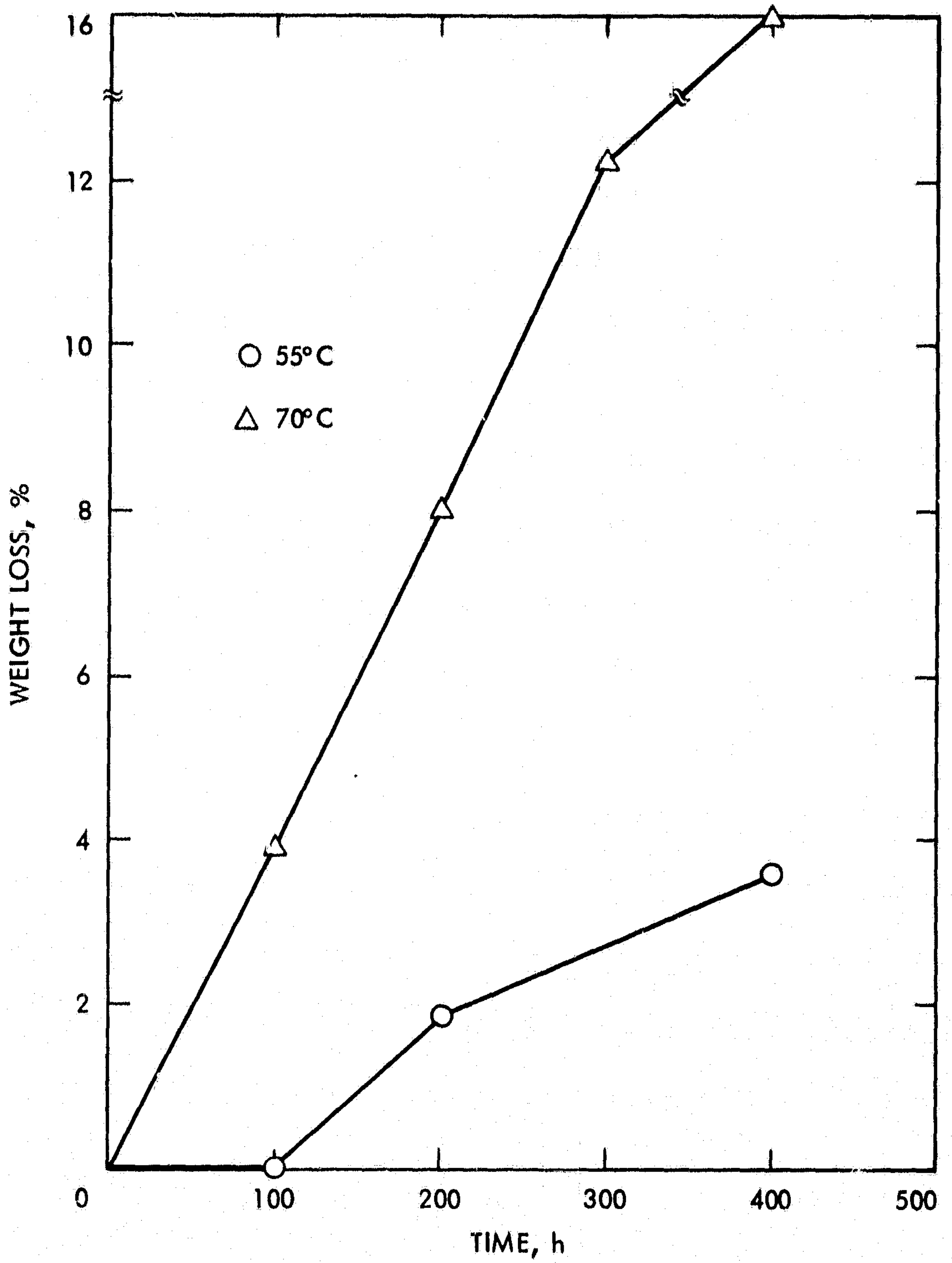

Figure 81. Weight Loss as a Function of Open Photothermal Aging of Polyurethane (Quinn) at 55°C and 70°C

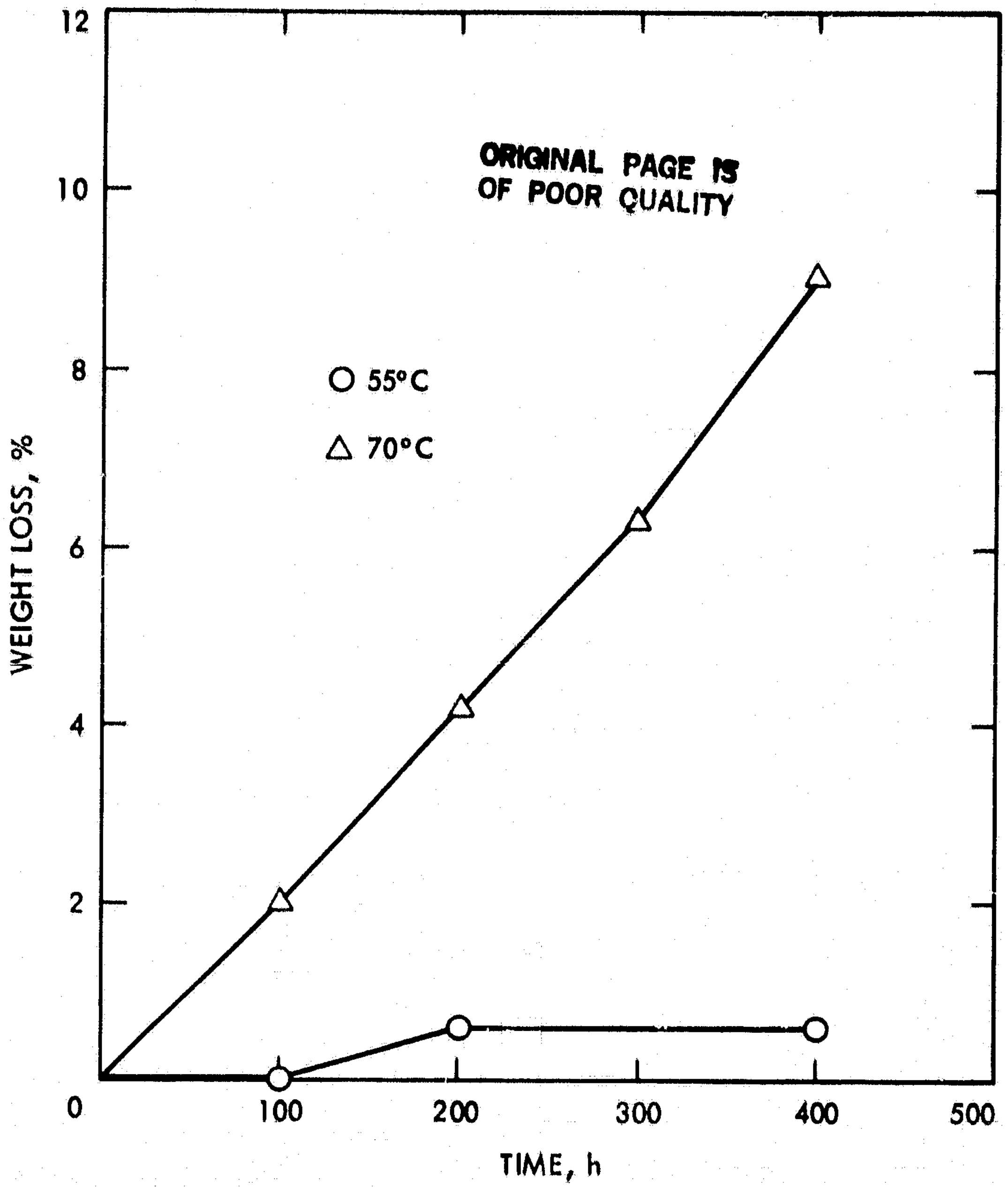

Figure 82. Weight Loss as a Function of Covered Photothermal Aging of Polyurethane (Quinn) at 55°C and 70°C

