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Environmental Exposure Effects on Composite Materials for Commercial Aircraft

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ENVIRONMENTAL EXPOSURE EFFECTS ON COMPOSITE MATERIALS FOR COMMERCIAL AIRCRAFT

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Prepared for

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Under Contract NAS1-15148

by

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FOREWORD

This is an interim technical report prepared by the Boeing Commercial Airplane Company, Seattle, Washington, under Contract NAS1-15148. It covers work performed between April 1, 1982 to March 31, 1985. The program is sponsored by the National Aeronautics and Space Administration, Langley Research Center. Dr. Ronald K. Clark is the NASA Technical Representative.

This contract is being performed by the Advanced Structures Staff organization. Key personnel associated with the program during the reporting period and their area of responsibility are:

R. D. Wilson	Program Manager
R. L. Coggeshall	Technical Leader

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1.0 SUMMARY AND PROGRAM STATUS

A long term experimental program is being conducted to evaluate the influence of aircraft associated environments on the environmental performance of commercially available composite material systems. This report covers the period of performance from April 1, 1982, to March 31, 1985. During this period, the contract was modified to restrict efforts to three materials (T300/5208, T300/5209, and T300/934 graphite/epoxy composite materials) and to eliminate laboratory activities to develop accelerated environmental test procedures.

Progress during this period included testing and data analysis of two and three year exposure specimens from the Dallas exposure rack, 3-year exposure specimens from the Wellington exposure rack, 5-year exposure specimens from the Honolulu exposure rack, 5-year exposure specimens from the Edwards exposure rack, and 2- and 3-year exposure specimens from Southwest Airlines aircraft.

Results of strength testing to date show a continuation of existing trends with a slight clarification of these trends as 5-year data becomes available. The moisture content measurements are becoming asymptotic showing levels of stabilization consistent with predicted values.

Identification of commercial products in this report is used to adequately describe the test materials. Neither the identification of these commercial products nor the results of the investigation published herein constitutes official endorsement, expressed or implied, of any such product by either the Boeing Company or NASA.

2.0 INTRODUCTION

The introduction of any new material system into commercial aircraft structure requires that an information data base be available to the designer in such a form that one can accept the material as a viable alternate to the current material system in use. Composite material components on airplanes in scheduled commercial service have accumulated experience which provides confidence in current design and fabrication methods. To assess the requirements for a production commitment to primary airplane structure, the long-term durability of composites in commercial service needs an expanded data base.

This contract focuses on expanding the data base for composite materials' properties as they are affected by the environments encountered in operating conditions, both in flight and at ground terminals. It is well known that absorbed moisture will degrade the mechanical properties of graphite/epoxy laminates at elevated temperatures. Since airplane components are frequently exposed to atmospheric moisture, rain, and accumulated water, quantitative data are required to evaluate the amount of fluids absorbed under various environmental conditions and the subsequent effects on material properties.

The program, as currently funded, has a duration of approximately 11 years and is performed in two tasks as follows:

- Task I - Flight Exposure
    - Confidence through long-term exposure data
    - Interior and exterior exposure on three airlines for up to 10 years
- Task II - Ground Based Exposure
    - Confidence through long-term exposure data
    - Solar and nonsolar exposure at four different ground stations for up to 10 years

Among the parameters to be investigated are: geographic location, flight profiles, solar heating effects, ultraviolet degradation, retrieval times, specimen types, test temperatures, and others. The experimental program includes in-flight and ground exposures of up to 10 years and will obtain mechanical, physical, and chemical data from about 17,000 specimens. A complete description of the program content was given in the first Quarterly Report (ref. 1). Other reports (refs. 2-15) have covered progress to date. The program schedule is shown in figure 2-1. All tables and figures appear after the text.

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3.0 LONG TERM EXPOSURE AND TEST

A summary of the status of long term ground and flight exposure specimens is shown in Tables 3-1 and 3-2. The ground rack data is shown including exposure time at removal or on March 31, 1985. The specimens exposed at Edwards were temporarily removed from exposure for three months to facilitate required roof repairs. The aircraft exposure data also includes removal time or time as of March 31, 1985. Specimens deployed on Aloha aircraft have been transferred to several aircraft due to sales and leasing activity; however, accurate records of specimen exposure are being maintained.

During this reporting period, results for ground exposure specimens were analyzed for the testing performed on 2-year Dallas, 3-year Dallas, 3-year Wellington, 5-year Dryden, and 5-year Honolulu specimens. Results for flight exposure specimens were analyzed for the testing performed on 2- and 3-year Southwest Airlines specimens. Testing of the 5-year Honolulu and 5-year Edwards ground exposure specimens has been completed except for the dryout of selected specimens for moisture content determination.

Tabulation of test data and graphical representation of changes in strength over time are reported. All strengths are reported as a percentage of baseline unexposed strengths. Baseline values are tabulated for each material on Tables 3-3 through 3-5.

Summaries of test results for the 2- and 3-year ground exposure specimens at Dallas are shown on Tables 3-6 through 3-9. The specimen residual strengths are shown plotted against time on figures 3-1 through 3-7. Moisture content plotted against exposure time is shown on figure 3-8. In general, it appears that the mechanical performance improvement or degradation has stabilized between the second and third years of exposure. The primary exception to this trend is the hot compression strengths. The moisture content data also appears to be stabilizing. This stabilization at about 1 percent after approximately two years is consistent with findings reported in reference 17.

Test data for the 3-year ground exposure specimens deployed at Wellington is shown on Tables 3-10 and 3-11. Residual strength data as a function of time is shown on figures 3-9 through 3-15. Moisture content values are plotted against time on figure 3-16. The same trends shown in the Dallas strength data are repeated in the Wellington data. The stabilization of the specimen moisture content is slightly more difficult to ascertain, due to data scatter.

Results from the 5-year ground exposure specimens at Edwards are summarized on Tables 3-12 and 3-13. Dryout tests have not been completed. Strength changes over time are shown on figures 3-17 through 3-23. The trends previously discussed follow with these specimens. The hot-wet compression strength continues to show very slight degradation between years 3 and 5 for two materials. The third material shows a slight improvement. The amount of these slight changes that is attributable to test data scatter is difficult to determine. The first year data showed large fluctuations.

The 5-year ground exposure specimens at Honolulu are shown on Tables 3-14 and 3-15. The mechanical properties data are plotted against time on figures 3-24 through 3-30. Moisture dryout tests have not been completed. As in the 5-year Edwards data, the longer term exposure history curves tend to smooth out individual fluctuations in strength values.

Flight service exposure specimens were returned and tested after two and three years on Southwest Airlines aircraft. Solar, nonsolar, and interior exposed specimen test data is summarized on tables 3-16 through 3-21. The mechanical properties data is plotted on figures 3-31 through 3-42. The flight service specimens have exhibited similar trends over time compared to the previously described ground exposure data.

Results of testing to date indicate the continuation of several trends. One noticeable effect is the lower residual strengths for elevated temperature tests relative to room temperature values. While this meets with expectations, it is especially pronounced in the hot-wet compression strengths. A downward trend with time in this test mode suggests that the concurrent increase in the laminate moisture content is a contributing factor. With the stabilization of moisture contents, the continuation of strength trends remains to be seen.

In general, the lowest residual strength values at elevated temperature were obtained for T300/5209 specimens. The T300/5209 material is a 250°F cure system as opposed to 350°F cure temperatures for T300/5208 and T300/934 materials. The T300/5209 material also exhibits the lowest moisture content percentages although saturation has nearly been reached. The T300/5208 material tends to have the lowest residual strength values for hot-wet compression strength. The data obtained for the room temperature tests show no easily discerned pattern based on material type although the T300/5208 compression specimens are somewhat lower in strength.

The specimens exposed at Edwards tend to have higher residual strengths compared to baseline data. Specimens exposed at Honolulu tend to have lower residual strengths. These trends are independent of solar or nonsolar conditioning and moisture content. One possible explanation is the difference of humidity cycling. Dryden specimens would experience a greater range of humidity conditions and subjected to a varying absorption description cycle. Honolulu specimens, however, would be exposed to a more consistent humidity level.

When evaluating any of the test values obtained, attention should be paid to the data scatter involved with test specimens of this quantity, type, and material. Small differences in mechanical properties due to environmental effects are easily masked by data scatter especially when only a few specimens are tested.

4.0 CONCLUSIONS

While there is a large amount of data involved, detailed conclusions are difficult to obtain. This is a result of few replicate specimens for each test condition. In addition, the test data scatter, while small, may be as significant as any performance changes due to exposure. Test scatter is generally more noticeable for the elevated temperature tests. Regardless of this, several observations have been made.

Moisture content as measured in short beam shear specimens has appeared to have stabilized after three years of exposure. The laminate moisture content appears to be a function of material type with the T300/5208 and T300/934 (350°F cure) stabilized at 1.0 percent and T300/5209 (250°F cure) stabilized at 0.6 percent.

The mechanical property data generated from short beam shear tests showed no discernable changes due to solar exposure or exposure location. There is a slight reduction in strength for the elevated temperature tests. Strength is also slightly degraded over time. Material T300/5208 consistently has the highest residual strength while T300/5209 has the lowest.

The flexure specimen mechanical test data shows no strength changes dependent on temperature, solar exposure, or exposure location. The material type effects follow the trend of the short beam shear tests. Flexure strength does show a very slight increase over time.

The ± 45 tensile specimens showed no clear strength change trends as a function of temperature, solar exposure, or material type. The location of exposure showed some influence. Specimens exposed at Edwards and Honolulu had greater strength degradations than specimens exposed at Dallas and Wellington.

In general, the 0° compression specimens showed no changes attributed to exposure location, solar exposure, or material type. There is a slight decrease in strength over time for the elevated tests while the room temperature tests showed a very slight increase in strength over time.

The stressed tension specimens showed no clear strength change trends except the T300/5209 material appears to have experienced the greatest degradation.

The short beam shear specimens exhibited the largest strength degradation. This may be attributed to the resin dominated nature of this type of test specimen. The flexure, ± 45 tension, and stressed tension specimens showed a slight increase in strength over time. These specimens tend to be fiber dominated. Changes in laminate stiffness have not been evaluated but may contribute to this slight strength increase. The 0° compression specimen strength is a function of the fiber/resin interface. At room temperature, there is a very slight increase in strength over time suggesting no adverse effects due to exposure. At elevated temperatures, however, the resin shows some reaction and a slight decrease in strength over time is apparent.

The exposure location varies the humidity, temperature, and ultraviolet exposure values for the specimens. UV exposure is of minor concern as all specimens were painted and the paint performed adequately. The only noticeable pattern of strength change as a function of location is for the ±45 tension specimens. These specimens exhibited greater strength degradation at the worst exposure locations, Edwards and Honolulu, compared to Dallas and Wellington.

The changes in mechanical properties of all specimens tested are slight. Composite structures can be designed for current service environments based on information to date.

