Ind. Eng. Chem. Prod. Res. Dev. 1982, 21, 691–704

Evaluation of Elastomers for Use in Thermal Solar Collectors

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As part of a national program to develop sealant and gasketing materials for use in solar heating and cooling applications, work sponsored by DOE was begun at the Westinghouse Research Laboratories to identify improved materials through synthesis and/or reformulation of existing compounds. This paper will describe our evaluation of improved commercial materials covering six classes of polymers: silicones, fluoroelastomers, EPDM, acrylic, ethylene–acrylic, and chlorobutyl elastomers. Data will be presented on initial screening test results as well as on extended aging tests covering the following properties: tensile strength, tensile modulus, elongation, weight loss, compression set (−10 and 150 °C), and hardness. A total of 33 materials that cover the six polymer classes are being evaluated.

Introduction

As a result of a study performed at the National Bureau of Standards in 1977, a number of test methods and standards were developed for the evaluation and specification of rubber seals and gaskets used in solar energy systems (Stiehler et al., 1978). These standards were developed to ensure that the materials being used would perform adequately for extended periods of time in the hostile environment of solar thermal collectors. The maximum service temperature for flat plate solar collectors is estimated to be about 200 °C (Stiehler et al., 1978). The primary function of the rubber is to seal or weatherproof the joints between the components of the system. The types of seals include preformed gaskets and liquid sealants or caulks designated PS and SC, respectively. The key properties of concern for evaluation are tensile strength, elongation, tensile modulus, compression set (low and high temperature), hardness, and weight loss (Mendelsohn et al., 1980; Morris and Schubert, 1980).

In previous studies a survey was made to identify those materials currently available to meet the proposed specifications. Five classes of polymers were identified as possible candidates for use in solar collectors. They are fluoroelastomers, silicones, EPDM, acrylic and ethylene–acrylic materials. Selected materials in each of the above classes were evaluated under an earlier contract (Mendelsohn et al., 1980). Since that time new materials and improved formulations have been developed that could be used in solar collectors. This paper will describe our evaluation of these new materials in each of the five classes mentioned above. Data will be presented on compound formulations, curing conditions, screening tests, and extended aging tests. The approach taken to acquire materials and make formulation changes was to work closely with the manufacturer of each material to provide a continuity of information exchange regarding the performance of their materials under test.

Flat Plate Collectors. There are many designs for solar energy collectors. A few words about the flat plate collector would perhaps help the reader have a better understanding of the material problems involved. A flat plate collector transmits the sun's energy to a heat transfer medium which circulates to heat a variety of structures. The plate is contained in an insulated metal housing, usually aluminum to minimize weight, which is faced with an insulating glass cover. The absorber plate can be metal or plastic and is usually coated black for maximum radiation absorption. The heat transfer medium can be a silicone fluid, water, water–glycol mixtures, or air.

Table I. Screening Tests for Class PS Materials[a]

property	suggested requirements	method
ultimate elongation, % min	100–350[d]	D412
compression set, % max		
after 70 h at 150 °C	30	D395[b]
after 166 h at −10 °C	60	D1229[c]
resistance to heating, 166 at 150 °C		
hardness change, max	10	Shore A
ultimate elongation change, % max	30	D412
tensile strength change, % max	20	D412
volatiles lost, % max	1	

[a] As suggested in NBSIR 77-1437. [b] Method B. [c] Measured 10 s after release of pressure. [d] Depending on the design of the solar collector.

Table II. Screening Tests for Class SC Materials[a]

property	suggested requirements	method
ultimate elongation, % min	100–200	D412
resistance to heating, 166 h at 125 °C		D865
hardness change, max	10	C661
ultimate elongation change, % max	30	D412
tensile strength change, % max	20	D412
volatiles lost, % max	1	

[a] As suggested in NBSIR 77-1437.

The primary purpose of the collector is to convert as much radiation as possible into heat and as a result the unit can become very hot. Under stagnant conditions, when the heat transfer medium is not circulating because there is no demand, the temperature can exceed 235 °C, and at night the temperature can drop substantially as a result of black body radiation. Thus a daily temperature differential of up to 260 °C is not uncommon during the winter in some climates.

Much swifter temperature cycling can also occur. For example, on a cold winter day, a cloud passing between the sun and the collector may cause a temperature change of as much as 40 °C within a few minutes.

The differential expansion and contraction of the materials of construction caused by these extreme temperature changes create a sealing problem, and flat plate col-

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Table III. Solar Collector Materials

code	polymer class	material grade	supplier
PS-1	fluoroelastomer	Fluorel 2179	3M Co.
PS-2	fluoroelastomer	Viton AHV	Du Pont Co.
PS-3	EPDM	Epsyn 4506	Copolymer Co.
PS-4	EPDM	Royalene 580HT	Uniroyal Co.
PS-5	EPDM	Vistalon 404	Exxon Co.
PS-6	EPDM	Nordel 1070	Du Pont Co.
PS-7	EPDM	Epcar 545	B.F. Goodrich Co.
PS-8	EPDM	Epcar 585	B.F. Goodrich Co.
PS-9	silicone	Silastic 747U	Dow Corning Co.
PS-10	silicone	Silastic 745U	Dow Corning Co.
PS-11	silicone	Tufel 845	General Electric Co.
PS-12	silicone	SE-7603U	General Electric Co.
PS-13	silicone	SE-3715U	General Electric Co.
PS-14A	silicone	SWS-7162 Nat.	SWS Co.
PS-14B	silicone	SWS-7162 Red	SWS Co.
PS-15	acrylic	Cyanacryl R	American Cyanamid Co.
PS-16	acrylic	Hycar 4054	B.F. Goodrich Co.
PS-17	ethylene-acrylic	Vamac B-124	Du Pont Co.
PS-18	chlorobutyl	1066	Exxon Co.
PS-19	silicone	6002 Red	Groendyk Co.
PS-20	fluoroelastomer	Viton AHV Modified	Du Pont Co.
PS-21	fluoroelastomer	Viton B-70	Du Pont Co.
PS-1A	fluorosilicone	Fluorel 2460	3M Co.
SC-1	silicone RTV	1576LV Red	General Electric Co.
SC-2	silicone RTV	160-3-381 Black	General Electric Co.
SC-3	silicone RTV	1573 Black	General Electric Co.
SC-4	silicone RTV	3145	Dow Corning Co.
SC-5	silicone RTV	3140	Dow Corning Co.
SC-6	silicone RTV	795 Black	Dow Corning Co.
SC-7	silicone RTV	738	Dow Corning Co.
SC-8	silicone RTV	951	SWS Co.
SC-9	silicone RTV	934	SWS Co.
SC-10	silicone RTV	106 Red	General Electric Co.
PS-22	acrylic	Cyanacryl L	American Cyanamid Co.
PS-23	acrylic	Cyanacryl L	American Cyanamid Co.

lectors must be tightly sealed to avoid heat loss. Any condensation of moisture or condensation of volatile components of the sealant on the underside of the glass cover will reduce the transmittance of solar light and reduce the efficiency of the unit. Also, to be economical, solar collectors should operate trouble- and maintenance-free for tens of years. Moisture entering the unit can cause corrosion and damage to the insulation. The sealant must also remain flexible at subzero temperatures and not soften or degrade at the extremely high temperatures occasionally experienced by the collector. It must remain flexible despite exposure to ultraviolet radiation and ozone, the effects of which are magnified by the high service temperatures. And, of course, to seal effectively, the sealant must not absorb moisture after curing or give off any volatile components under any of these conditions. One design of a solar collector is shown in Figure 1.