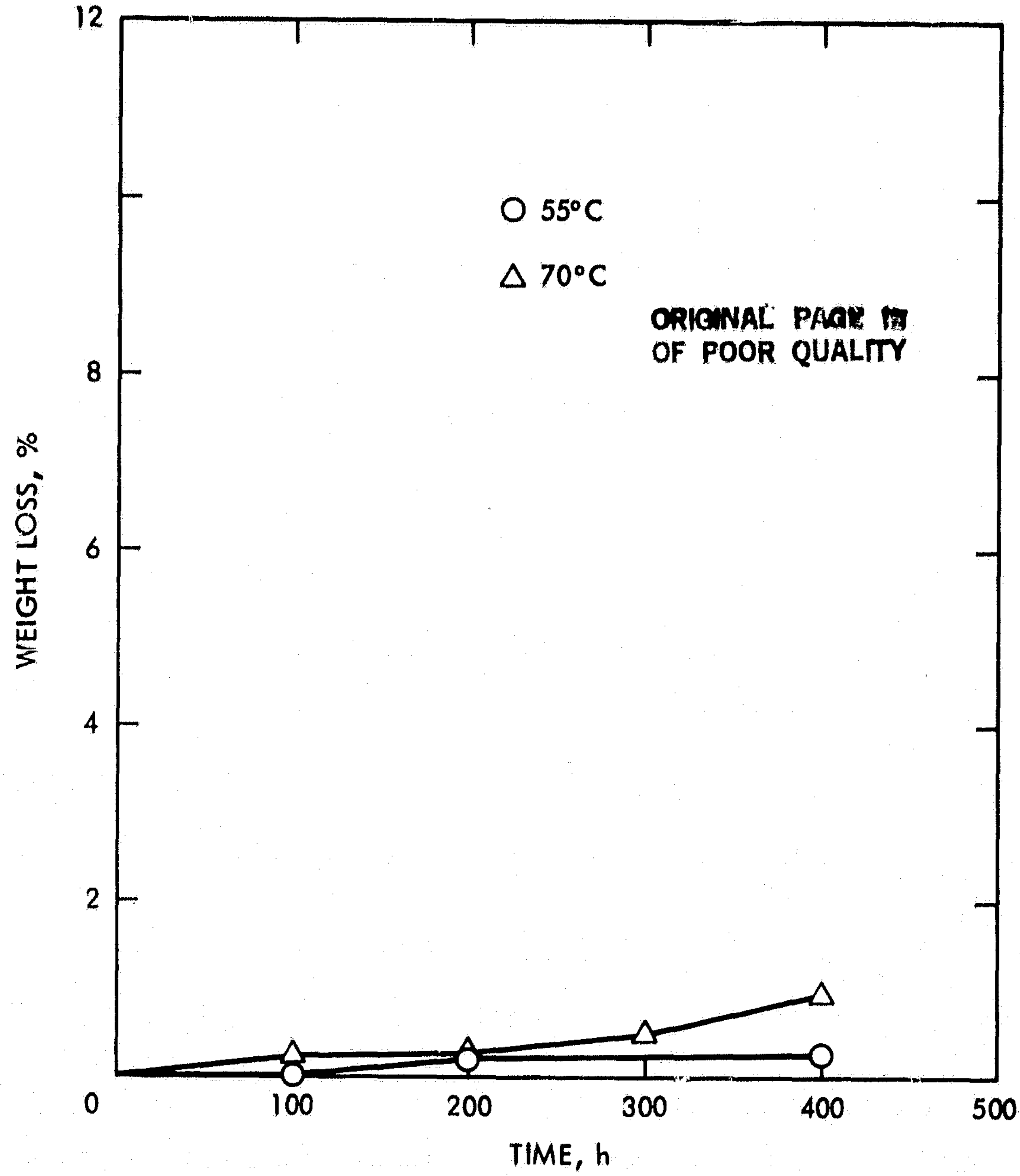

Figure 83. Weight Loss as a Function of Thermal Aging of Polyurethane (Quinn) at 55°C and 70°C

D. OTHER PROPERTIES

Table 33. Sol/Gel and Molecular Weight Data as a Function of Open Photothermal Aging of Polyurethane at 30°C and 70°C

T, °C	TIME OF AGING, h	CROSSLINKING DENSITY, MOL/cm³		SOL, %		GEL, %		MOL WT (SOL)	
		SAMPL 1	SAMPLE 2	1	2	1	2	1	2
30	0	166.0×10^{-6}	71.0×10^{-6}	4		96			
70*	400	57.0×10^{-6}		21		79		10,000	

* PU (QUINN)

Table 34. Sol/Gel and Molecular Weight Data as a Function of Covered Photothermal Aging of Polyurethane at 30°C, 70°C and 135°C

T, °C	TIME OF AGING, h	CROSSLINKING DENSITY, MOL/cm^3		SOL, %		GEL, %		MOL WT (SOL)	
		SAMPLE 1	SAMPLE 2	1	2	1	2	1	2
30		166.0×10^{-6}	71.0×10^{-6}	4		96		5,000	
70*	400	52.0 ×		25		75		10,000	
135**	168		$\times 10^{-6}$		18		82		
	336		1.1×10^{-6}		12		88		

* PU (QUINN)
** PU (DEVELOPMENT ASSOCIATES Z-2591)

Table 35. Sol/Gel and Molecular Weight Data as a Function of Thermal Aging of Polyurethane at 30°C, 70°C and 135°C

T, °C	TIME OF AGING, h	CROSSLINKING DENSITY, MOL/cm^3		SOL, %		GEL, %		MOL WT (SOL)	
		SAMPLE 1	SAMPLE 2	1	2	1	2	1	2
30	0	166.0×10^{-6}	71.0×10^{-6}	4		96		5,000	
70*	400	105.0×10^{-6}						10,000	
135**♦	168		27.6×10^{-6}		8		92		
	336		4.4×10^{-6}		17		83		

* PU (QUINN)
** PU (DEVELOPMENT ASSOCIATES Z-2591)
♦ IN A COVERED (SANDWICH) CONFIGURATION

SECTION VIII

KORAD (XCEL CORP.)

Figure 84 offers data on transmittance spectra of Korad (Xcel Corp.).