5.0 REFERENCES

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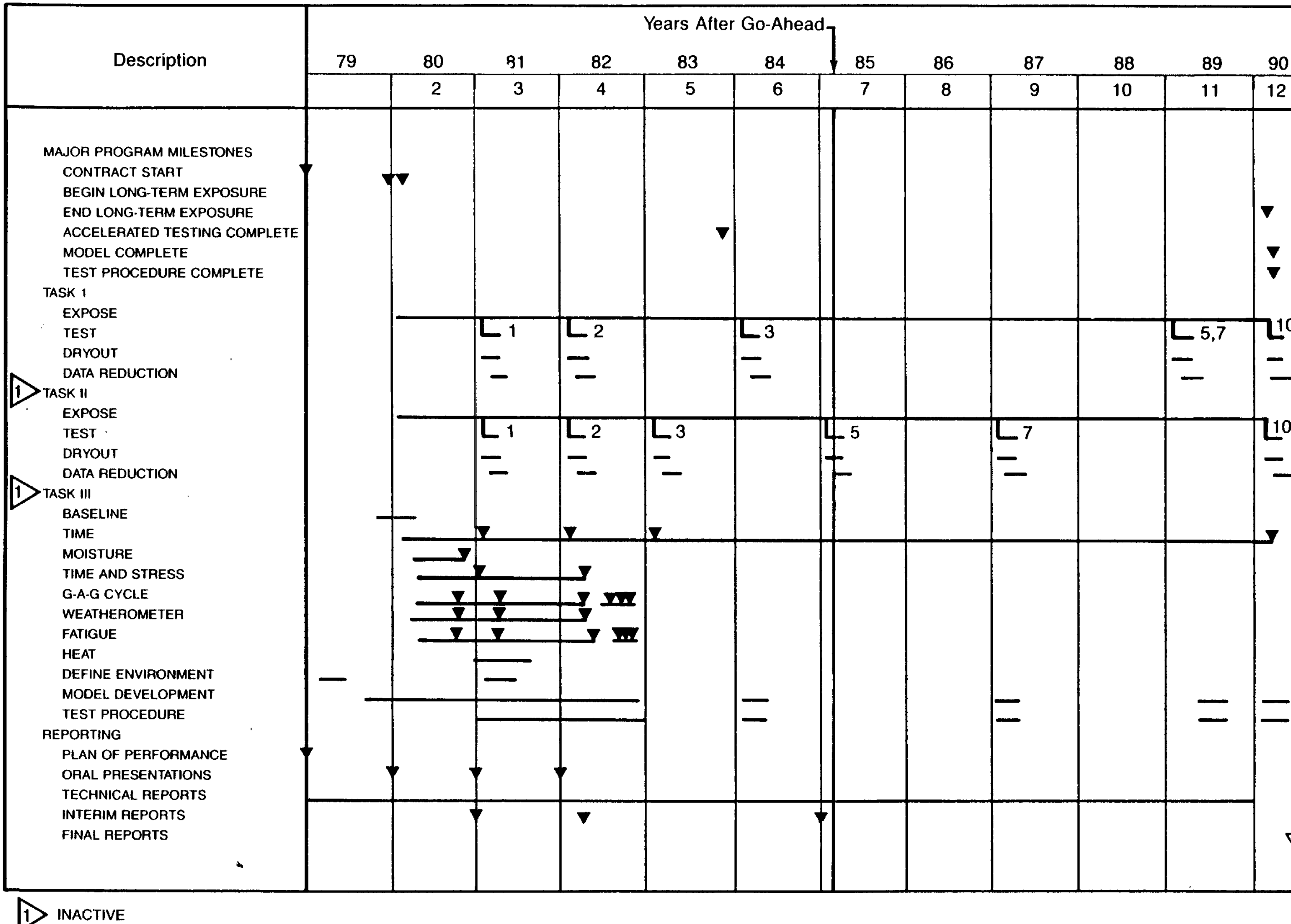

Figure 2-1. Program Schedule

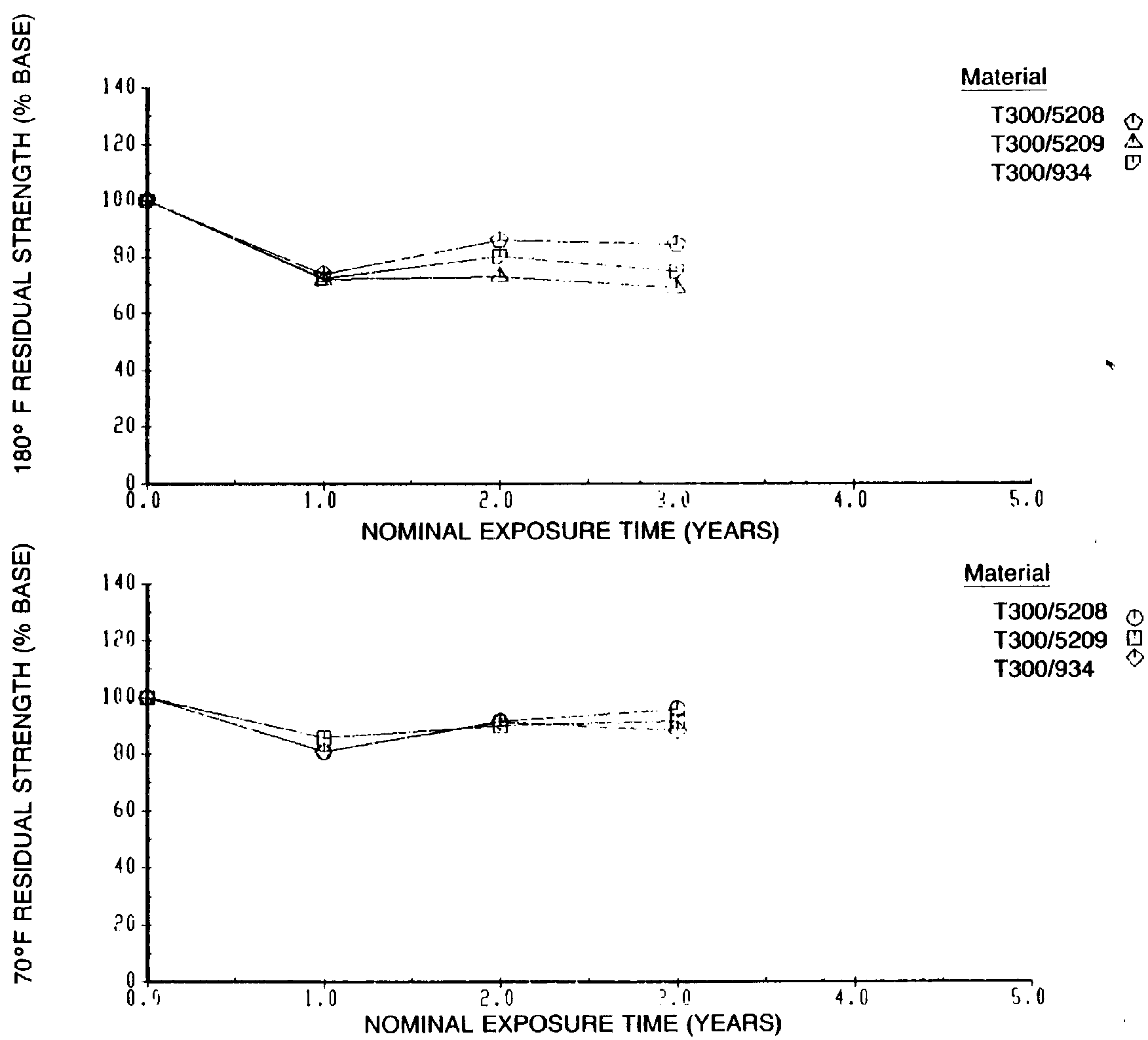

Figure 3-1. Short Beam Shear Strength Results for Solar Ground Exposure at Dallas, TX

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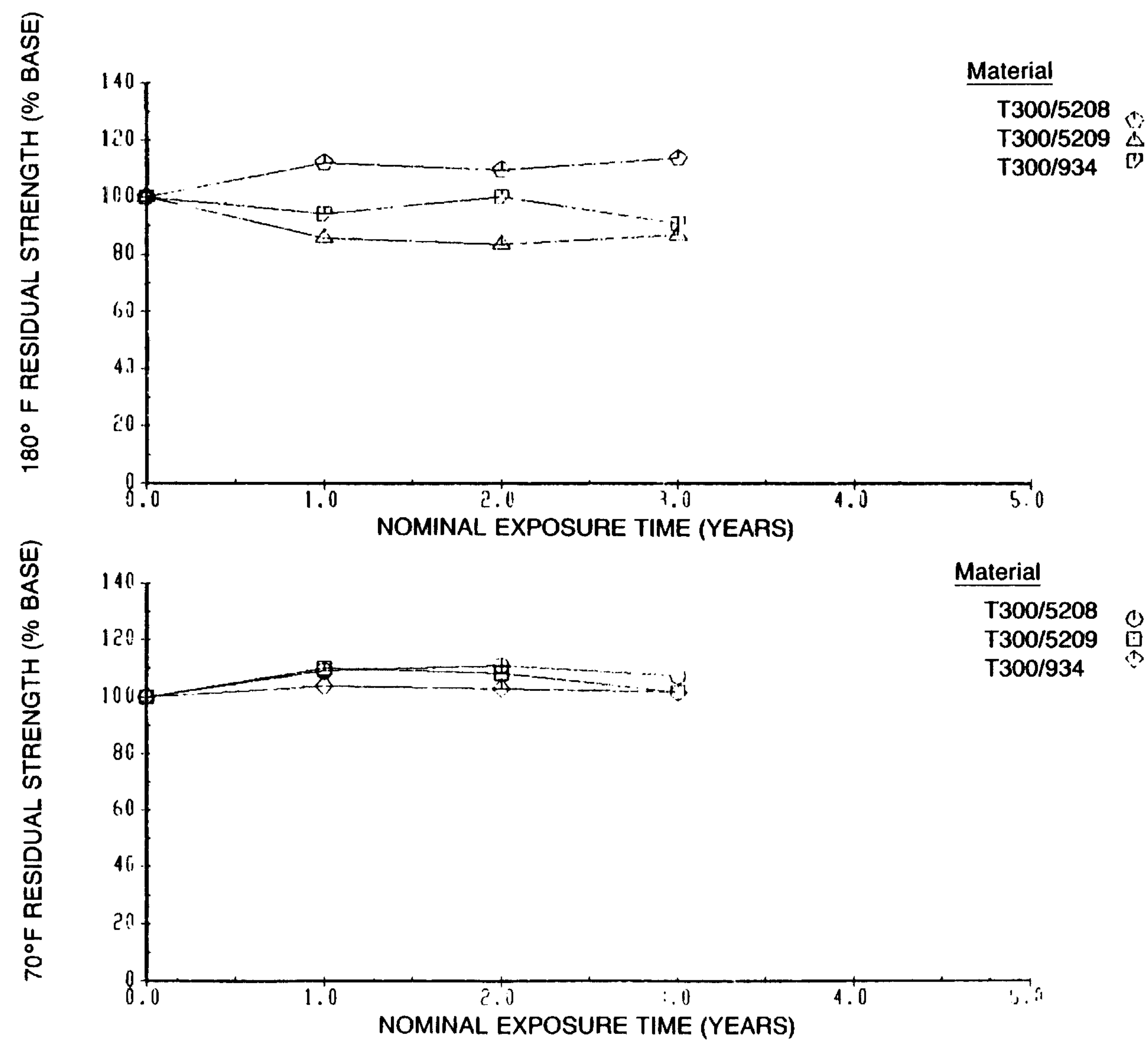