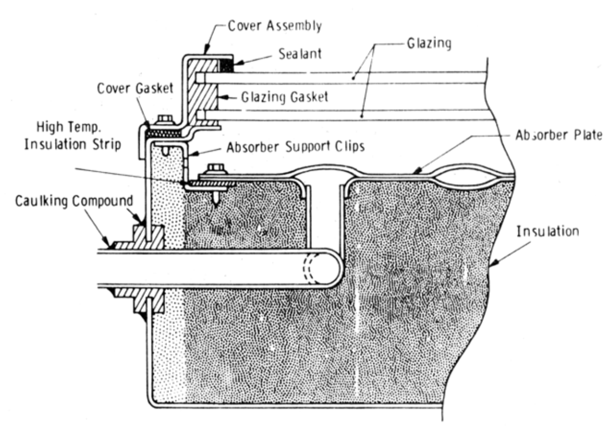

Figure 1. Assembly of a typical solar collector.

Experimental Section

Material Section. Each of the major manufacturers of the six classes of polymers was contacted and asked to supply their best formulation that would meet the specifications shown in Tables I and II. The type, grade, and supplier of these materials are listed in Table III.

Compounding and Molding. Materials coded PS-1, 3, 4, 15, 19, and 1A were compounded and cured by the manufacturer; all the rest were compounded at the Westinghouse R&D Laboratories using a conventional two-roll rubber mill. The formulations are shown in Table IV. The compounded stock was compression molded into $6 \times 6 \times 0.090$ in. test slabs in a preheated four-cavity mold. The cure condition for each compound was established using the Monsanto oscillating disk rheometer Model 100. Information on the rheograph properties and cure conditions for each compound is presented in Table V.

The SC materials were squeezed from their cartridges into an open face aluminum mold whose dimensions are $5.5 \times 1.125 \times 0.090$ in., and the material was spread with a razor blade to give a smooth surface. A Tedlar release sheet was used on one side of the mold. All SC materials were cured at room temperature and 50% relative humidity for a minimum of 14 days prior to testing. The type of cure system for each sealant is given in Table VI.

Testing. All PS and SC materials were evaluated as per the screening tests listed in Tables I and II according to ASTM procedures. Tensile modulus at 100 and 200% was also measured as per ASTM D1415. Extended aging tests were performed on the more promising materials in forced air circulating ovens at temperatures from 125 to 225 °C. Data from these aging studies will be used to construct Arrhenius curves to estimate the material's service life.

Table IV. Elastomer Formulations (PS Materials)

	pbw
PS-1	
Fluorel 2179	100
MgO	3
$Ca(OH)_2$	6
medium thermal black	10
Austin Black	10
PS-1A	
Fluorel 2460	80
GE FSE 2080	20
Mapico 297	2
Aerosil R-972	20
Carb-O-Sil HS-5	6.5
$Ca(OH)_2$	3
Luperco 101XL	1.3
TAIC	1.1
PS-2	
Viton AHV	100
MT908 Thermax black	12.5
Austin Black 325	12.5
Maglite D	3
$Ca(OH)_2$	6
VPA no. 1	1.5
curative no. 20	1.3
curative no. 30	2.8
PS-3	
Epxyn 4506	100
N-762 black	60
Ricon 154	15
Agerite MA	1
methyl nicalate	1
DiCup 40C	4
PS-3A	
Epsyn 4506	50
Epsyn 40A	50
N-762 black	60
Ricon 150	15
Agerite MA	1
methyl nicalate	1
DiCup 40C	4

	pbw
PS-4	
Royalene 580HT	100
zinc oxide	20
N-650 black	55
Sunpar 2280	27
Nanguard 495	3
zinc stearate	0.5
Dri-Mix Tac 75	1.3
DiCup 40KE	13
dibenzo-*p*-quinone dioxime	1
PS-5	
Vistalon 404	100
Agerite resin D	1.5
N-787 SRF-HM	30
N-330 HAF	30
zinc oxide	3
MgO	3
Sartomer 350	2
DiCup	7
Petrolatum SR-172	5
PS-6	
Nordel 1070	100
zinc oxide	5
Nanguard 495	2
N-550 FEF black	60
DuCup 40C	8
HVA-2	2
PS-7	
Epcar 545	100
N-550 FEF black	40
Sunpar 2280	5
zinc oxide	5
Agerite resin D	1
DiCup 40C	7
PS-8	
Epcar 585	100
N-550 FEF black	40
Sunpar 2280	5
zinc oxide	5
Agerite resin D	1
DiCup 40C	7

	pbw
PS-9	
Silastic 747U	100
Varox	0.43
PS-10	
Silastic 745U	100
Varox	0.53
PS-11	
Tufel SE-845	99
CA-2	1
PS-12	
SE-7603U	100
Varox	0.8
PS-13	
SE-3715	100
Varox	1
PS-14A	
SWS-7162U	100
Varox	0.8
PS-14B	
SWS-7162U	100
Varox	0.8
CM-100	2
PS-15	
Cyanacryl R	100
Agerite white	2
N-550 FEF black	60
stearic acid	1.5
Curative C-50	7
spider sulfur	0.25
PS-16 and 16A	
Hycar 4054	100
Acrawax C	2
TE-80	2
Phil. black N-550	60
Witco sodium stearate	4
poly. disp. T(KD)D-75	2
PS-17	
Vamac B-124	124
Armeen 18D	0.5
Vanfre UN	2
ISAF-N-220 black	25
Paraplex G-25	5
MDA	1.25
DOTG	4

	pbw
PS-18	
Chlorobutyl 1066	100
HAF-HS347 black	30
FEF N-550 black	30
petrolatum	10
Sunpar 2280	5
MgO	0.3
zinc oxide	5
TMTDS	1
MBTS	2
PS-20	
Viton AHV	93.35
MT(N-908) Thermax black	10
Austin black 325	10
Maglite D	3
$Ca(OH)_2$	6
VPA no. 1	1
curative no. 20	1.65
curative no. 30	4
PS-21	
Viton B-70	93.8
MT(N-908) Thermax black	10
Austin black 325	10
Maglite D	3
$Ca(OH)_2$	6
VPA no. 1	1
curative no. 20	2.2
curative no. 30	4
PS-22	
Cyanacryl L	100
N-774 (SRF-HM)	50
spider sulfur	0.3
TP-759	5.0
stearic acid	2.0
Curatine C-50	7.0
PS-23	
Cyanacryl L	100
N-774 (SRF-HM)	42
N-326 (HAF-LS)	13
spider sulfur	0.3
TP-759	2.0
stearic acid	2.0
NPS red oil soap	3.5

Table V. Cure Data on Commercial PS Elastomers

code	rheometer readings at cure temp: torque, in.-lb min[a]	torque, in.-lb max[b]	T_2, min[c]	cure conditions: time, min	cure conditions: temp, °C	post cure: time, h	post cure: temp, °C
PS-1	--	--	--	10	177	20	254
PS-2	28	114	3	17	168	24	171
PS-3	13.3	115	1.7	30	160	1	160
PS-4	--	--	--	30	166	0.5	151
PS-5	14	44	1.7	32	160	12	66
PS-6	31	119	1.1	32	160	--	--
PS-7	9	109	1.0	16	177	--	--
PS-8	9.5	134	1.2	18	177	--	--
PS-9	8.5	84.5	1.1	10	171	--	--
PS-10	3	56	1.5	10	171	--	--
PS-11	4	39	1.5	22	154	4	204
PS-12	5	38	1.5	10	177	4	249
PS-13	7.5	96	1.5	18	160	4	204
PS-14A	6	63	1.6	15	171	--	--
PS-14B	6	62	1.6	15	171	--	--
PS-15	10	86	1.2	15	166	4	177
PS-16	6	20	6.4	7	170	8	175
PS-17	2	56	3.6	42	177	4	176
PS-18	9	30	3.4	24	160	--	--
PS-19	--	--	--	--	--	--	--
PS-20	12.5	62	3.6	14	169	24	171
PS-21	4.5	81	2.3	8	169	24	171
PS-1A	--	--	--	--	--	--	--
PS-3A	--	--	--	30	160	1	160
PS-16A	4	16	7.8	8	170	16	175
PS-22	--	55.8	2.5	15	166	4	176
PS-23	--	43	4.9	20	166	4	176

[a] A measure of the stiffness of the unvulcanized compound. [b] A measure of the stiffness (shear modulus) of the cured compound. [c] Time to incipient cure; a measure of processing safety.