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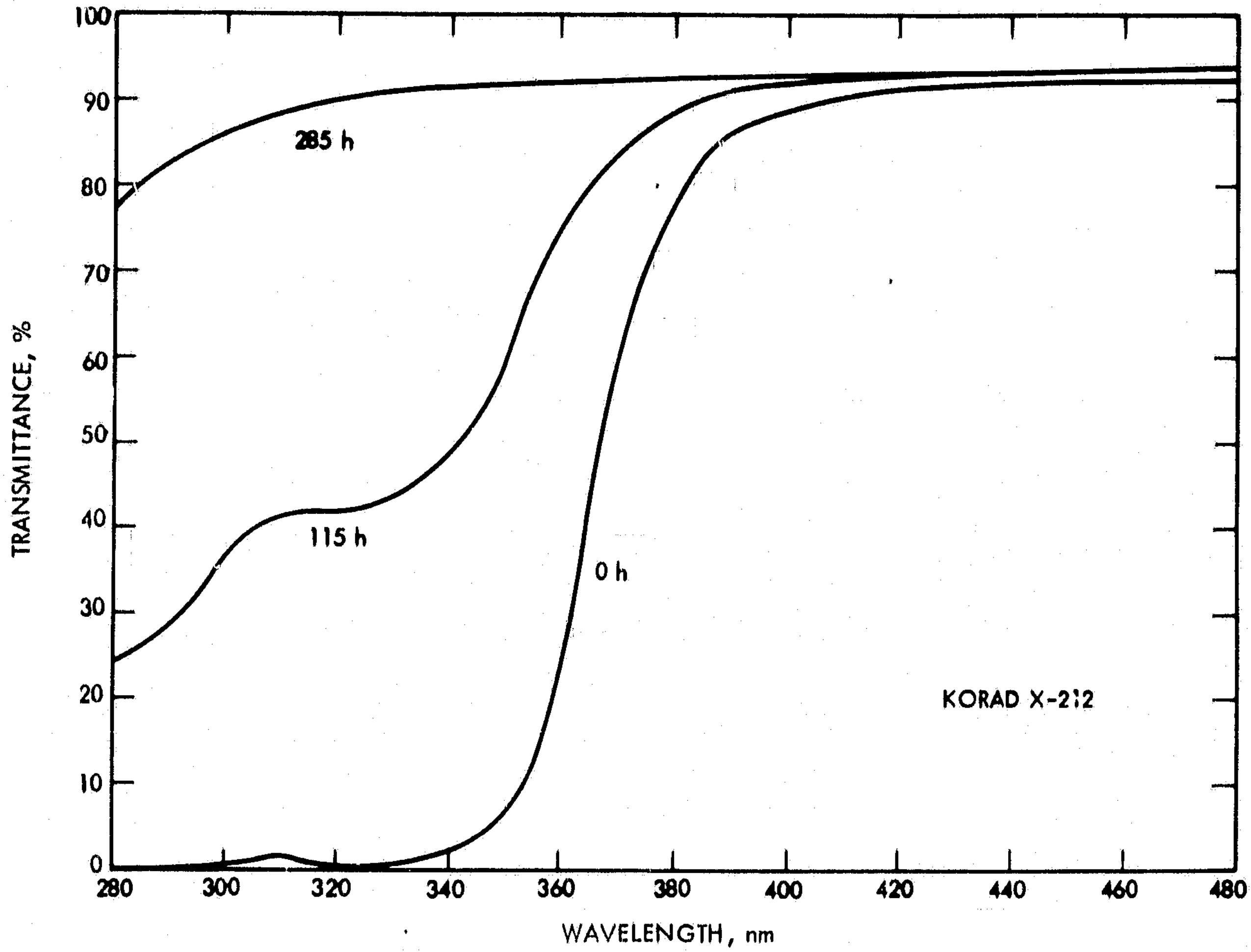

Figure 84. UV/VIS Transmittance Spectra as a Function of Open Photothermal Aging of Korad at 85°C

SECTION IX

TEDLAR (DU PONT UTB-100)

Figures 85 through 87 offer data on absorbance spectra of Tedlar (Du Pont UTB-100).

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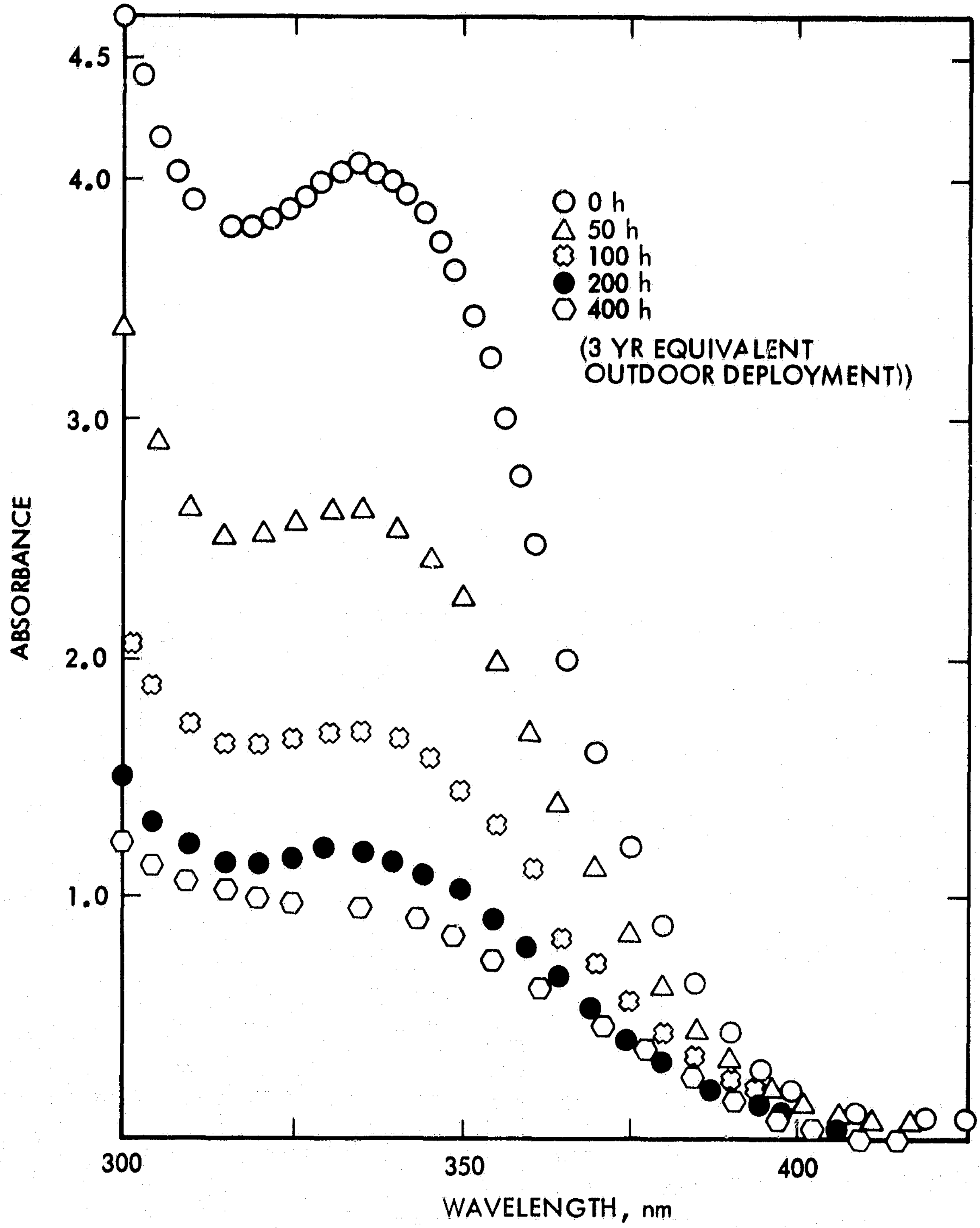

Figure 85. UV/VIS Absorbance Spectra as a Function of Open Photothermal Aging of Tedlar UTB-100 at 85°C