Figure 3-2. Flexure Strength Results for Solar Ground Exposure at Dallas, TX

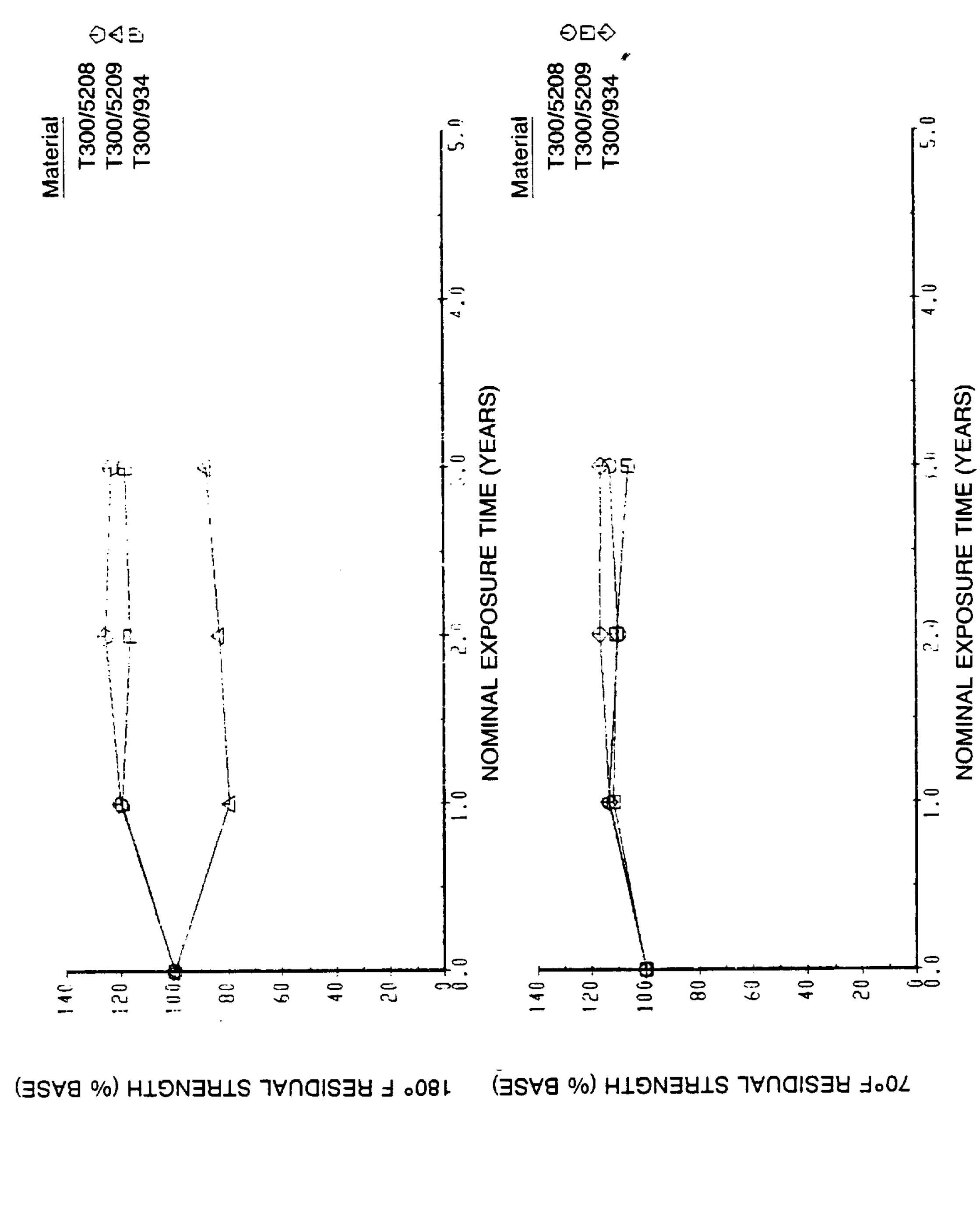

Figure 3-3. Tensile Strength Results for Solar Ground Exposure at Dallas, TX

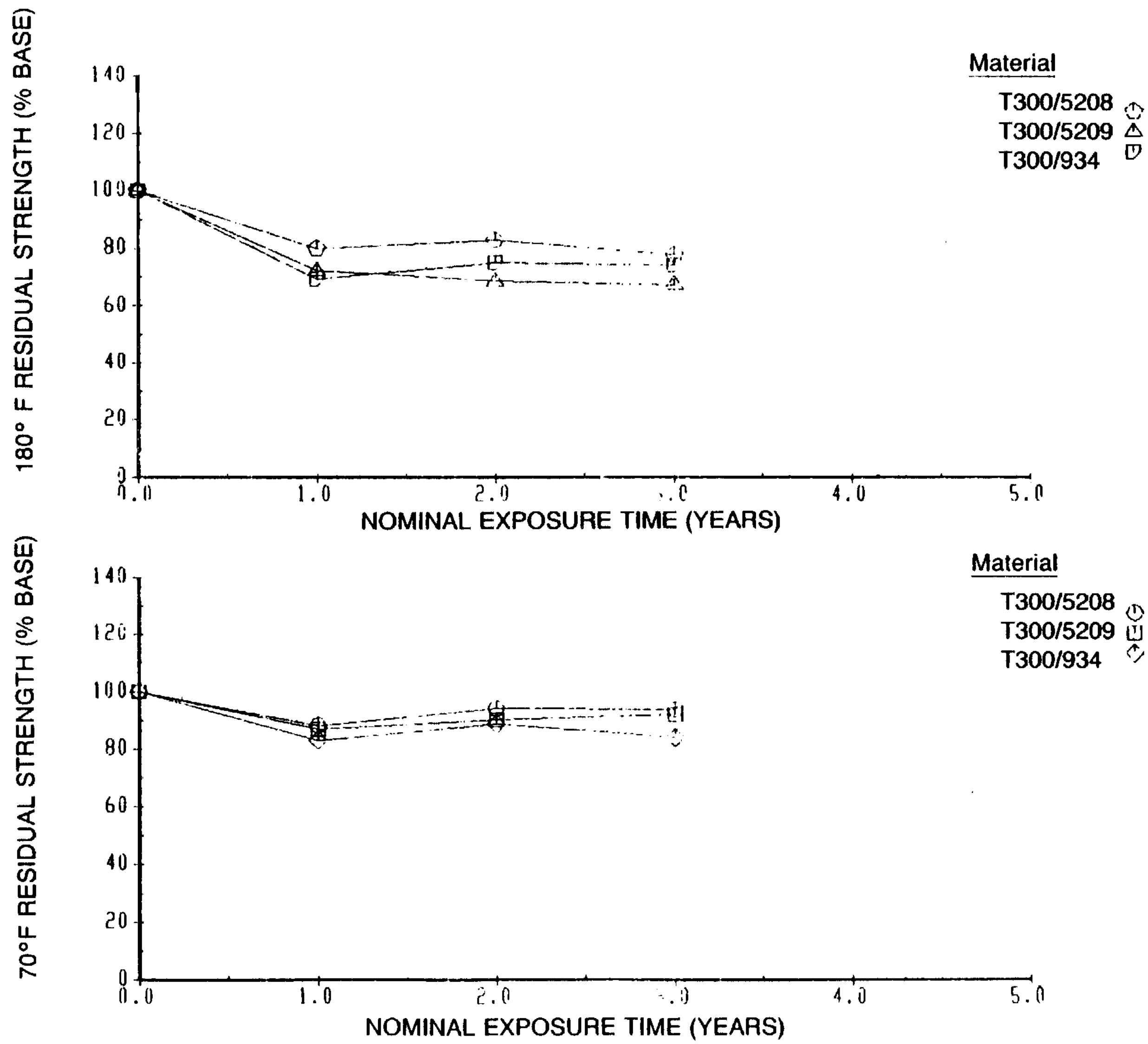

Figure 3-4. Short Beam Shear Strength Results for Nonsolar Ground Exposure at Dallas, TX