Table VI. Identification of SC Materials

SC-1:	a red RTV silicone with an octanoic acid cure
SC-2:	a black RTV silicone with an acetic acid cure
SC-3:	a black RTV silicone with an octanoic acid cure
SC-4:	a clear RTV silicone with an alcohol cure
SC-5:	a hazy RTV silicone with an alcohol cure
SC-6:	a black RTV silicone with an acetic acid cure
SC-7:	a white RTV silicone with an alcohol cure
SC-8:	a translucent RTV silicone with an acetic acid cure
SC-9:	a white RTV silicone with an amine cure

Results and Discussion

Material Selection. Although the material list in Table III is quite large and contains many types of materials within a given polymer class, they do represent the manufacturers' recommendation on their best candidates for the initial screening tests. Because of variations in the base polymer and in compound formulations, it was imperative to test all possible candidates in order to choose the most promising materials for further evaluation. The screening test results and suggestions for improvements in compound formulations were passed on to the manufacturers for their review. Only a few compounds were suggested for reformulation. They were Viton AHV, Epsyn 4506, Cyanacryl R, and Fluorel 2179. All the other formulations were considered the best available at the time to meet the property requirements for solar collectors outlined in Tables I and II, and no recommendations were made by the manufacturer for reformulation.

Compounding and Curing. All materials were compounded on a conventional two-roll rubber mill. Every effort was made to ensure thorough mixing of the ingredients while minimizing mixing time to prevent temperature buildup and shear degradation of the rubber stock. Stock temperatures were kept below 45 °C. Each time a compound was prepared the cure condition of that particular batch was determined in order to account for variations in compound processing and to ensure optimum cure. Table V presents the cure information. No difficulties were encountered in mixing any of the compounds on the mill.

Screening Tests on PS Materials. The results of the screening tests on all PS materials are summarized in Table VII.

Compression Set. This property gave the most distinguishable results among the six classes of polymers. Ten of the materials gave low-temperature compression set values higher than the maximum allowable limit of 60. These materials in order of decreasing compression set are PS-2, PS-15 > PS-1A > PS-18 > PS-1 > PS-5 > PS-3A > PS-21 > PS-3 > PS-17, and they represent the failure of at least one material from each of the six polymer classes evaluated. On the other hand, six of the materials failed the high-temperature compression set test (maximum allowable limit of 30). Ranked in order of decreasing compression set, they are PS-18 > PS-16A > PS-1A > PS-16 > PS-17 > PS-5. Of the 25 compounds tested, 16 failed the initial compression set screening test. The fact that not all of the compounds failed suggests that indeed there are formulations within each polymer class that can be made with improved compression set values. Let us rank the remaining materials in the order of the best compression set values. At the low-temperature end we have PS-10 > PS-11 > PS-14 > PS-16 > PS-14A,B > PS-12 > PS-19 > PS-8 > PS-7 > PS-4 > PS-6 > PS-20 > PS-22 > PS-16A > PS-23. At the high-temperature end of the scale they are ranked as follows: PS-10 > PS-1 > PS-9, PS-13 > PS-14A > PS-7, PS-8, PS-11 > PS-6, PS-14B > PS-2, PS-20 > PS-21, PS-12 > PS-3A > PS-3, PS-15 > PS-4 > PS-23 > PS-22. The silicone elastomers exhibit the best overall compression set values at both low

Table VII. Status of Materials in the Solar Program. Results of Screening Tests[a]

code	polymer class	material grade	supplier	compression set, %: high temp[b]	compression set, %: low temp[c]	elongation, %: I	elongation, %: F	elongation, %: % chg[d]	tensile strength, psi: I	tensile strength, psi: F	tensile strength, psi: % chg	tensile modulus, psi: I	tensile modulus, psi: F	tensile modulus, psi: % chg	wt loss[e]: normal cure	wt loss[e]: post-cure	hardness, Shore A: I	hardness, Shore A: F	hardness, Shore A: % chg[f]
PS-1	fluoro	Fluorel 2179	3M Co.	7	73	157	161	+3	1604	1635	+2	1002	1089	+6	0		79	79	0
PS-2	fluoro	Viton AHV	Du Pont Co.	17	84	268	257	−4	1423	1588	+12	723	839	+16			76	78	+2
PS-3	EPDM	Epsyn 4506	Copolymer Co.	25	66	217	178	−18	2253	2100	−7	669	866	+29	0.9		74	77	+3
PS-4	EPDM	Royalene 580HT	Uniroyal	26	38	350	317	−9	1630	1767	+8	411	542	+32	1.2	0.9	65	66	+1
PS-5	EPDM	Vistalon 404	Exxon	29	72	870	448	>−7	1597	1564	−2	212	256	+21	0.6		65	68	+3
PS-6	EPDM	Nordel 1070	Du Pont	15	43	202	222	+10	1463	1952	+33	433	508	+17	2.2	0.6	72	74	+2
PS-7	EPDM	Epcar 545	Goodrich	14	30	290	272	−6	2010	2208	+10	365	498	+36	1.4	0	68	69	+1
PS-8	EPDM	Epcar 585	Goodrich	14	28	247	203	−18	2287	2348	+3	476	599	+26	1.4	0	69	71	+2
PS-9	silicone	Silastic 747U	Dow Corning	13	14	167	141	−16	1067	1107	+4	720	804	+12	1.0	0.45	73	76	+3
PS-10	silicone	Silastic 745U	Dow Corning	4	9	250	225	−10	781	828	+6	273	304	+11	1.5	0.75	59	57	−2
PS-11	silicone	Tufel 845	G.E.	14	12	450	417	−7	915	991	+8	212	216	+2	0.3		56	54	−2
PS-12	silicone	SE-7603U	G.E.	18	21	475	475	0	917	1028	+12	206	324	+57	0.1		64	63	−1
PS-13	silicone	SE-3715U	G.E.	13	16	129	122	−5	1132	1127	0	394	931	+4	0.2		79	79	0
PS-14A	silicone	SWS-7162 Nat.	SWS Co.	15	20	302	329	+9	953	1066	+12	330	363	+10	1.7	0.54	63	67	+4
PS-14B	silicone	SWS-7162 Red	SWS Co.	10	20	337	311	−8	1050	1049	0	329	378	+15	1.7		68	72	+4
PS-15	acrylic	Cyanacryl R	Amer. Cyan.	25	84	157	127	−20	1770	1668	−6	1070	1189	+11	0.4		78	79	+1
PS-16	acrylic	Hycar 4054	Goodrich	40	53										1.3		68	72	+4
PS-17	ethylene–acrylic	Vamac B-124	Du Pont	38	65	390	305	−22	2305	2323	+1	458	641	+39	1.8		74	71	−3
PS-18	chlorobutyl	1066	Exxon	88	75										1.5		64	71	+7
PS-19	silicone	6002 Red	Groendyk	28	24	770	783	+2	1000	1076	+8	107	97	−9	1.1		46	49	+3
PS-20	fluoro	Viton AHV + cure conc. increase	Du Pont	17	48	215	200	−7	1337	1445	+8	713	734	+6	0.2		76	76	0
PS-21	fluoro	Viton B-70	Du Pont	18	67	218	182	−13	1248	1076	−14	662	739	+12	0.2		74	75	+1
PS-1A	fluorosilicone	Fluorel 2460	3M Co.	44	80	370	320	−14	1984	1939	−2	596	676	+13					
PS-3A	EPDM	4416-30		19	68	292	205	−30	2274	1741	−23	416	552	+33					
PS-16A	acrylic	PS-16 with more cure		51	53	174	158	−9	928	1110	+20	407	619	+52	1.2		73	71	−2
PS-22	acrylic	Cyanacryl L	Amer. Cyan.	29	49											1.2	64	65	+1
PS-23	acrylic	Cyanacryl L	Amer. Cyan.	25	76											1.1	66	68	+2