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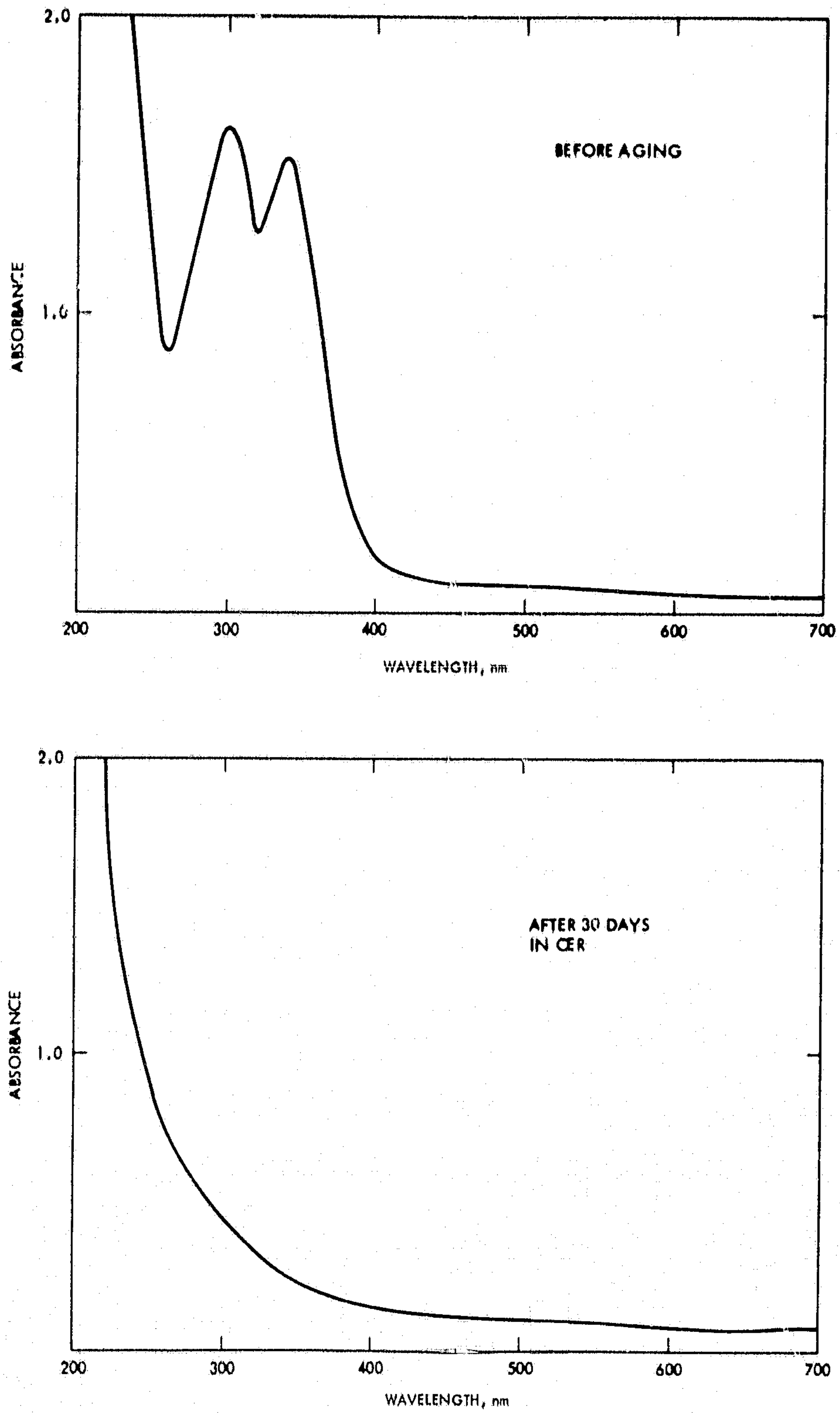

Figure 86. UV/VIS Absorbance Spectra Before and After 30 days of Aging of Tedlar UTB-100 in CER at 55°C

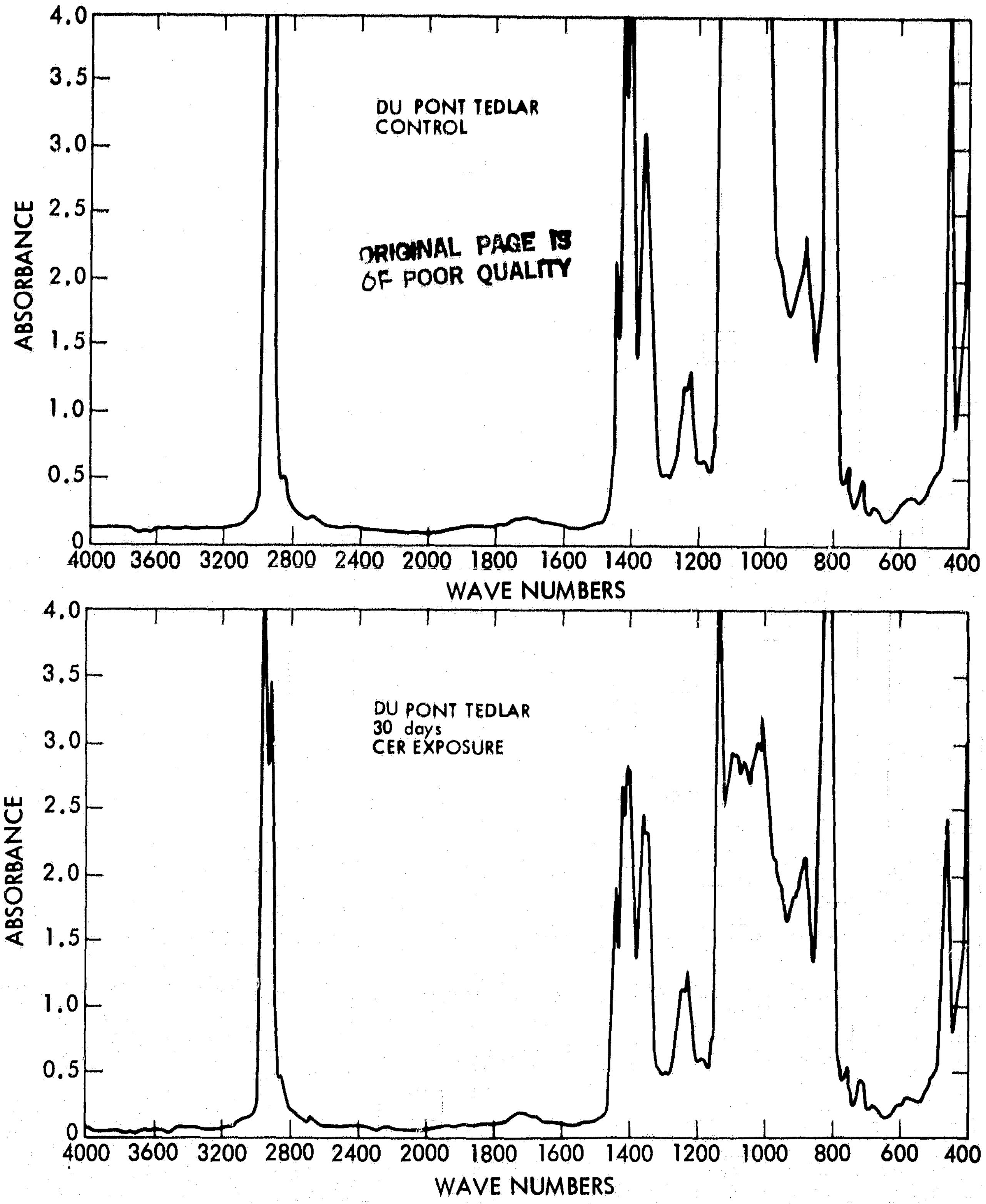

Figure 87. FT-IR Absorbance Spectra Before and After 30 days of Aging of Tedlar UTB-100 in CER at 55°C

SECTION X

ACRYLAR (3M CO. X-22416)

Figures 88 through 93 offer data on optical properties of Acrylar (3M Co. X-22416).