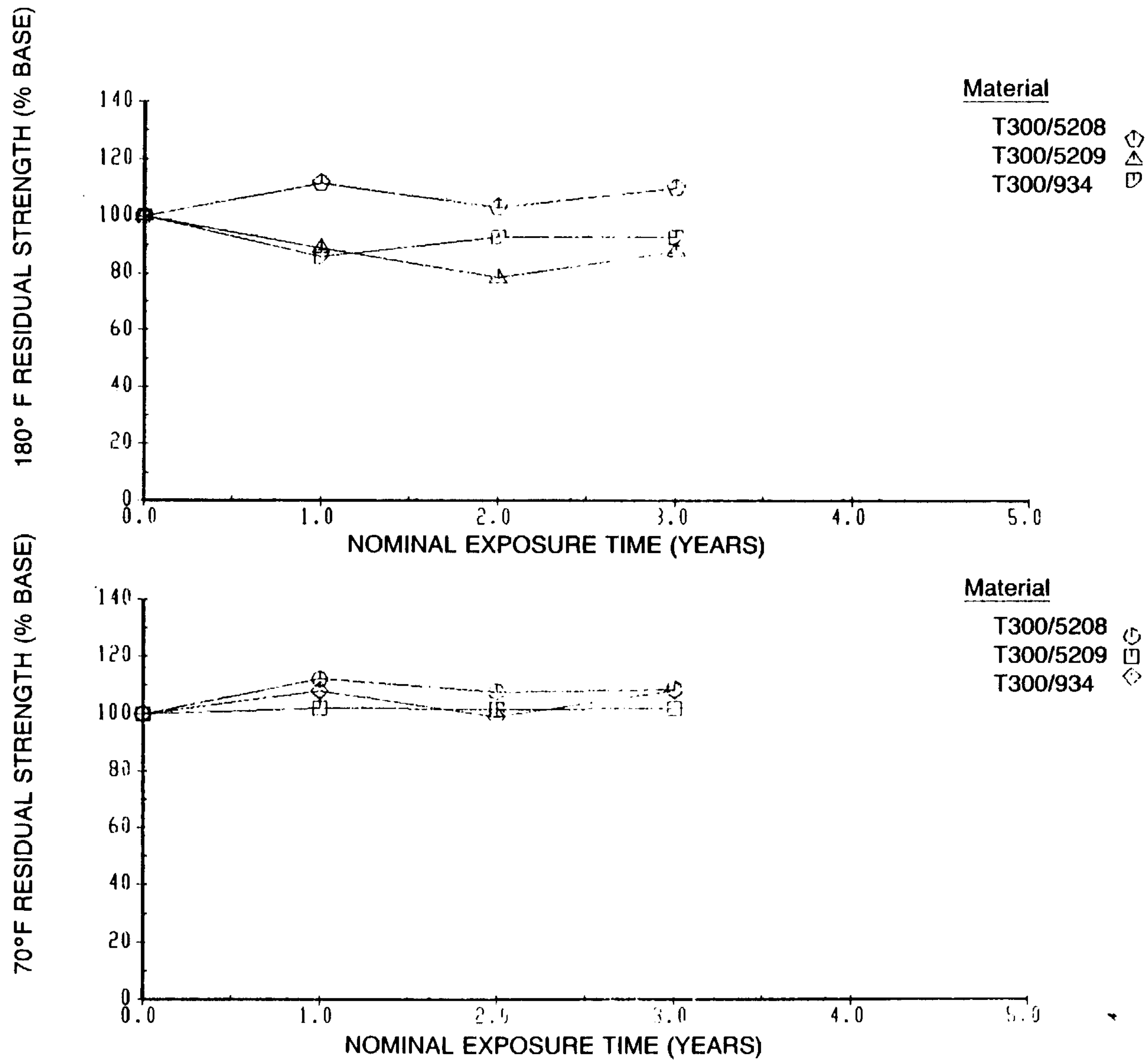

Figure 3-5. Flexure Strength Results for Nonsolar Ground Exposure at Dallas, TX

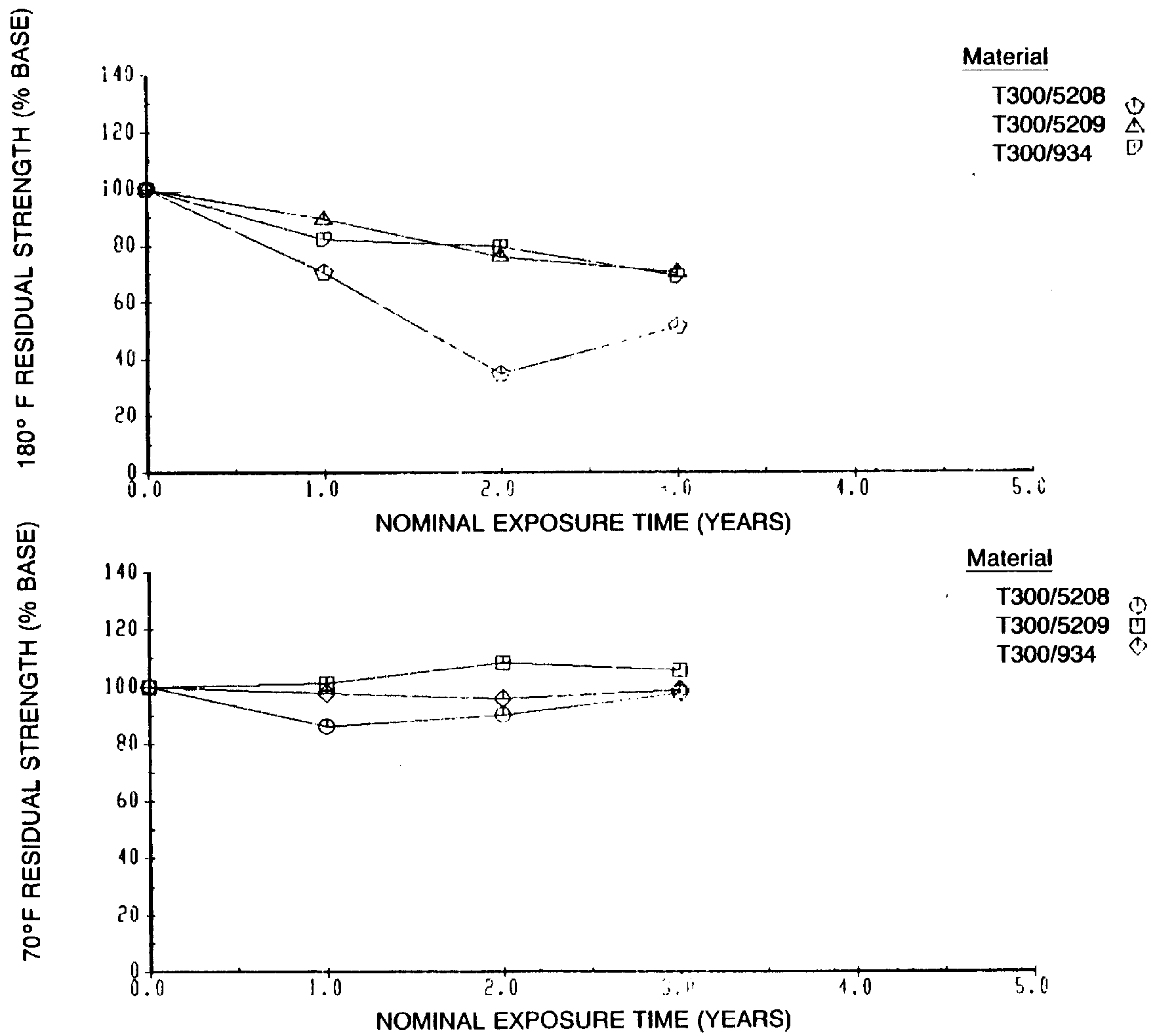

Figure 3-6. 0-deg Compression Strength Results for Nonsolar Ground Exposure at Dallas, TX

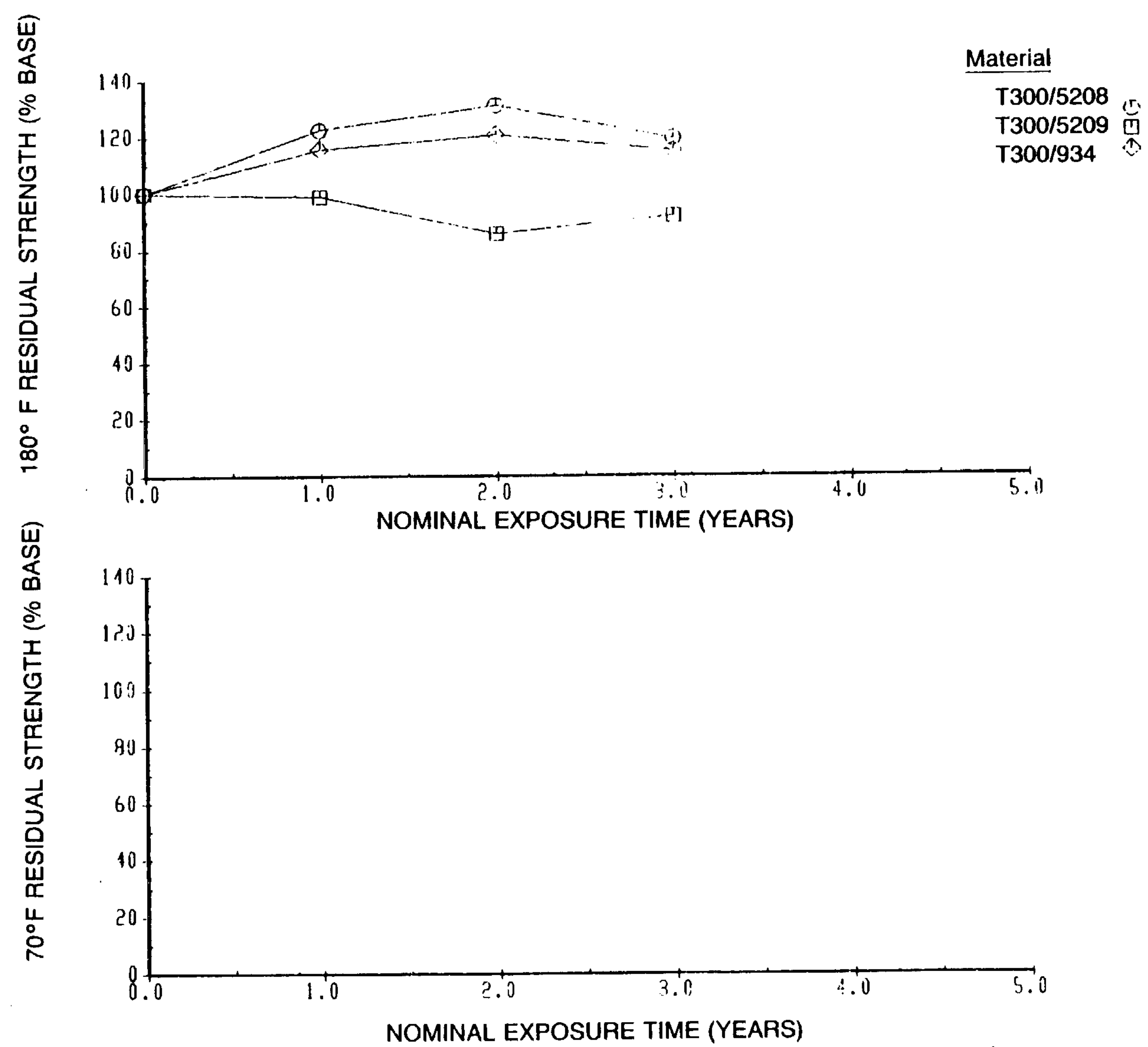

Figure 3-7. Stressed Tension Strength Results for Nonsolar Ground Exposure at Dallas, TX

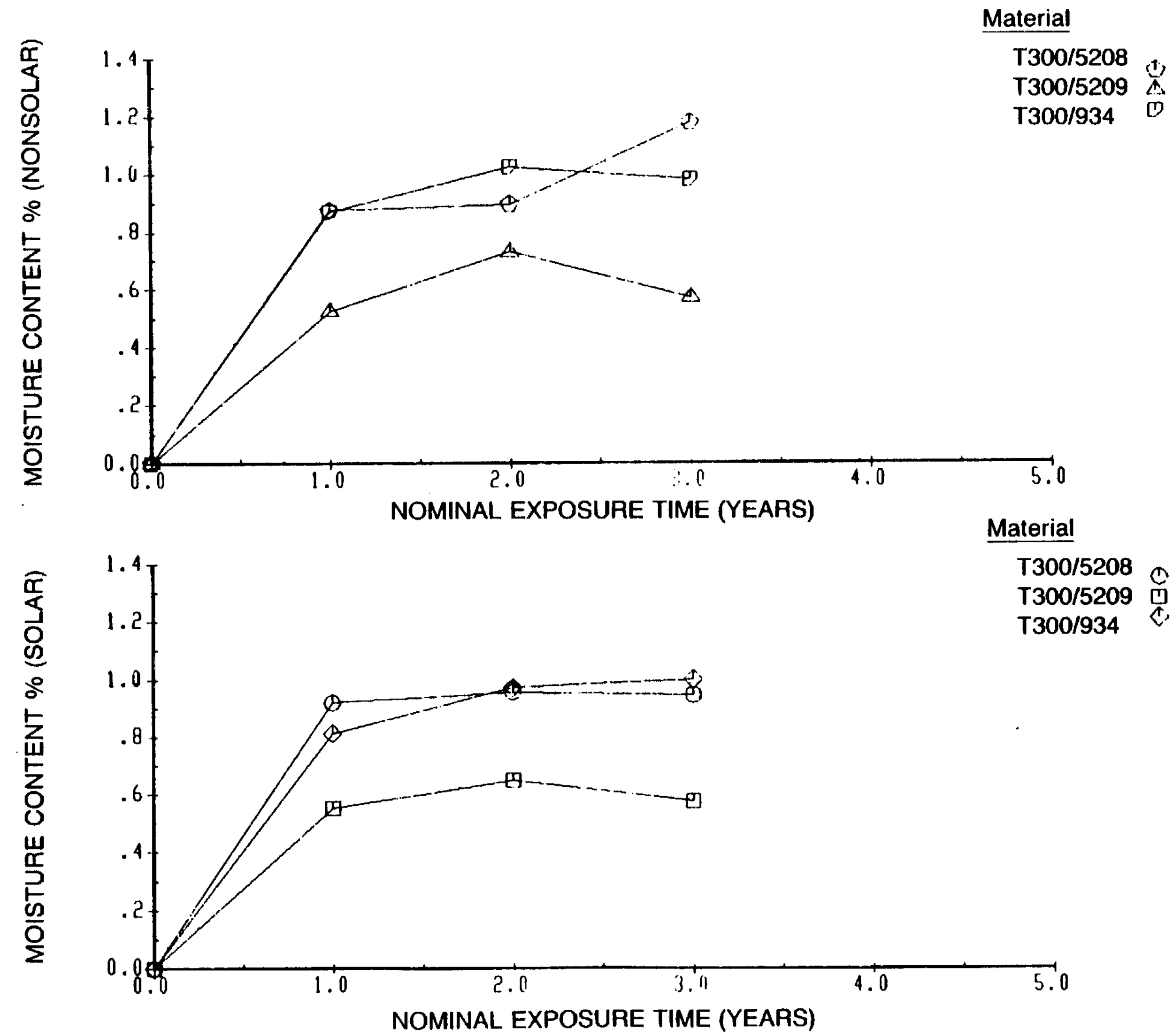

Figure 3-8. Moisture Content Results for Solar and Nonsolar Ground Exposure at Dallas, TX