[a] See Table IX for aging conditions. [b] 70 h, 150 °C; maximum acceptable = 30%. [c] 166 h, −10 °C; maximum acceptable = 60%. [d] Maximum acceptable = 30%. [e] Maximum acceptable = 1%. [f] Maximum acceptable = 10.

Table VIII. Screening Test Results for SC Materials[a]

code	polymer class	material grade	supplier	elongation, %			tensile strength, psi			tensile modulus, psi			wt loss, %[d]		hardness, Shore A		
				I	F	% chg[b]	I	F	% chg[c]	I	F	% chg	normal cure	post cure[e]	I	F	chg[f]
SC-1	silicone	1576LV Red	G.E.	130	140	+8	353	444	+25	296	339	+14	1.7	1.6	61	63	+2
SC-2	silicone	160-3-381 blk.	G.E.	241	259	+7	318	404	+27	150	169	+13	0.9	0.8	48	48	0
SC-3	silicone	1573 blk.	G.E.	134	140	+4	295	334	+13	255	289	+13	1.7	1.4	61	63	+2
SC-4	silicone	3145	Dow Corning	527	500	−5	652	558	+14	144	135	−6	1.3	1.1	49	49	0
SC-5	silicone	3140	Dow Corning	262	266	+1	258	267	+3	100	98	−2	0.9	0.7	45	42	−3
SC-6	silicone	795 blk.	Dow Corning	376	337	−10	118	110	−7	70	65	−7	0.8	0.7	38	33	−5
SC-7	silicone	738	Dow Corning	423	420	−1	255	209	−18	65	59	−9	5.1	3.4	39	40	+1
SC-8	silicone	951	SWS Corp.	276	282	+2	528	549	+4	171	161	−6	0.9	0.7	50	49	−1
SC-9[g]	silicone	934	SWS Corp.	98	108	+10	478	495		<100	460		0.4		64	63	−1

[a] Aged for 166 h at 125 °C. [b] Maximum acceptable = 30%. [c] Maximum acceptable = 20%. [d] Maximum acceptable = 1%. [e] 8 h, 150 °C. [f] Maximum acceptable = 10. [g] Aged for 166 h at 150 °C.

and high temperature. The EPDM materials are ranked next followed by the fluoroelastomers and the acrylics. The best silicones are PS-10 and 11, the best EPDM are PS-7 and 8, the best fluoroelastomer is PS-20, and the best acrylic is PS-22. The chlorobutyl material performed very poorly and was eliminated from further testing. A couple of the compounds were reformulated based on manufacturers' recommendations. For example, in PS-20 the concentration of curatives no. 20 and 30 was increased and the compression set value at low temperature improved considerably (84 decreased to 48). Viton B-70 was recommended as an alternative to Viton AHV for improved low-temperature compression set. Some improvement was obtained (84 decreased to 67). Compare PS-2 with PS-21. The addition of a silicon into the fluoroelastomer did not improve the low-temperature compression set (compare PS-1 and PS-1A). Reformulaton of PS-3, and EPDM elastomer, did not improve its compression set (compare PS-3 with PS-3A). Recommendations by the manufacturer to increase the post cure of PS-16 did not improve the compression set values (see PS-16A). However, when the acrylic elastomer Cyanacryl R was replaced with Cyanacryl L, the low-temperature compression set improved from a value of 40 (PS-16) to 25 and 29 (PS-22 and 23).

Tensile Properties. These properties include tensile strength, modulus, and elongation. Although changes occurred in these properties, they were all within the acceptable limit and all 27 materials passed the initial screening test with respect to these properties.

With the exception of PS-1, PS-6, PS-14A, and PS-19, all the other materials exhibited a decrease in elongation after the screening test. In general the order of increasing percent change in elongation is fluoroelastomer < silicone < EPDM < acrylic < ethylene–acrylic. Six of the materials exhibited a decrease (−2 to −23%) in tensile strength; all the rest showed an increase (+2 to +33%). Although tensile modulus is not part of the recommended screening tests, it was included in this study to aid in characterizing changes in the aging behavior of the materials. It is significant to note that all the materials except PS-19 showed an increase in their tensile modulus (+2 to +57%). Within each polymer class some compounds were better than others. In general, the order of increasing percent change in modulus is as follows: fluoroelastomer < silicone < fluorosilicone < EPDM < acrylic < ethylene–acrylic.

Weight Loss and Hardness. Volatile material evolved from the rubber components could adversely affect the efficiency of the solar collector if these volatiles collected on the cover plate to cause a reduction in transmittance of the solar radiation. Therefore it is important to minimize or eliminate material that would be fugitive under the operating conditions of solar thermal collectors. Weight loss values of 0 for PS-1 to 2.2% for PS-6 were obtained in the initial screening tests. However, these values can be reduced below the 1% allowable limit by post-curing the rubber compositions. The post-cure operation also serves to optimize the other properties of the rubber. The fluoroelastomers and silicones tested exhibited the lowest weight loss. These materials were followed by EPDM and the acrylic compositions. After post-curing, the weight loss of all the materials was reduced to below 1%.

Only slight changes in hardness were observed after the screening test and these changes were within the 10% allowable limit. It is expected that significant changes in hardness would occur only on those materials that are rapidly degraded under the test conditions as was the case for the chlorobutyl compound.