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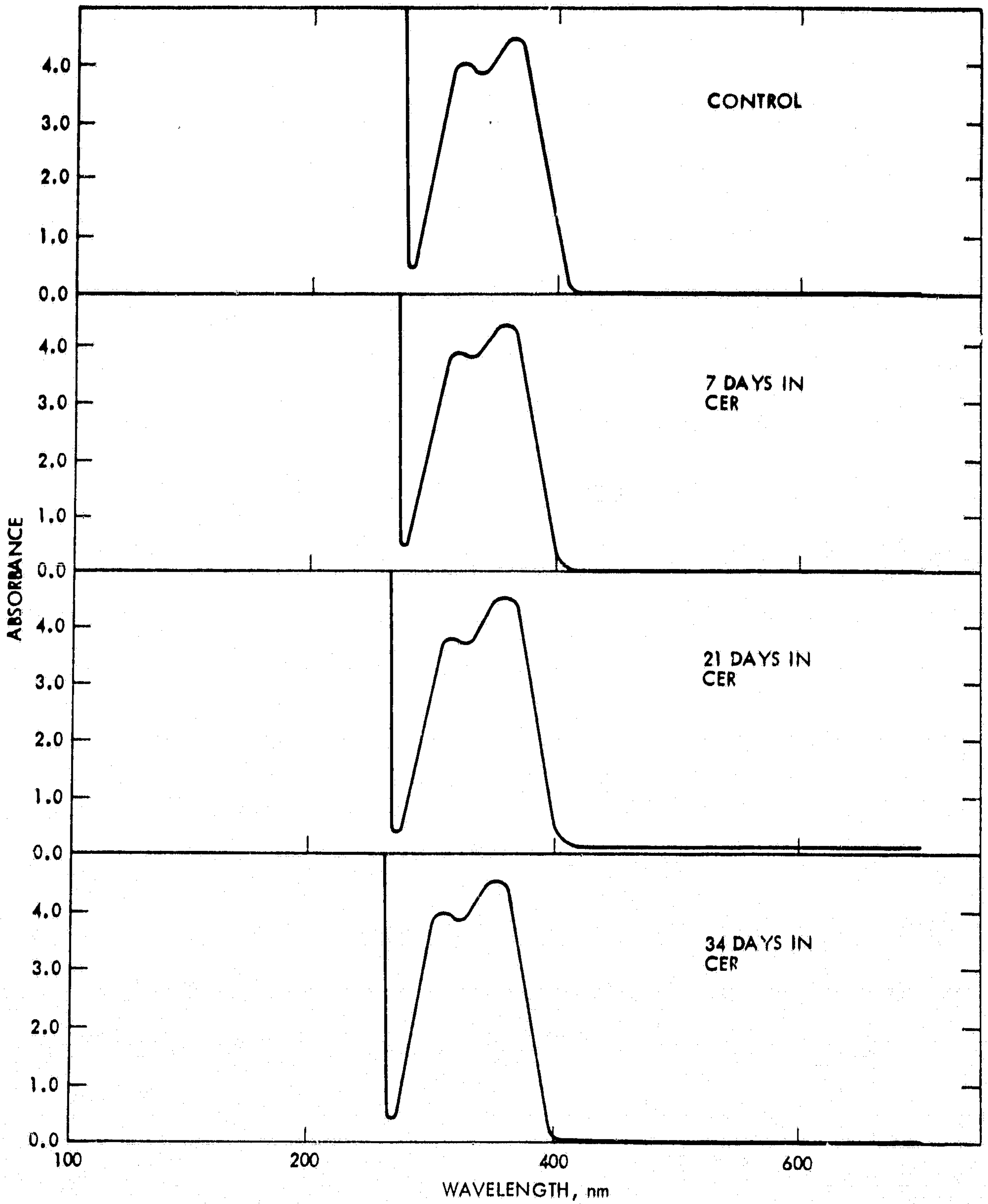

Figure 88. UV/VIS Absorbance Spectra Before and After 34 days of Aging of Acrylar Films (X-22416) in CER

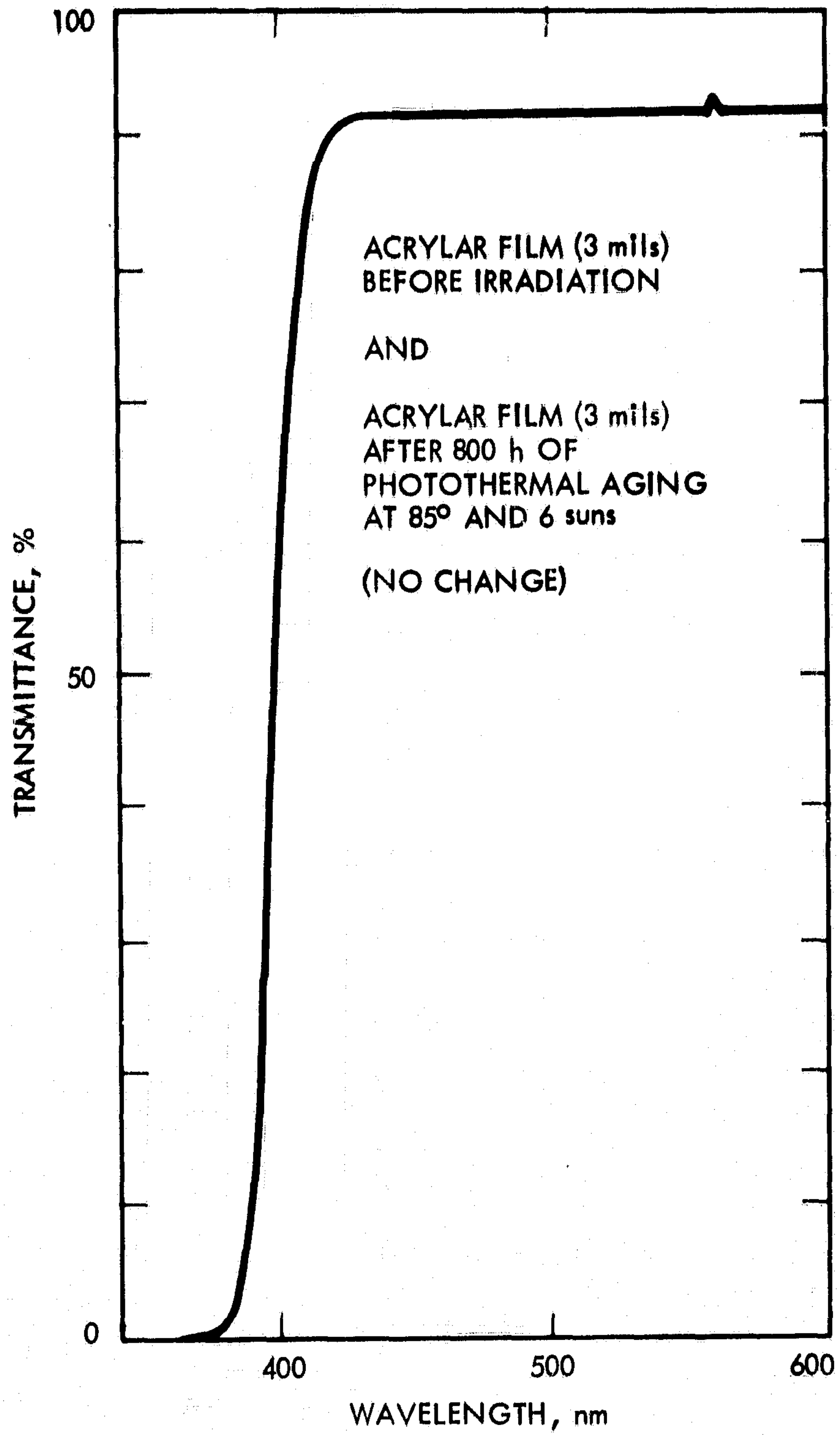

Figure 89. UV/VIS Transmittance Spectra Before and After 800 h of Open Photothermal Aging of Acrylar Film at 85°C