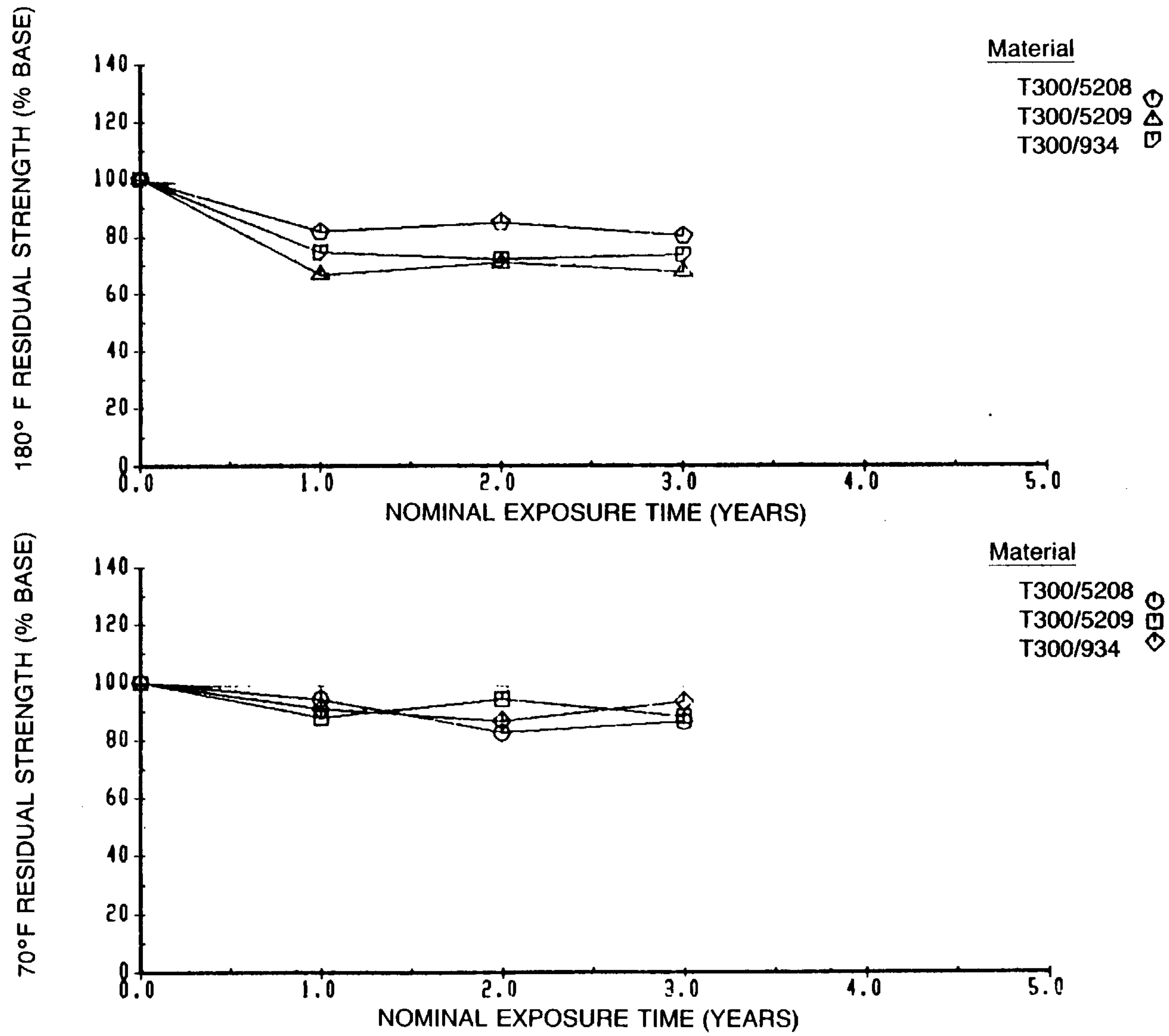

Figure 3-9. Short Beam Shear Strength Results for Solar Ground Exposure at Wellington, N.Z.

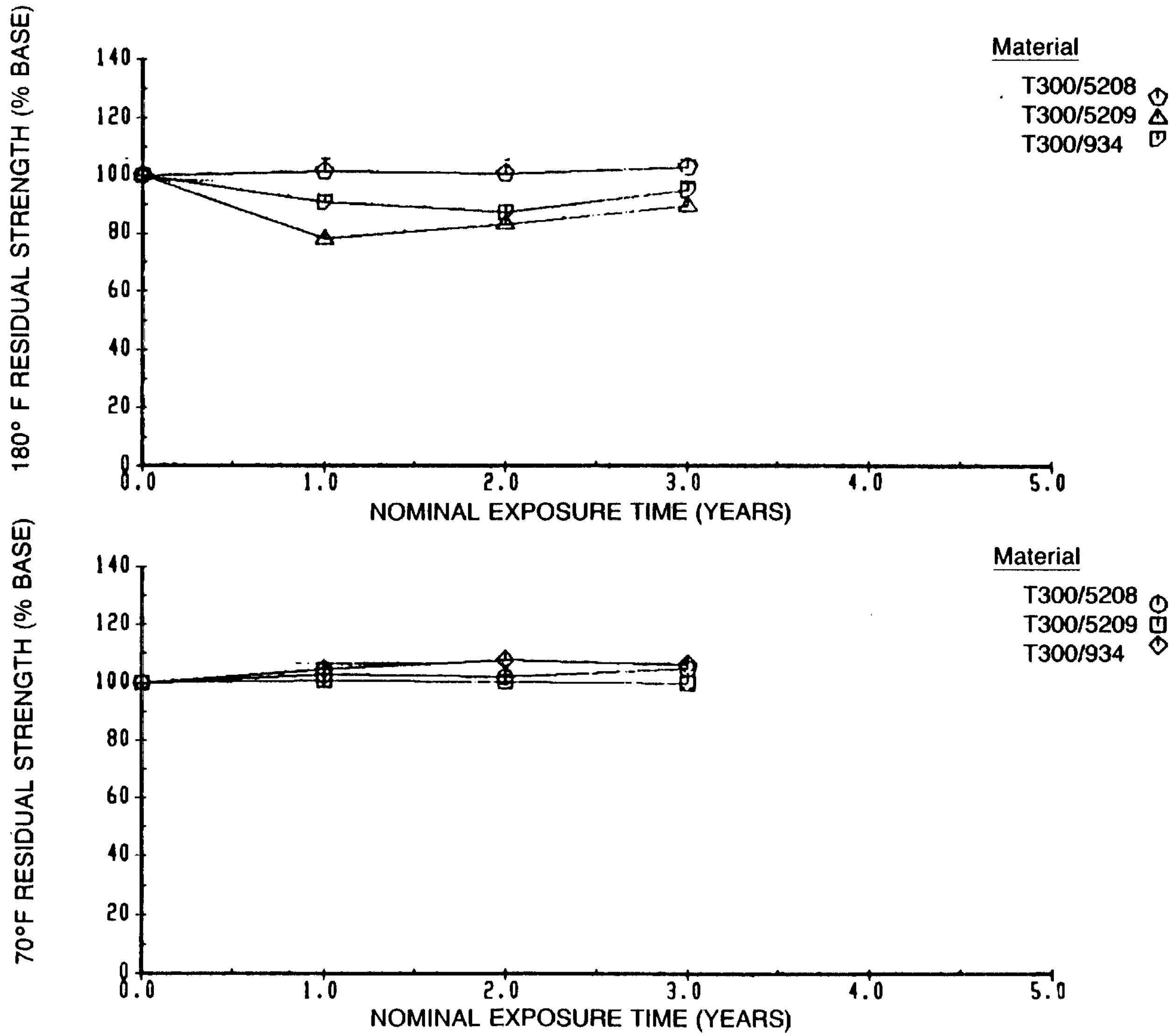

Figure 3-10. Flexure Strength Results for Solar Ground Exposure at Wellington, N.Z.