Table IX. Compression Set Aging Data

code	aging temp, °C	compression set, % after aging time (days) 1	2	3	5	6–7	9	13–14	16	27–30	42–45	56	70	97–102	149–154
PS-1	225	6	8		13		17		21	28	32	36	44	45	
	200	2	4		7		9		16	17	22		24		30
	175		4		5		6		7	9	11		13	14	17
PS-2	175		21		27		31		36	40	43		49	52	
	150			14		17		21		26	29				
PS-4	150			26		39		49		51					
PS-6	175		16		22		26		30	57					
	150			15		20		25		35	45	47	52		
	125					12		15		21	28	32(62)			
PS-7	175		18		24		29		48	64					
	150			14		21		28		37	44	49	50		
PS-8	175		17		24		30		52						
	150			14		18		24		32	40	44	53		
	125			11		14		18		26	30	34		42	
PS-9	225	31	42	59											
	200	15		26		36									
	175	11		17		22		31		42	60(48)[a]				
	150			13		15		21		26					
PS-10	225	31	39	55											
	200	15		26		36									
	175	8		14		19		27		40	52(48)				
	150			4		8		12		17	21	24(51)	27	31(84)	50(164)
PS-11	175			23		26		36		45		55			
	150			20		24		27		31		40	44	50	
PS-12	150			18		31		41		53					
PS-13	225	52	69												
	200	25		48		65									
	150			13		18		22		30	36	41	44	49	
PS-14A	150			15		25		27		35		49	52		
PS-14B	225	75	86												
	200	40		55		71									
	175	27		34		39		49		72					
	150			10		11		19		19	29	35	39	48	
PS-20	200	31		39		46		49							
	175	20		28		37		36		40		45			
	150			17		19		23			30				

[a] Numbers in parentheses are days of aging.

Table X. Weight Loss and Hardness after Aging Fluoroelastomers

code	aging temp, °C	property	aging time, days 0	2	6	10	16	30	60	102
PS-2	225	wt loss, %		0.6	1.3	1.9	3.0	4.9	10.0	17.7
		hardness	76	92	80	80	79	78	78	82
PS-2	200	wt loss, %		0.2	0.4	0.7	1.1	1.8	3.2	4.5
		hardness	77	80	78	80	78	76	79	79

Screening Test Results for SC Materials. While the requirements for the sealant materials are not as stringent as for the PS materials, these must at least function as a vapor barrier to prevent the ingress of moisture at the seal locations. Furthermore, they must not absorb moisture nor give off a substantial amount of volatile components that could adversely affect the collector. The results of the screening tests are summarized in Table VIII. In contrast to the PS materials, the sealants show a higher weight loss. This was expected due to the nature of the curing mechanism of these types of materials. Post-curing does reduce the amount of volatile material but not significantly. Excessive weight loss occurred with SC-7 which was eliminated from further testing. The remaining materials are ranked in decreasing order with respect to their overall change in properties: SC-9 > SC-8 > SC-5 > SC-6 > SC-2.

Long-Term Aging of PS Materials. Compression Set. Long-term aging data are presented in Table IX for selected elastomer compositions which include the fluoroelastomers, EPDM's, and silicones. The acrylic and ethylene–acrylic elastomers were not placed on extended aging tests because of poor performance in the screening tests.

Of the fluoroelastomers, the composition containing Fluorel 2179 (PS-1) provided the best hot compression set values after aging. After 100 days at 175 °C the compression set for PS-1 was 14 vs. 52 for the other fluoroelastomer composition designated PS-2. Even though the percent increase in compression set is 250% for PS-1 vs. 147% for PS-2, the absolute value for PS-1 is three times lower than for PS-2.

In the silicone class the composition containing Silastic 745 (PS-10) is superior to all the other silicones evaluated.

Table XI. Weight Loss and Hardness after Aging EPDM Elastomers

code	aging temp, °C	property	aging time, days													
			0	2	4	7	8	12	15	25	29	42	50	57	114	148
PS-6	225	wt loss, %		4.5												
		hardness	71	89												
PS-7	225	wt loss, %		4.2												
		hardness	69	90												
PS-8	225	wt loss, %		3.1												
		hardness	71	86												
PS-6	175	wt loss, %			0.8		1.0		2.2		5.6			7.6		
		hardness	71		73		70		84		94			95		
PS-7	175	wt loss, %			0.7		0.8		3.2		5.4			7.0		
		hardness	69		71		71		93		94			90		
PS-8	175	wt loss, %			0.5		0.5		2.1		2.9			4.4		
		hardness	71		73		85		94		94			95		
PS-6	150	wt loss, %				0.6			0.6		0.7	0.6		0.7	2.6	
		hardness	71			74			75		76	76		76	90	
PS-7	150	wt loss, %				0			0		0	0		0	5.2	
		hardness	67			70			71		73	74		77	96	
PS-8	150	wt loss, %				0			0		0	0		0	1.6	
		hardness	71			75			75		79	83		90	97	
PS-6	125	wt loss, %						0.3		0.3			0.4			0.5
		hardness	70					73		72			75			75
PS-8	125	wt loss, %						0.5		0.5			0.5			0.5
		hardness	71					74		72			75			78

After 84 days at 150 °C the compression set is 31. Next in line is SWS-7162 Red (PS-14B) with a compression set of 39 after 70 days at 150 °C. This is followed by SE-3715U (PS-13) with a compression set value of 44 after 70 days at 150 °C.

Turning to the EPDM elastomers, the compositions containing Nordel 1020 (PS-6) and Epcar 585 (PS-8) offer the best compression set resistance after aging. For example, after 70 days at 150 °C, the compression set values for the two materials are equal (50–53).

Based on the preliminary aging data, the fluoroelastomers are the materials of choice for elevated temperature (175–200 °C) performance. The silicone materials appear to be useful in the temperature range 150–175 °C while the EPDM materials would be satisfactory below temperatures of 150 °C.

Hardness and Weight Loss. Data on the effects of long-term aging at various temperatures on the weight loss and hardness for selected elastomers are shown in Tables X–XII. The order of increasing resistance to weight loss is as follows: silicones > fluoroelastomers > EPDM's. After about 100 days aging at 225 °C the fluoroelastomer (PS-2) showed an 18% weight loss compared to only 8% weight loss for the silicone elastomers. In general the silicones exhibit a lower weight loss than the fluoroelastomers at 225 °C. However, at 200 °C the weight loss for both materials after 100 days is about the same (5%). Of the five silicone compositions evaluated, PS-9 shows the least weight loss at 225 °C; PS-11 shows the least weight loss at 200, 175, and 150 °C. As expected, the EPDM materials are not thermally stable at or above 175 °C. The sample designated PS-8 is the most stable. All the elastomers increased in hardness with aging time with the EPDM exhibiting the most change followed by the fluoroelastomers and silicones. PS-10 and 11 are softer (initial hardness of 56–58) elastomers than PS-9, 13, and 14 (initial hardness of 68–78). The changes in hardness become more discernible after aging at temperatures above 175 °C for the silicones and above 125 °C for the EPDM elastomers.

Tensile Properties. The tensile properties after aging are summarized in Table XIII. No significant deterioration in properties occurred for the fluoroelastomer composition designated PS-1 after 13 days at 225 °C. However, the silicones begin to deteriorate after three days at this temperature. Compositions PS-9 and 10 are the most stable while PS-11 deteriorates very rapidly and loses half its strength after six days at 225 °C. In general, elongation deteriorates more rapidly than tensile strength for all the elastomers.

The Nordel EPDM composition (PS-6) is more stable than Epcar 585 composition (PS-8) in terms of retention of tensile properties after 28 days aging at 150 °C.

Long-Term Aging of SC Materials. Weight loss and hardness data as a function of temperature and time are presented in Table XIV. Material designated SC-8 (SWS-951) is the best material with respect to weight loss and hardness at all three temperatures studied (125, 150, and 175 °C). It lost only 3.9% of its weight after 100 days at 175 °C, 2.3% after 100 days at 150 °C, and 1.5% after 93 days at 125 °C. Its nearest competitor is sample SC-2 which lost 4.7, 3.1, and 1.5% of its weight after 100 days at 175, 150, and 125 °C, respectively. All the remaining SC materials showed weight losses of >10% at 175 °C, >5% at 150 °C, and >3% at 125 °C. The change in hardness after aging of SC-2 and SC-8 is negligible at all temperatures.