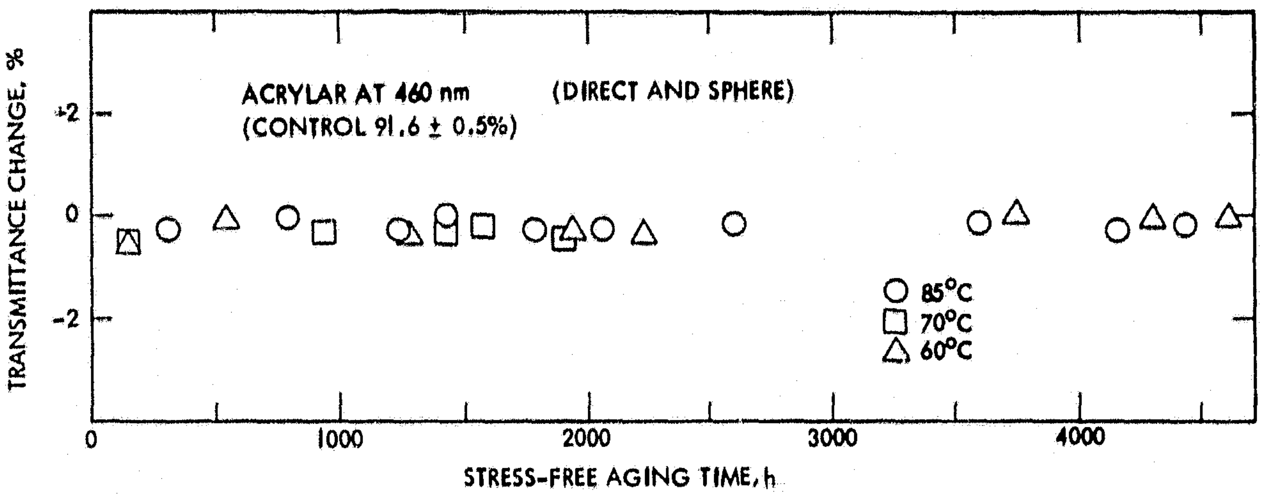

Figure 90. Change in Transmittance of Acrylar Films at 460 nm at 60°C, 70°C and 80°C

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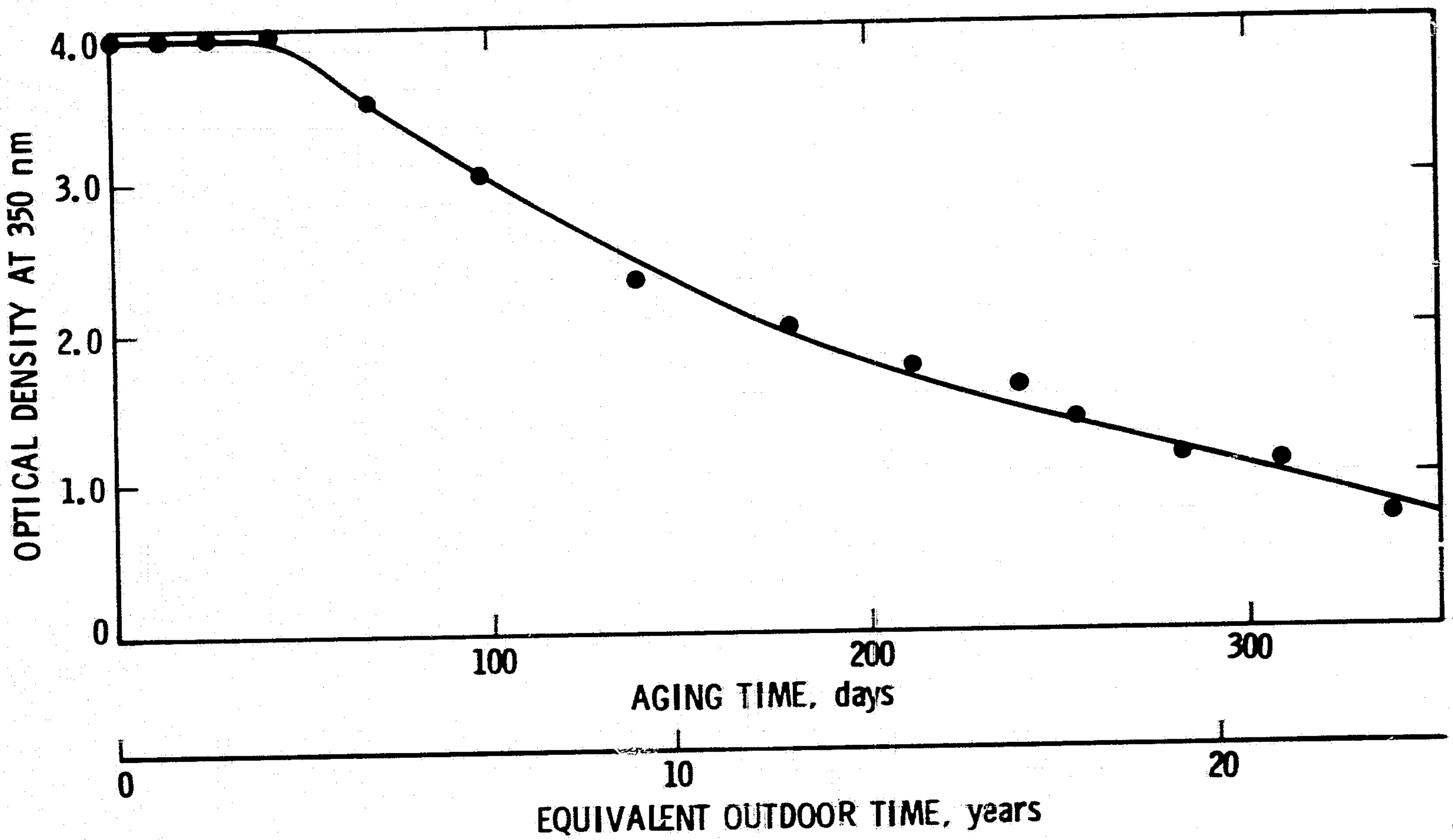

Figure 91. UV-Screening Capability of Acrylar as a Function of Accelerated Aging Inside the CER at 55°C