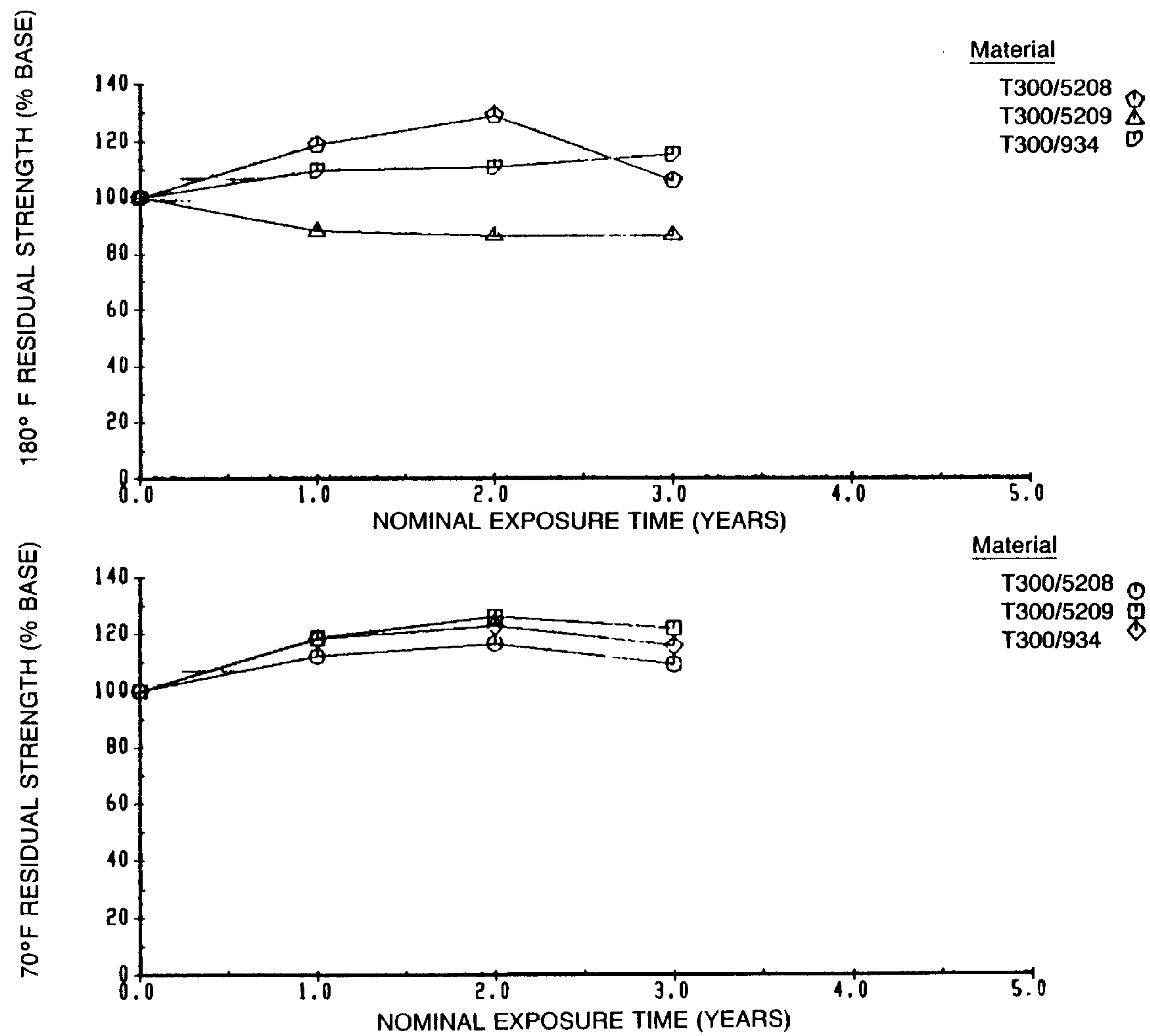

Figure 3-11. ±45-deg Tension Strength Results for Solar Ground Exposure at Wellington, N.Z.

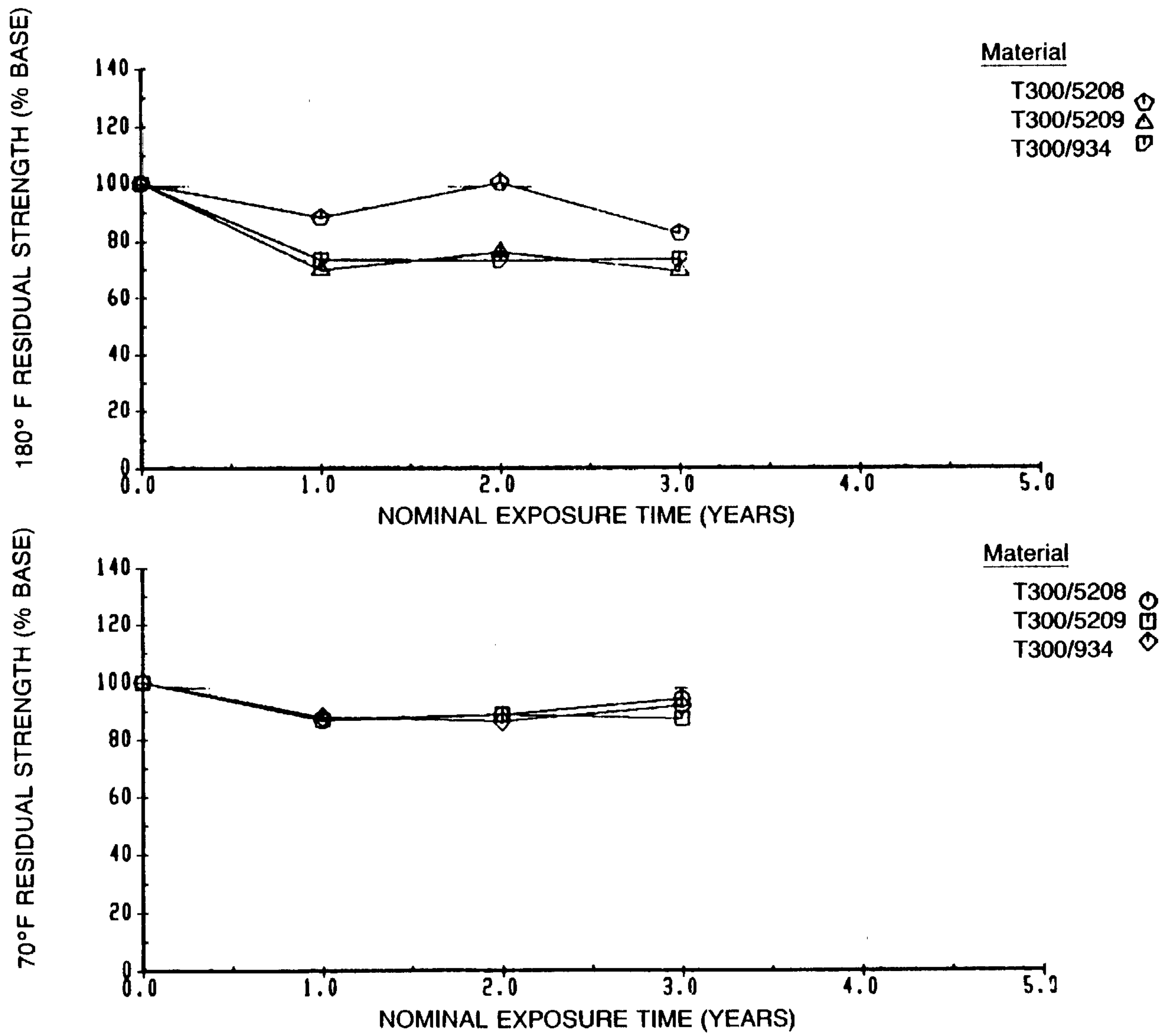

Figure 3-12. Short Beam Shear Strength Results for Nonsolar Ground Exposure at Wellington, N.Z.

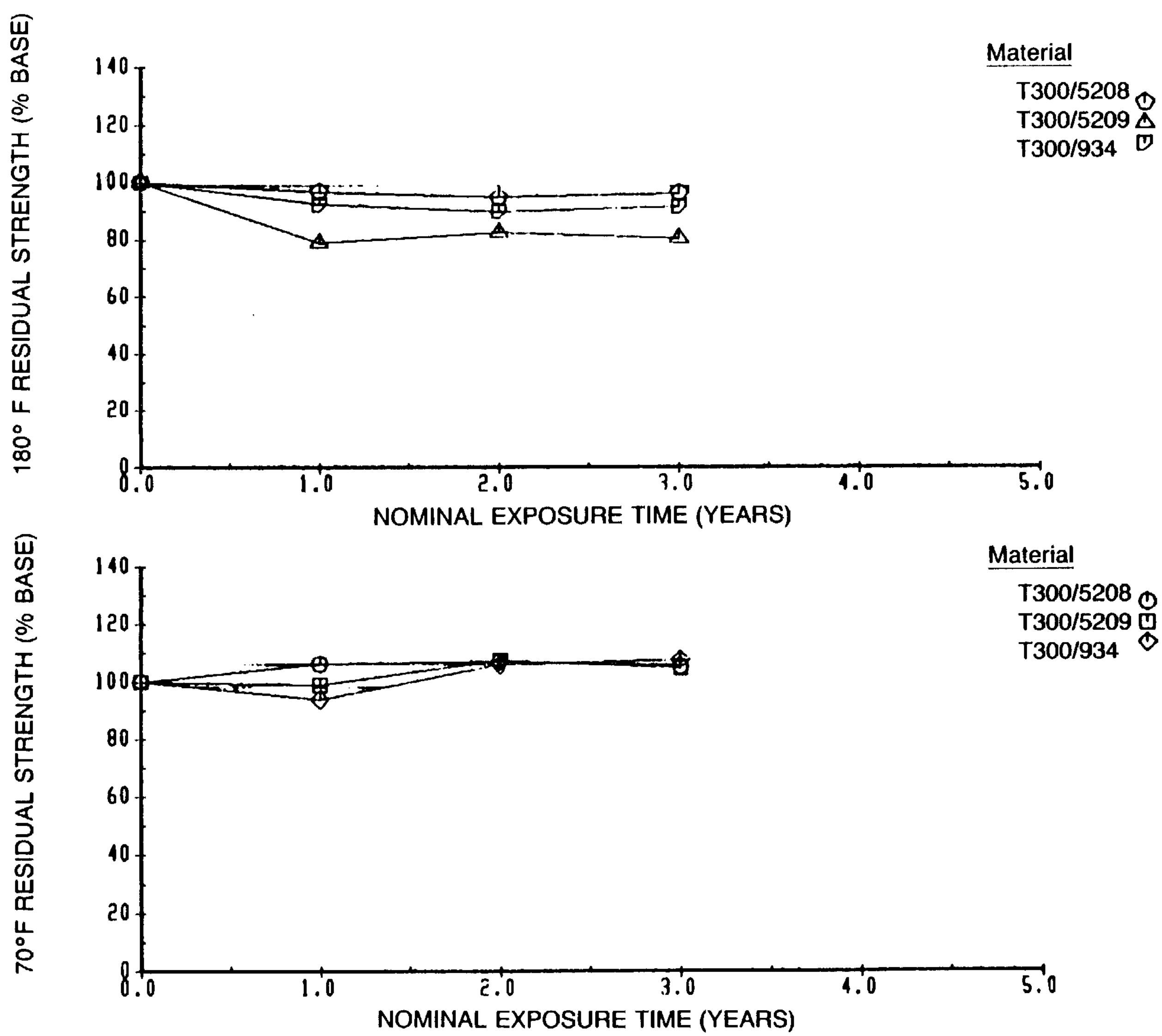

Figure 3-13. Flexure Strength Results for Nonsolar Ground Exposure at Wellington, N.Z.