The actual hardness values (45–51) are equivalent for both materials. The hardness of SC-1 and 3 seem to be affected the most by thermal aging at all temperatures since the greatest change occurred with these two materials. The tensile properties of some of the SC materials after aging are shown in Table XV. Insufficient data have been obtained on the materials at this point to draw any definitive conclusions concerning long term performance.

Conclusions

The fluoroelastomers and silicones still appear to be the most resistant materials to the degradative effects of the solar collector environment. The silicone elastomers ex-

Table XII. Weight Loss and Hardness after Aging Silicone Elastomers

code	aging temp, °C	property	aging time, days 0	2	4	5	8	15	23	29	37	57	68	91	104	128	150
PS-9	225	wt loss, %		1.2		1.4	1.5	1.8	2.0		2.5		3.5		4.6	5.4	5.7
		hardness	75	78		77	75	80	83		81		83		83	84	85
PS-10	225	wt loss, %		1.6		1.7	1.8	2.1	2.4		2.9		4.2		6.1	7.9	9.0
		hardness	58	58		57	55	56	56		58		60		61	64	65
PS-11	225	wt loss, %		0.9		1.2	1.3	1.8	2.1		3.4		8.0		12		
		hardness	57	56		50	45	52	50		59		83		90		
PS-13	225	wt loss, %		1.1		1.5	1.8	2.4	2.9		3.9		6.0		8.1		
		hardness	78	81		81	81	84	82		84		87		90		
PS-14B	225	wt loss, %		1.5		1.9	2.0	2.5	3.1		5.0		12		16		
		hardness	68	73		73	72	76	75		80		87		90		
PS-9	200	wt loss, %		1.2	1.2		1.2	1.5		1.8		3.3		5.3			8.1
		hardness	76	77	77		78	78		80		80		80			86
PS-10	200	wt loss, %		1.3	1.5		1.7	1.8		2.0		3.7		6.4			11
		hardness	58	60	57		58	59		59		6.0		60			65
PS-11	200	wt loss, %		0.6	0.9		1.0	1.1		1.3		1.5		1.9			2.5
		hardness	52	59	54		55	55		55		54		53			54
PS-14B	200	wt loss, %		1.1	1.5		1.6	1.9		2.4		6.6		10			
		hardness	68	71	72		75	74		75		77		84			
PS-9	175	wt loss, %		0.7	0.9		1.0	1.1		1.3		1.7			2.8		3.3
		hardness	75	77	77		76	78		79		79			80		82
PS-10	175	wt loss, %		1.1	1.4		1.4	1.8		2.1		2.2			3.4		4.0
		hardness	57	58	60		61	61		62		60			61		62
PS-11	175	wt loss, %		0.3	0.6		0.6	0.7		0.8		1.0			1.3		1.5
		hardness	55	55	56		55	55		56		54			55		
PS-13	175	wt loss, %		0.4	0.6		0.8	1.0		1.5		3.1					
		hardness	79	80	80		80	81		83		84					
PS-14B	175	wt loss, %		0.7	1.1		1.2	1.3		1.5		2.1			5.0		
		hardness	69	72	72		72	75		75		74			79		

code	aging temp, °C	property	aging time, days 0	3	7	14	28	42	56	92	114	151
PS-9	150	wt loss, %			0.5	0.5	0.6	0.7	0.7		1.0	
		hardness	73		75	76	77	78	79		77	
PS-10	150	wt loss, %			0.8	0.8	1.0	1.0	1.1		1.3	
		hardness	57		60	59	59	59	59		59	
PS-11	150	wt loss, %			0.3	0.3	0.4	0.5	0.5		0.6	
		hardness	56		53	55	54	53	54		51	
PS-13	150	wt loss, %			0.2	0.2	0.4	0.5	0.5		0.8	
		hardness	79		79	80	80	81	81		81	
PS-14B	150	wt loss, %		0.6	0.6	0.7	0.9		1.1	1.2		1.6
		hardness	70	73	73	72	75		75	74		76

Table XIII. Tensile Properties of PS Materials after Thermal Aging

code	aging temp, °C	property	days aged 0	1	2	3	6	13	27	41	48	62
PS-1	225	tensile str., psi	1604	1657		1814	1774	1775				
		% retention		103		113	111	111				
		elongation, %	157	173		178	170	168				
		% retention		110		113	108	107				
		100% mod., psi	1022	1058		1102	1124	1178				
PS-9	225	tensile str., psi	1067	1080	1052	1033	887	856	693			
		% retention		102	99	97	82	80	65			
		elongation, %	167	160	151	148	123	138	93			
		% retention		96	90	89	74	80	57			
		100% mod., psi	720	736	715	723	724	680				
PS-10	225	tensile str., psi	781	809	844	720	737	680	563			
		% retention		104	108	92	94	87	72			
		elongation, %	250	255	244	227	237	229	196			
		% retention		102	97	91	95	91	79			
		100% mod., psi	273	257	266	269	262	238	251			
PS-11	225	tensile str., psi	1009	786		607	485		371			
		% retention		78		60	48		37			
		elongation, %	489	370		293	268		0			

Table XIII (*Continued*)

code	aging temp, °C	property	days aged 0	1	2	3	6	13	27	41	48	62
		% retention		76		60	55		0			
		100% mod., psi	218	226		209	177					
PS-13	225	tensile str., psi	1132	1014	1034	881	900	734	757			
		% retention		90	91	78	80	65	67			
		elongation, %	129	126	124	104	104	91	63			
		% retention		98	96	81	81	72	49			
		100% mod., psi	984	840	876	877	840					
PS-14B	225	tensile str., psi	1050	1116	896	877	805	739	576			
		% retention		106	85	84	77	70	55			
		elongation, %	337	330	316	315	296	250	133			
		% retention		98	94	94	88	74	39			
		100% mod., psi	329	337	343	333	339	391	517			
PS-1	200	tensile str., psi	1604			1741	1743	1735				
		% retention				109	109	108				
		elongation, %	157			167	170	170				
		% retention				106	108	108				
		100% mod., psi	1022			1167	1136	1131				
PS-9	200	tensile str., psi	1067	1081		1003	1026	962	705		701	599
		% retention		101		94	96	90	66		66	56
		elongation, %	167	165		140	143	137	98		85	83
		% retention		99		84	86	82	59		51	50
		100% mod., psi	720	708		730	739	699	720			
PS-10	200	tensile str., psi	781	780		874	827	790	556		559	
		% retention		100		112	106	101	71		72	
		elongation, %	250	250		270	249	243	188		185	
		% elongation		100		108	100	97	74		74	
		100% mod., psi	273	256		265	278	257	260		278	
PS-11	200	tensile str., psi	1009	966			761	536				
		% retention		96			75	53				
		elongation, %	489	461			305	277				
		% retention		96			84	57				
		100% mod., psi	218	213			215	184				
PS-13	200	tensile str., psi	1132	1054		1098	927	854	715(23)		577	536
		% retention		93		97	88	75	62		51	47
		elongation, %	129	133		122	121	181	68		36	27
		% retention		103		95	94	140	53		35	19
		100% mod., psi		851		1189	1135	586				
PS-14B	200	tensile str., psi	1056	1023		984	933	865	721	618	517(55)	
		% retention		97		94	89	82	69	59	49	
		elongation, %	337	351		342	317	269	215	147	115	
		% retention		104		102	94	80	64	44	34	
		100% mod., psi	329	332		331	351	335	417	494	484	