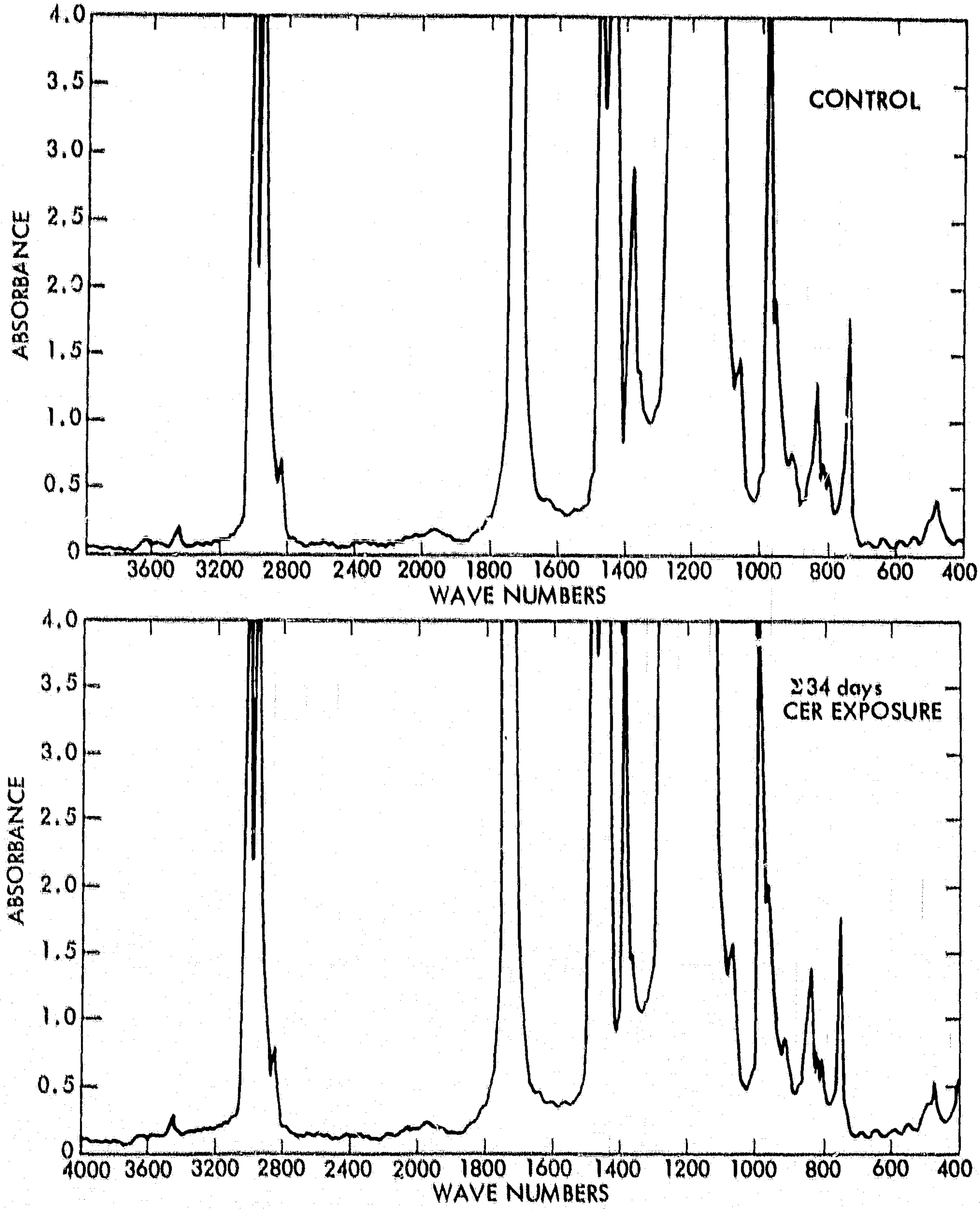

Figure 92. FT-IR Absorbance Spectra Before and After 34 days of Aging of Acrylar Films (X-22416) in CER at 55°C

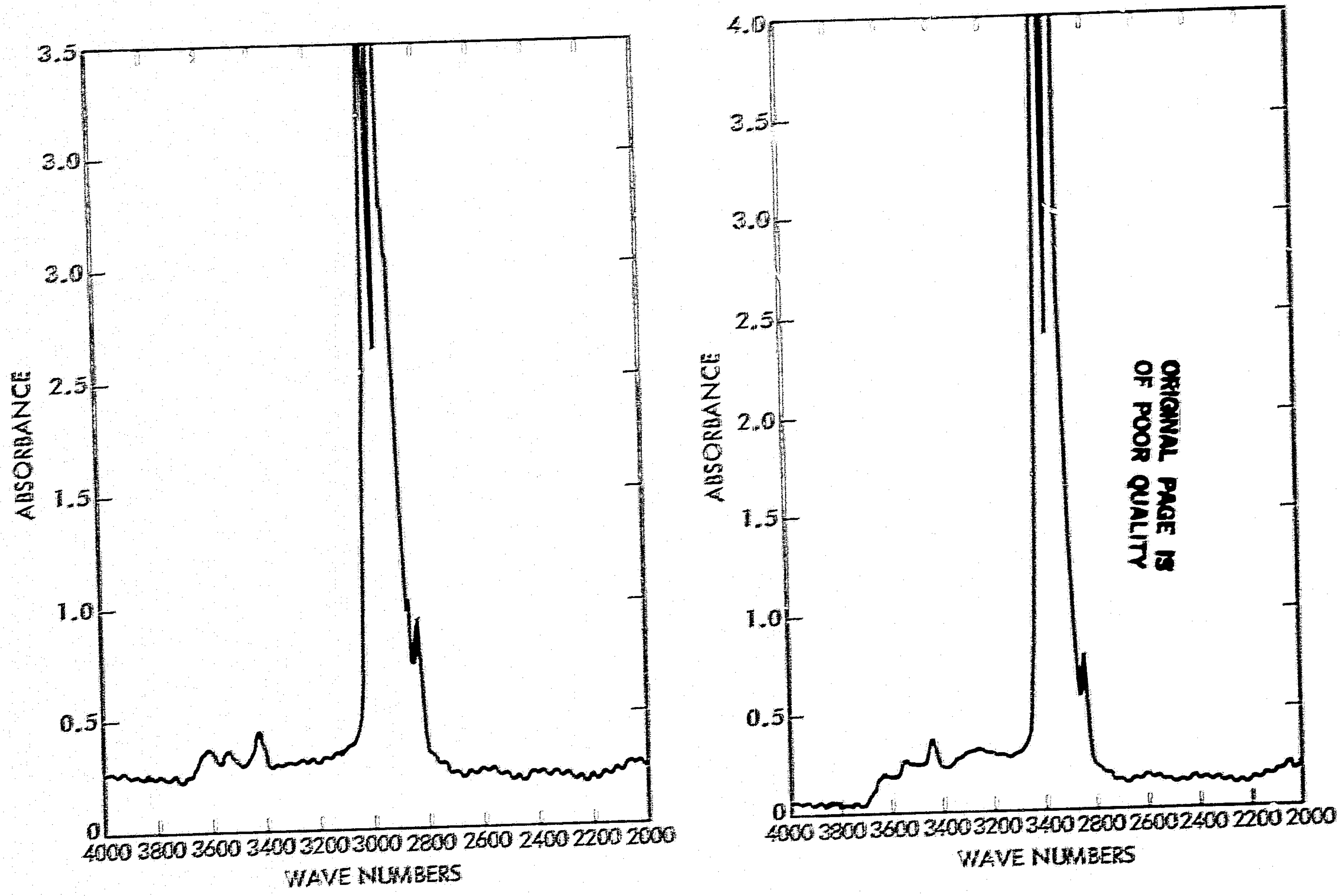

Figure 93. FT-IR Absorbance Spectra Before and After 282 days of Aging of Acrylar Films (X-22416) in CER at 55°C

SECTION XI

KYNAR (PENNWALT CORP.)

Figures 94 and 95 offer data on optical properties and Table 36 offers data on shrinkage of Kynar (Pennwalt Corp.)