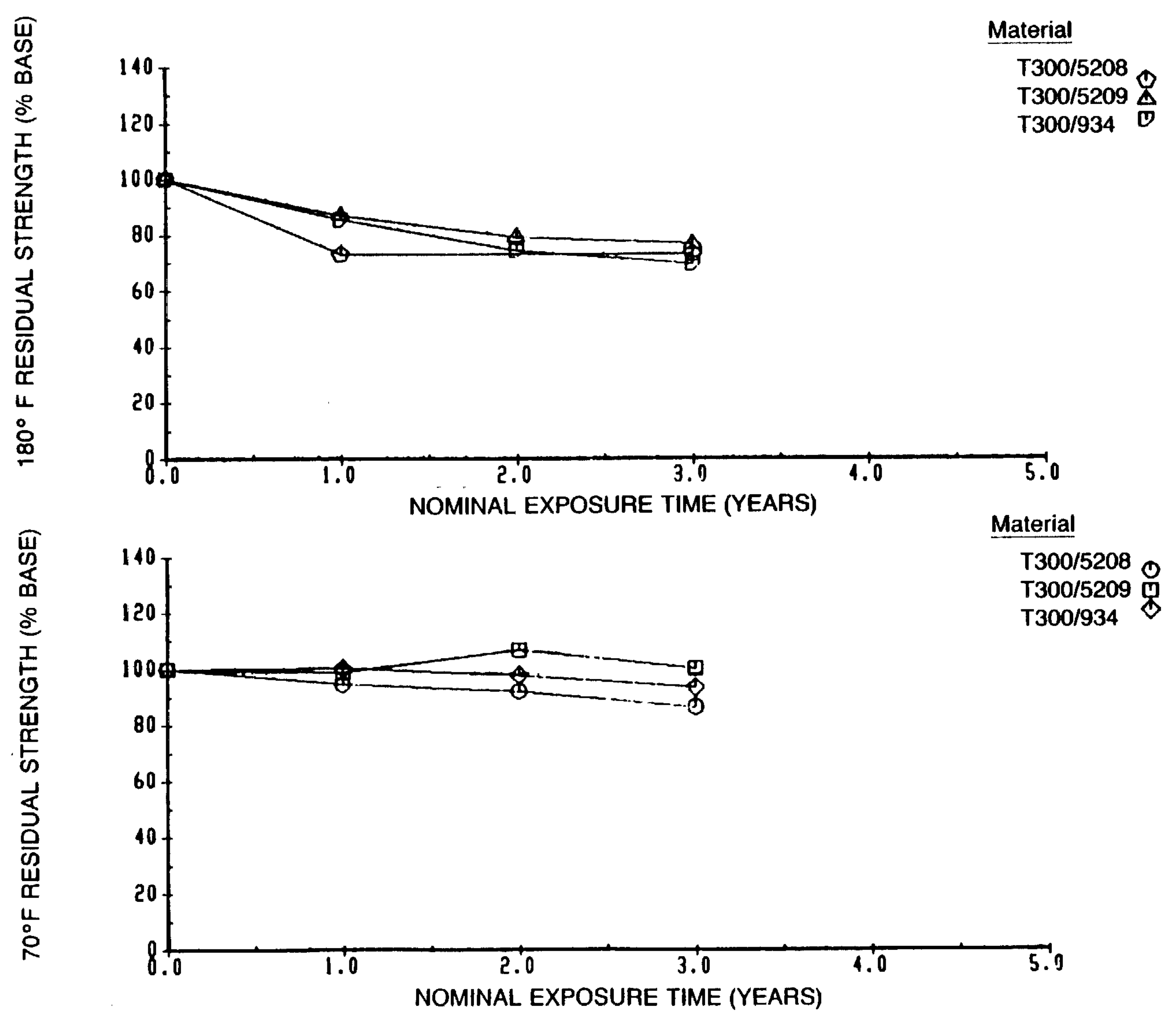

Figure 3-14. 0-deg Compression Strength Results for Nonsolar Ground Exposure at Wellington, N.Z.

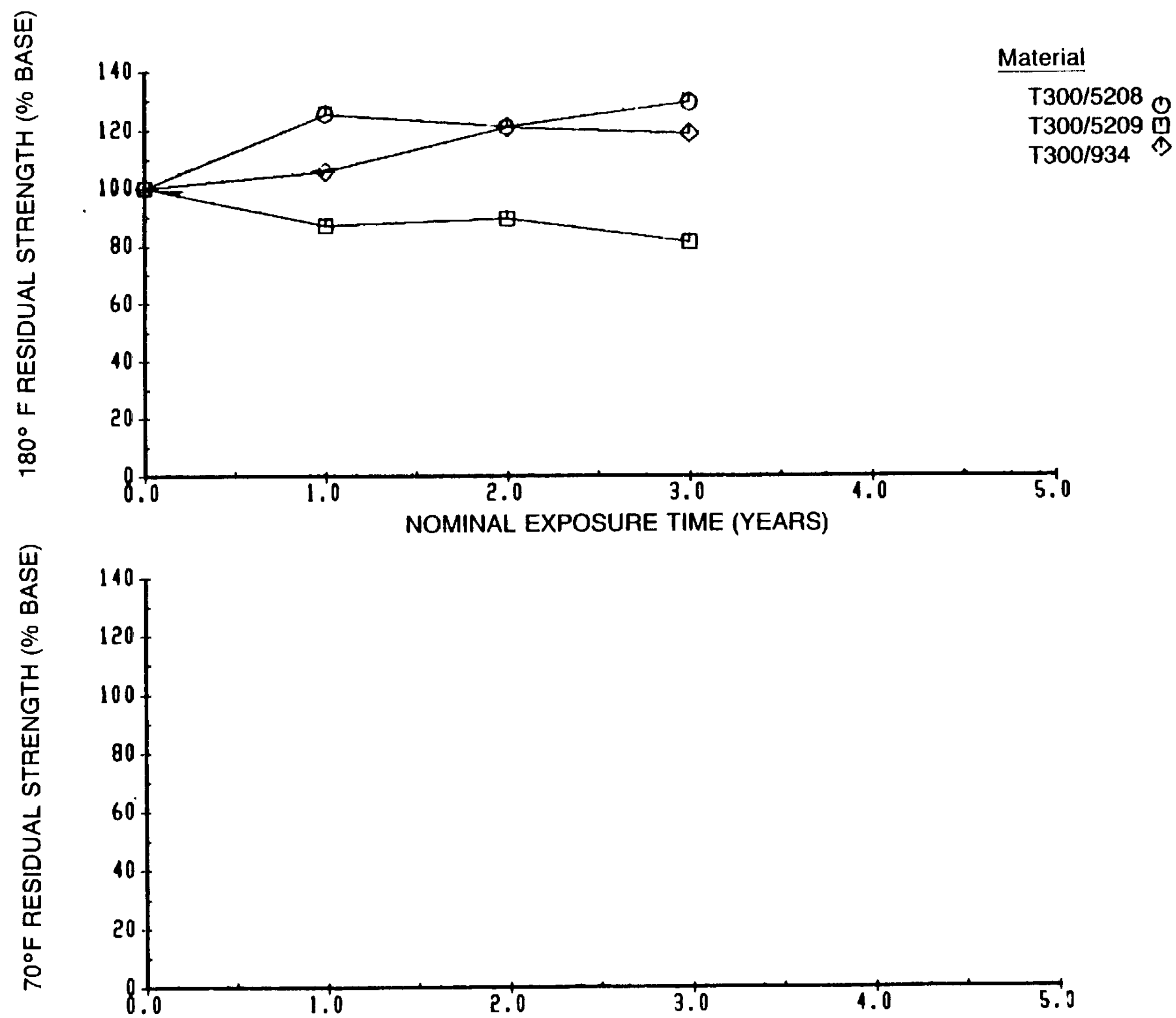

Figure 3-15. Stressed Tension Strength Results for Nonsolar Ground Exposure at Wellington, N.Z.

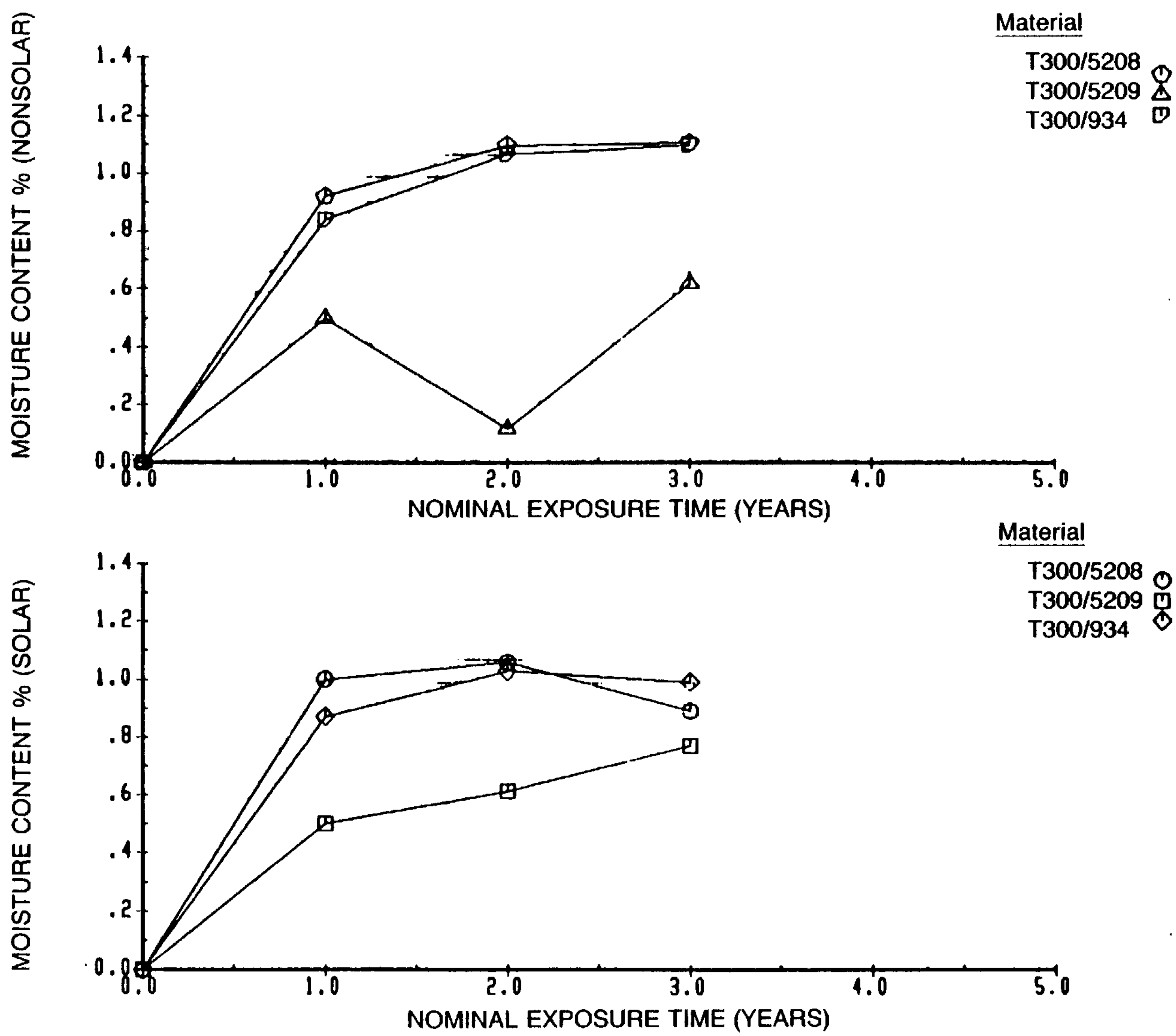

Figure 3-16. Moisture Content Results for Solar and Nonsolar Ground Exposure at Wellington, N.Z.