code	aging temp, °C	property	days aged 0	1	3	6	13	27	41	48
PS-8	175	tensile str., psi	2287	2184	1027	366				
		% retention		95	45	16				
		elongation, %	247	200	124	29				
		% retention		81	50	12				
		100% mod., psi	476	670	687					
PS-9	175	tensile str., psi	1067	1097	1120	1083	1081	1038		965
		% retention		103	105	102	102	97		90
		elongation, %	167	166	124	155	153	145		137
		% retention		100	74	93	92	88		82
		100% mod., psi	720	705	736	722	744	733		736
PS-10	175	tensile str., psi	781	1021	845	866	824	778		852
		% retention		131	108	111	106	100		109
		elongation, %	250	266	260	267	255	238		245
		% retention		107	104	107	102	95		98
		100% mod., psi	273	264	275	256	263	259		303
PS-11	175	tensile str., psi	1009	968	1019	937	851	777		
		% retention		96	101	93	84	77		
		elongation, %	489	480	519	463	365	333		
		% retention		98	106	95	75	68		
		100% mod., psi	218	216	282	161	240	242		
PS-13	175	tensile str., psi	1132	1112	1110	1113	1069	974		737
		% retention		98	97	98	96	88		66
		elongation, %	129	138	142	136	110	108		62
		% retention		107	111	105	79	79		48
		100% mod., psi	894	826	849	935	964	869		

Table XIII (*Continued*)

code	aging temp, °C	property	days aged 0	1	3	6	13	27	41	48
PS-14B	175	tensile str., psi	1050	1051	1066	1051	984	870	921	
		% retention		100	102	100	94	83	88	
		elongation, %	337	363	360	361	329	293	291	
		% retention		108	107	107	98	87	87	
		100% mod., psi	329	325	340	339	342	363	394	

code	aging temp, °C	property	days aged 0	1	3	6	13-14	27-28
PS-6	150	tensile str., psi	1463				1831	1576
		% retention					125	109
		elongation, %	202				163	147
		% retention					81	73
		100% mod., psi					856	1105
PS-8	150	tensile str., psi	2287	2335	2243	2338	2123	934
		% retention		102	98	102	93	41
		elongation, %	247	234	213	200	192	97
		% retention		95	86	81	78	39
		100% mod., psi	476	564	607	689	661	
PS-6	125	tensile str., psi	1463			1860	1995	1799
		% retention				127	136	123
		elongation, %	202			177	180	165
		% retention				87	89	82
		100% mod., psi				770	775	831

Table XIV. Weight Loss and Hardness (Shore A) of SC Materials after Aging

code	aging temp, °C	property	aging time, days 0	7	15	29	58	93
SC-1	125	wt loss, %		1.6	1.7	1.9	2.4	2.9
		hardness	59-65	60-65	63	63-66	64-67	65-68
SC-2	125	wt loss, %		0.8	0.9	1.0	1.3	1.5
		hardness	46-50	44-51	46-50	47-49	50-52	48-52
SC-3	125	wt loss, %		1.4	1.7	2.3	3.2	4.0
		hardness	60-62	62-66	63-64	60-65	64-70	66-70
SC-4	125	wt loss, %		1.1	1.3	2.0	3.0	4.1
		hardness	49-50	49-50	49-50	50	50-52	52-55
SC-5	125	wt loss, %		0.7	0.9	1.5	2.2	3.3
		hardness	42-48	43-46	40-43	40-45	43-47	45-48
SC-6	125	wt loss, %		0.7	0.8	1.5	2.6	3.5
		hardness	34-41	38-40	32-33	34-37	35-40	36-40
SC-8	125	wt loss, %		0.7	0.9	1.1	1.3	1.5
		hardness	47-52	48-50	47-50	45-50	46-52	50-52

code	aging temp, °C	property	aging time, days 0	3	7	14	46	73	100
SC-1	150	wt loss, %		1.4	1.6	2.0	3.1	4.0	5.2
		hardness	66	64	64	64	64	65	68
SC-2	150	wt loss, %		1.2	1.5	1.8	2.4	2.8	3.1
		hardness	46	49	49	50	51	49	50
SC-3	150	wt loss, %		1.5	2.0	2.7	4.7	6.1	7.3
		hardness	61	63	60	63	64	68	69
SC-4	150	wt loss, %		1.6	2.1	2.6	4.8	6.5	7.8
		hardness	46	51	52	51	52	50	57
SC-5	150	wt loss, %		1.1	1.7	2.4	4.9	6.9	8.6
		hardness	36	37	34	32	32	31	33
SC-6	150	wt loss, %		1.2	1.7	2.2	4.6		
		hardness	40-42	41-46	40-45	40-45	40-45		
SC-7	150	wt loss, %							
		hardness			Samples stuck to pan.				
SC-8	150	wt loss, %		1.2	1.4	1.5	1.9	2.1	2.3
		hardness	47	50	48	50	50	49	50

Table XIV (*Continued*)

code	aging temp, °C	property	aging time, days							
			0	3	7	14	28	42	63	100
SC-1	175	wt loss, %		2.1	2.4	3.2	4.6	5.7	7.6	10.3
		hardness	61	64	65	64	66	68	70	
SC-2	175	wt loss, %		2.3	2.7	2.9	3.4	3.7	4.1	4.7
		hardness	46	49	49	49	51	51	49	51
SC-3	175	wt loss, %		2.6	3.7	4.9	7.5	9.9	13.4	
		hardness	53-61	60-65	63-67	64-68	64-72	68-72	69-74	
SC-4	175	wt loss, %		2.1	3.0	4.0	6.2	7.9	10.2	12.7
		hardness	46	50	49	49	51	50	51	54
SC-5	175	wt loss, %		1.7	2.8	4.2	7.2	10.6	15.9	
		hardness	34-38	32-35	28-30	25-31	28-30	30	42-49	
SC-6	175	wt loss, %		1.7	2.6	3.6	6.0	8.0	10.3	12.7
		hardness	41	42	42	43	44	42	40	42
SC-7	175	wt loss, %		7.8	12.4	17.1	26	33		
		hardness	33-36	30-32	22-33	34-35	37-40	40-45		
SC-8	175	wt loss, %		1.6	1.9	2.1	2.6	3.0	3.4	3.9
		hardness	49	50	50	50	50	51	52	52

Table XV. Tensile Properties of SC Materials after Aging

code	aging temp, °C	property	days aged		
			0	1	6
SC-1	225	tensile str., psi	353	438	374
		% retention		124	106
		elongation, %	130	202	165
		% retention		155	127
		100% mod., psi	296	250	246
			0	1	3
SC-1	200	tensile str., psi	353	497	396
		% retention		141	112
		elongation, %	130	210	162
		% retention		161	124
		100% mod., psi	296	271	277
			0	2	4
SC-3	200	tensile str., psi	295	350	411
		% retention		119	139
		elongation, %	134	150	161
		% retention		112	120
		100% mod., psi	255	269	306

code	aging temp, °C	property	days aged					
			0	1	3	6	13	27
SC-4	200	tensile str., psi	652	511	371		316	
		% retention		78	57		48	
		elongation, %	527	447	355		312	
		% retention		85	67		59	
		100% mod., psi	144	122	119		127	
SC-5	200	tensile str., psi	258	210	211	203	185	131
		% retention		80	81	77	71	50
		elongation, %	262	248	272	270	282	207
		% retention		96	105	105	109	80
		100% mod., psi	100	85	80	88	75	64
SC-6	200	tensile str., psi	118	114	79			
		% retention		97	67			
		elongation, %	376	357	287			
		% retention		95	76			
		100% mod., psi	70	52	37			

code	aging temp, °C	property	days aged			
			0	3	6	28
SC-1	175	tensile str., psi	353	314	296	287
		% retention		89	84	81
		elongation, %	130	140	120	138
		% retention		108	92	106
		100% mod., psi	296	269	281	287