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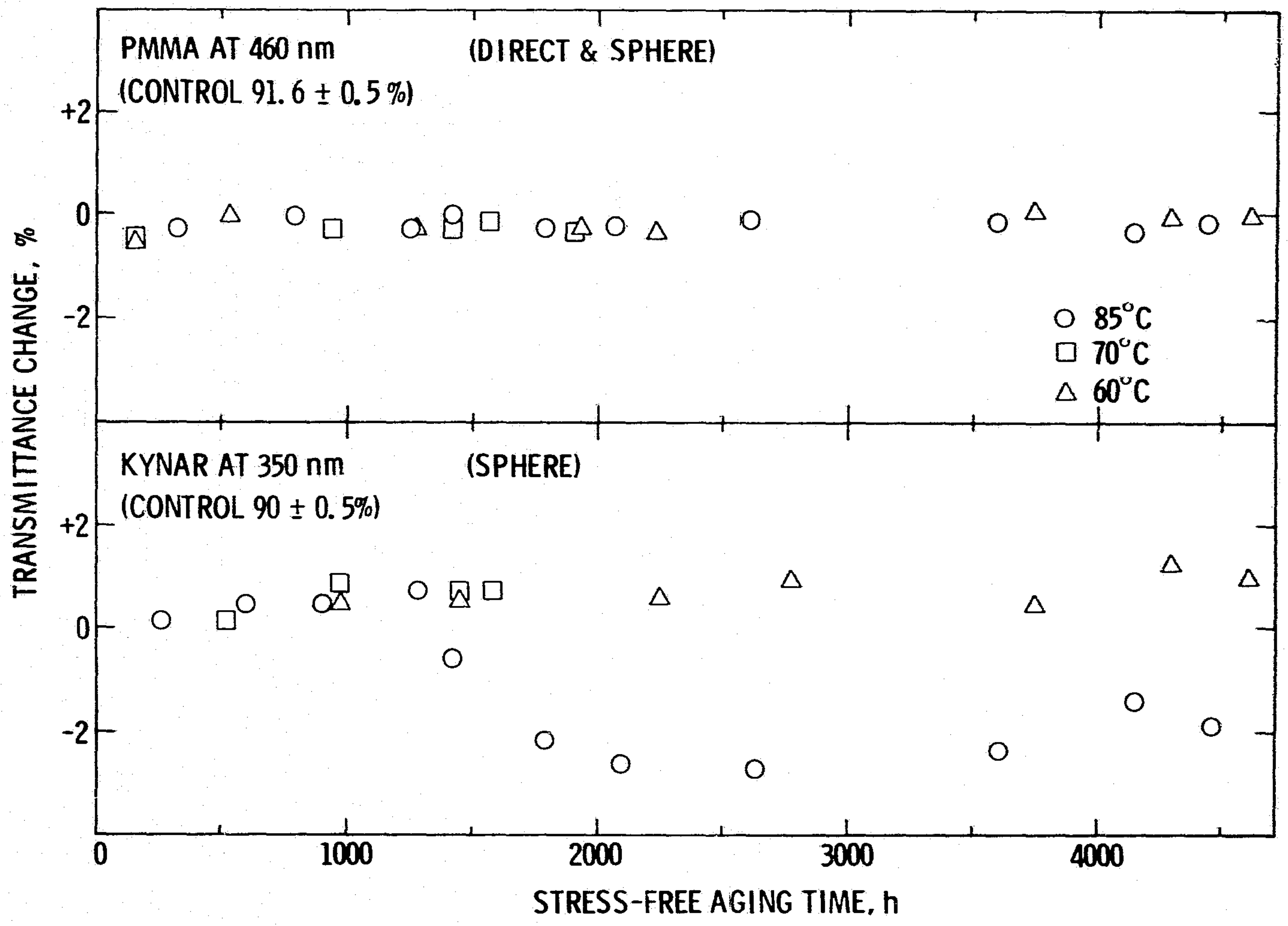

Figure 94. Change in Transmittance at 350 nm as a Function of Thermal Aging of Kynar in a Dark Oven at 60°C, 70°C. and 85°C

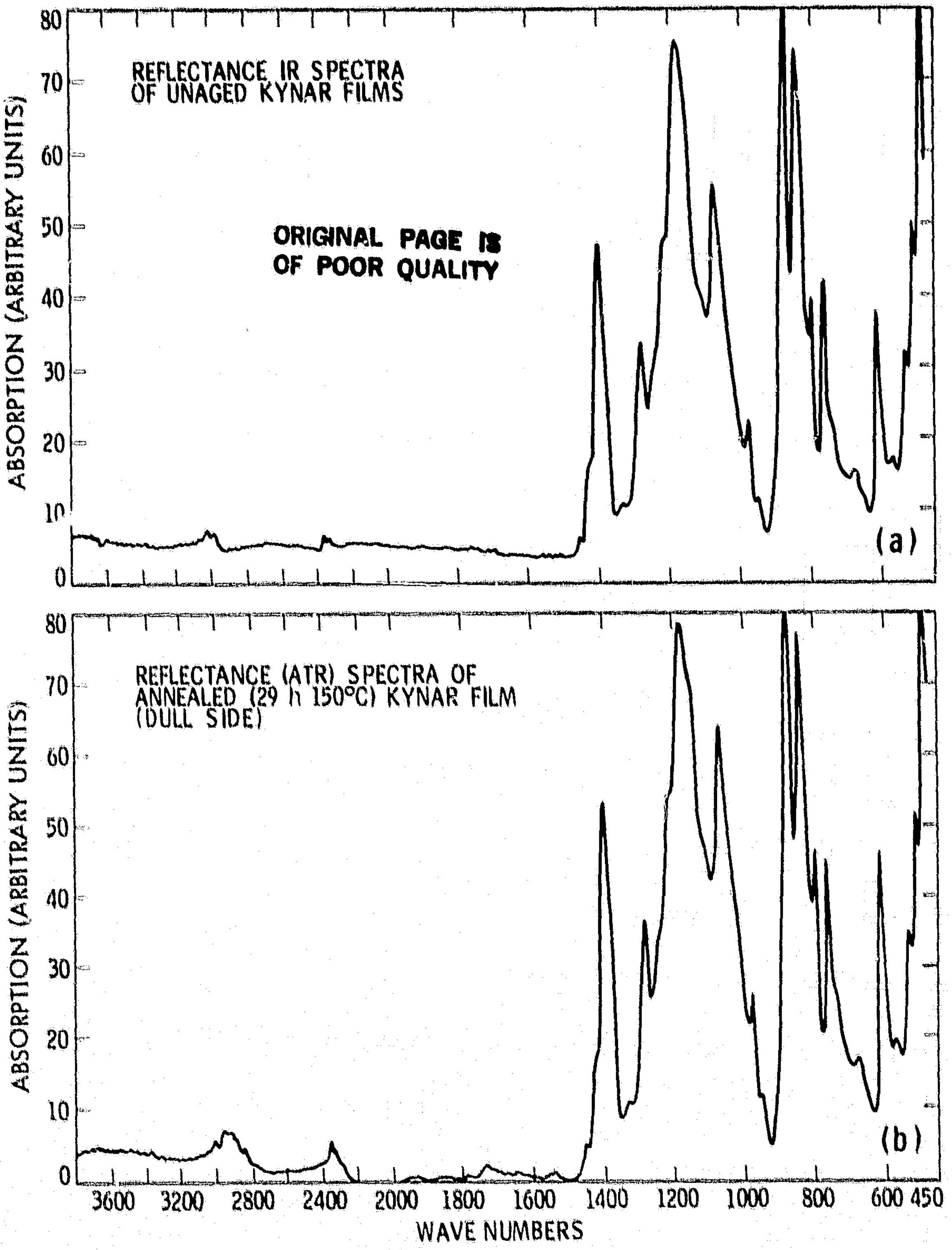

Figure 95. Reflectance IR Spectra Before and After 29 Hours of Thermal Aging of Kynar Film in a Dark Oven at 150°C

Table 36. Shrinkage as a Function of Thermal Aging of Kynar in Dark Oven at 150°C

TIME OF AGING, h	LINEAR SHRINKAGE, %
0.5	31
1.0	30
2.0	34
3.0	34
5.0	34
29.0	34

SECTION XII

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12. Liang, R., Coulter, D.R., and Gupta, A., "Novel Diagnostic Techniques for Early Detection of Photooxidation in Polymers," Polymer Preprints, Vol. 23, p. 215, 1982; Proceedings of the Symposium on Polymer Applications in Solar Energy, 183rd national meeting of American Chemical Society, Las Vegas. Nevada, March 1982.