Table XV (*Continued*)

code	aging temp, °C	property	days aged 0	4	7
SC-3	175	tensile str., psi	295	296	349
		% retention		100	118
		elongation, %	134	130	145
		% retention		97	108
		100% mod., psi	255	255	273

code	aging temp, °C	property	days aged 0	3	6	13–14	27–28
SC-4	175	tensile str., psi	652	553		423	
		% retention		85		65	
		elongation, %	527	503		368	
		% retention		96		68	
		100% mod., psi	144	121		130	
SC-5	175	tensile str., psi	258	265	212	203	217
		% retention		101	81	78	84
		elongation, %	262	297	268	286	260
		% retention		113	102	107	99
		100% mod., psi	100	92	82	69	70

			0	3	6	13	27–28
SC-6	175	tensile str., psi	118	122	97	83	
		% retention		104	82	70	
		elongation, %	376	443	320	412	167

code	aging temp, °C	property	days aged 0	3	6	13	27–28
		% retention		118	85	110	44
		100% mod., psi	70	46	46	70	

code	aging temp, °C	property	days aged 0	13	28	56
SC-1	150	tensile str., psi	353		492	
		% retention			139	
		elongation, %	130		190	
		% retention			146	
		100% mod., psi	296		283	
SC-3	150	tensile str., psi	295	333	365	
		% retention		112	124	
		elongation, %	134	132	158	
		% retention		99	118	
		100% mod., psi	255	280	270	
SC-4	150	tensile str., psi	652	518		
		% retention		79		
		elongation, %	527	489		
		% retention		93		
		100% mod., psi	144	131		
SC-5	150	tensile str., psi	258	233	262	265
		% retention		90	101	103
		elongation, %	262	278	297	312
		% retention		106	113	119
		100% mod., psi	100	81	72	69
SC-6	150	tensile str., psi	118	100	111	
		% retention		85	94	
		elongation, %	376	318	423	
		% retention		85	113	
		100% mod., psi	70	46	34	

hibit the best overall compression set at both high and low temperature followed by the fluoroelastomers, EPDM, acrylics, and chlorobutyl materials. Of the fluoroelastomers tested, formulation PS-1 had the best low-temperature compression set. For the silicones, PS-10 is superior to all the rest in compression set, while the EPDM elastomers designated PS-6 and PS-8 offer the best compression set in their class.

With respect to weight loss, the silicones are superior to the fluoroelastomers followed by the EPDM rubbers. PS-9 silicone shows the least weight loss at 225 °C while PS-11 silicone is superior at 200, 175, and 150 °C. PS-8, an EPDM material, shows the least weight loss. All elastomers increased in hardness with aging with the EPDM exhibiting the most change followed by the fluoroelastomers and silicones. Overall, these materials that had the best combination of properties and exhibited the best stability are PS-20, PS-6, PS-8, PS-9, and PS-10. The two sealant materials that exhibited the best combination of properties are SC-2 and SC-8.

Acknowledgment

This work was supported by the Solar Heating and Cooling Research and Development Branch, Office of Conservation and Solar Applications, U.S. Department of Energy, Contract No. DE-AC04-78CS15362MOD. The authors also wish to thank W. R. Koryak and B. L. Csontos for their assistance in this program.

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Received for review March 15, 1982
Accepted June 28, 1982

COMMUNICATIONS

A Look at Creosote vs. Chromated Copper Arsenate Salts as Wood Preservatives for the Marine Environment

Chromated copper arsenate (CCA) treatment at a retention above 0.6 pcf preserved wood better than coal-tar creosote treatment at 28 pcf in the warm-water harbor of Key West, FL, where teredine marine borers and *Limnoria tripunctata* are prevalent. CCA at between 1.1 and 2.4 pcf has prevented borer attack for over a decade. By contrast, untreated wood was destroyed in about 1 year. At Key West, CCA alone at 2.4 pcf protected wood as well from marine borers as did a combination treatment of CCA followed by creosote impregnation.

Introduction

Wood preservatives that provide long-term protection from decay fungi and terrestrial wood-boring insects often do not prevent degradation by marine borers. Annual expenditures for repair or replacement of wood damaged by marine borers may exceed $200 million (Parrish and Bultman, 1979). Creosote has long been the favored marine preservative and protects wood well from attack by molluscan-type borers such as teredines and pholads. It is effective against crustaceans, the other major group of borers, in northern waters but not in many southern waters where the species *Limnoria tripunctata* is prevalent. It had been observed that some salts of copper and arsenic inhibit wood degradation by limnoria. Therefore, a study was initiated in 1969 to determine what combination of preservative type, quality, and quantity would be the most effective and economical single or dual (combination) treatment to protect wood in waters where teredine borers and *Limnoria tripunctata* are prevalent.

Methods

Small wood panels, $^1/_4 \times 1^1/_2 \times 6$ in., treated with 130 different combinations of preservative salts and creosotes, have been submerged in the sea at Key West, FL, for 12 years. Complete details of experimental design and procedures have been published previously (Johnson et al., 1973) as has a tabulation of condition of panels after 9 years' exposure (Johnson and Gutzmer, 1981). This note describes and compares some commercially important preservative treatments that show a range of effectiveness in reducing marine borer attack. These treatments are the Type III formulation (Fed. Spec. TT-W-550) of chromated copper arsenate (CCA) waterborne salts at four retentions (concentrations within the wood), a marine-grade coal-tar creosote (Fed. Spec. TT-C-645) at a high retention (28 pounds of creosote per cubic foot of wood (pcf)), and combinations of these treatments where panels were pressure impregnated with aqueous CCA solution, dried, then impregnated with creosote. The proportions of components in CCA treating solution were 47% hexavalent chromium (calculated as CrO_3), 18% bivalent copper (as CuO), and 35% pentavalent arsenic (as As_2O_5). Performance in the exposure test is based on semiannual inspections where panels are rated by ASTM procedures for extent and type of marine borer attack. Marine borer activity is continuously monitored through installation and inspection of untreated controls at each inspection.

Results and Discussion

Untreated panels of southern pine sapwood were generally heavily attacked by limnoria and teredines in 6 months and destroyed in 6 to 24 months (Figure 1). This attack was observed over the entire 12-year exposure period. CCA panels at 0.25 pcf (as CrO_3, CuO, and As_2O_5), a retention normally recommended for wood exposed above ground out-of-doors but not in soil or water contact, remained free of attack for 18 months but then degraded rapidly to complete failure after 3 years' exposure. Panels treated quite heavily (28 pcf) with coal-tar creosote degraded less rapidly than panels with 0.25 pcf CCA, but still failed in about 5 years. This test with small panels is accelerated relative to the performance of dimension timbers or piling due to the greater surface-to-volume ratio of the panels and more exposure of earlywood preferred by borers. Despite this, such rapid degradation must be regarded as unsatisfactory. At 0.6 pcf CCA, the retention specified for wood (building) foundations, panels were heavily attacked after 6 years and destroyed in $8^1/_2$ years. Creosote-treated panels were attacked only by limnoria, but salt-treated panels at 0.25 and 0.60 pcf showed both