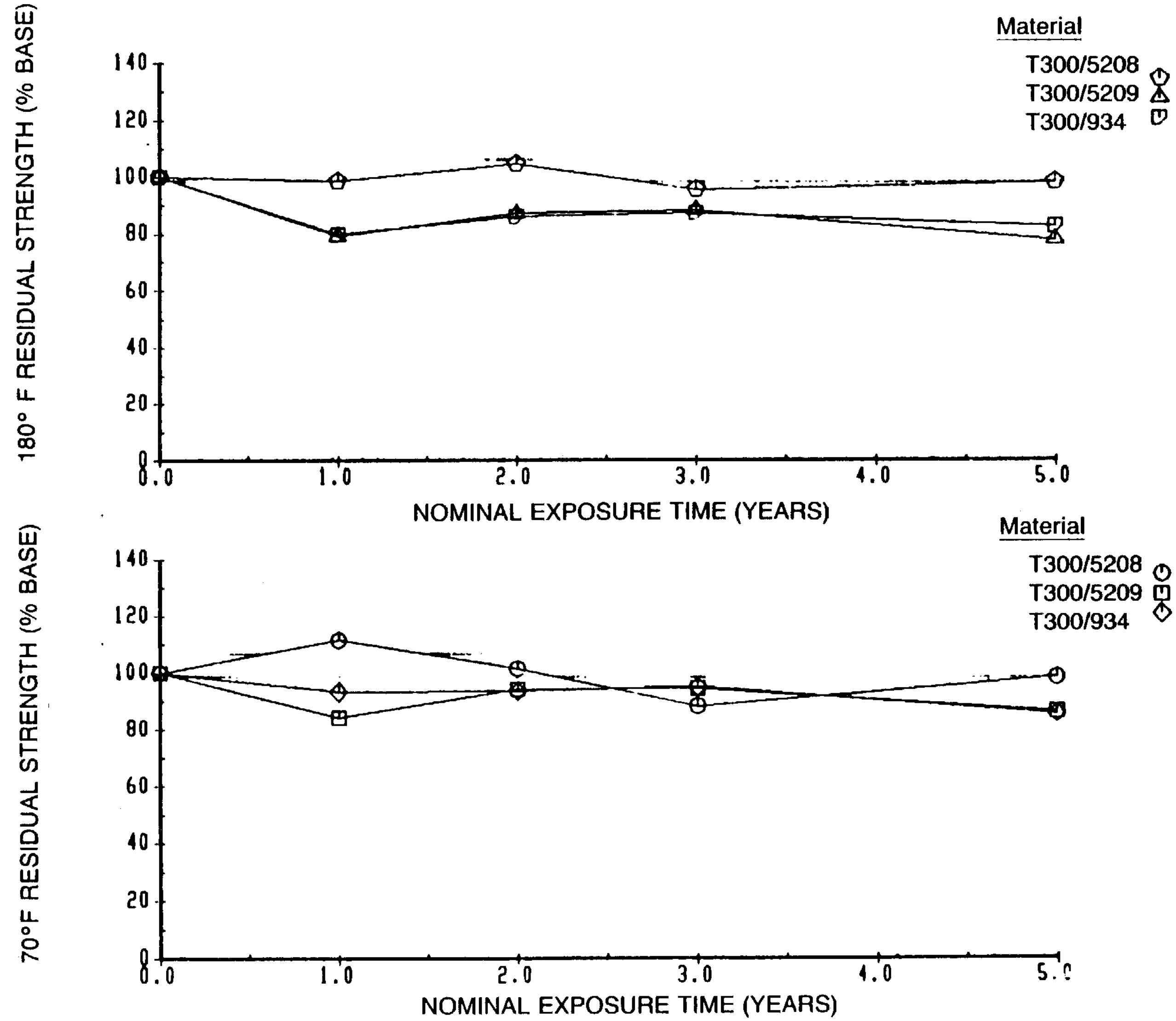

Figure 3-17. Short Beam Shear Strength Results for Solar Ground Exposure at Edwards AFB, CA

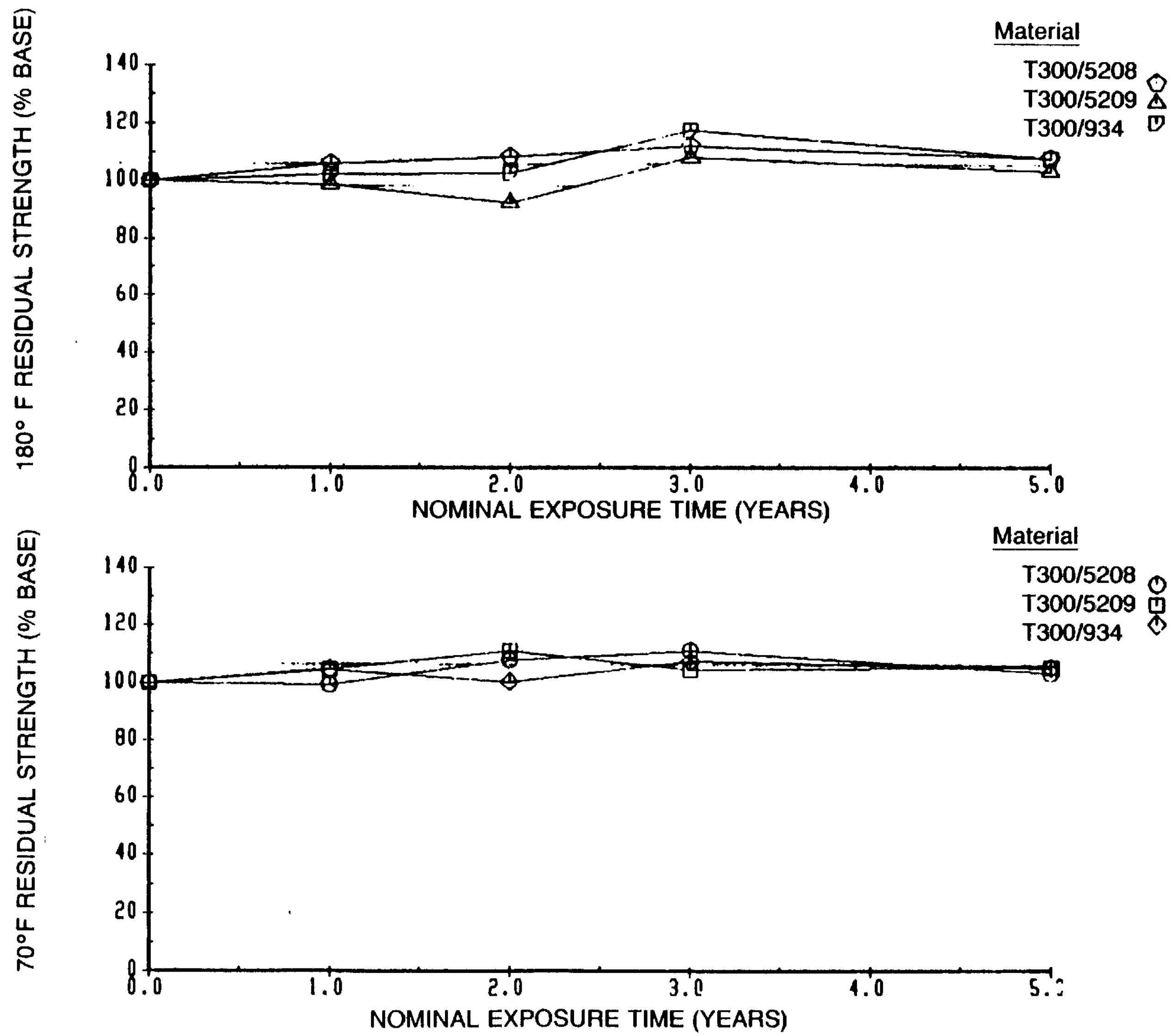

Figure 3-18. Flexure Strength Results for Solar Ground Exposure at Edwards AFB, CA

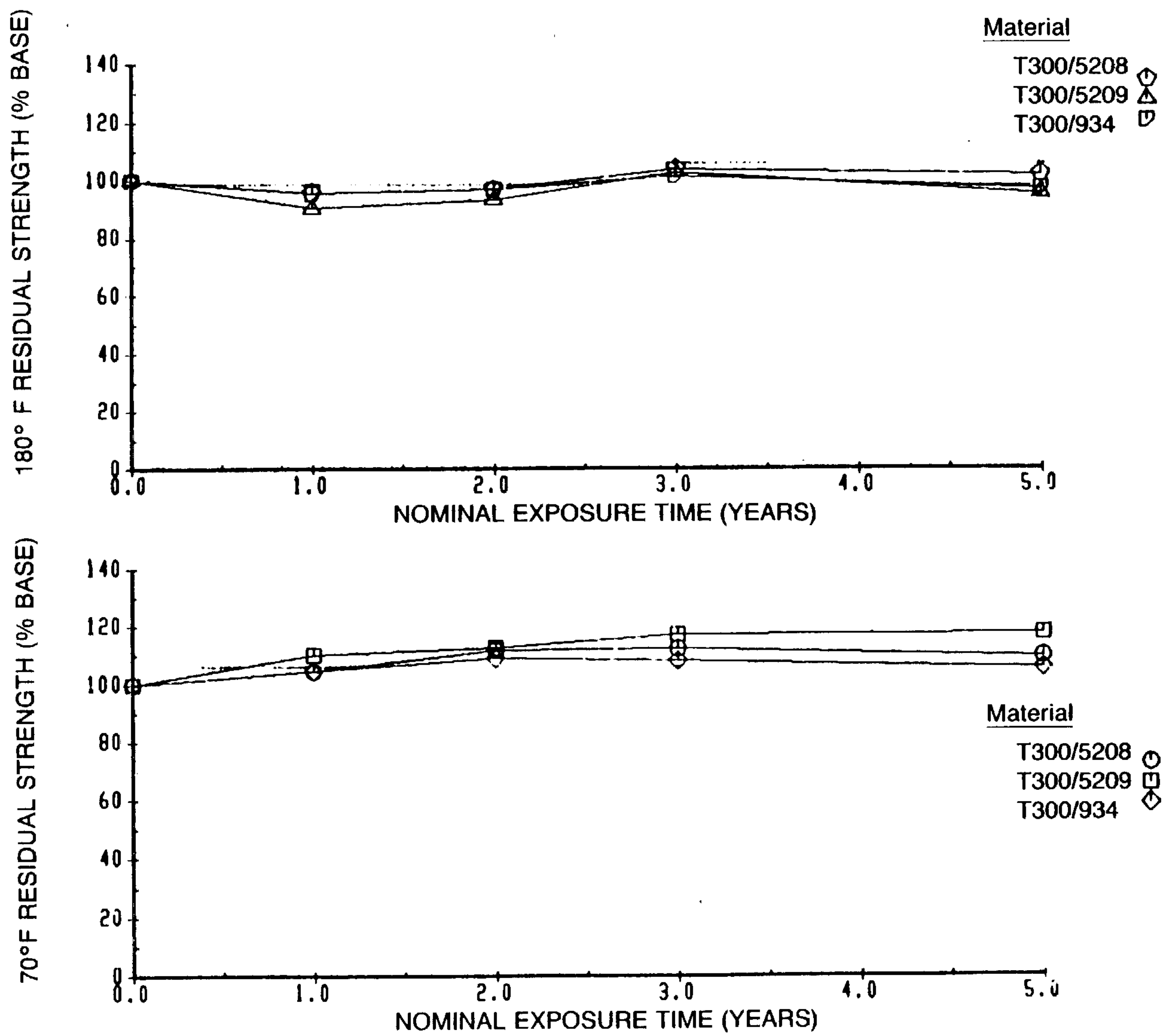

Figure 3-19. ± 45-deg Tension Strength Results for Solar Ground Exposure at Edwards AFB, CA

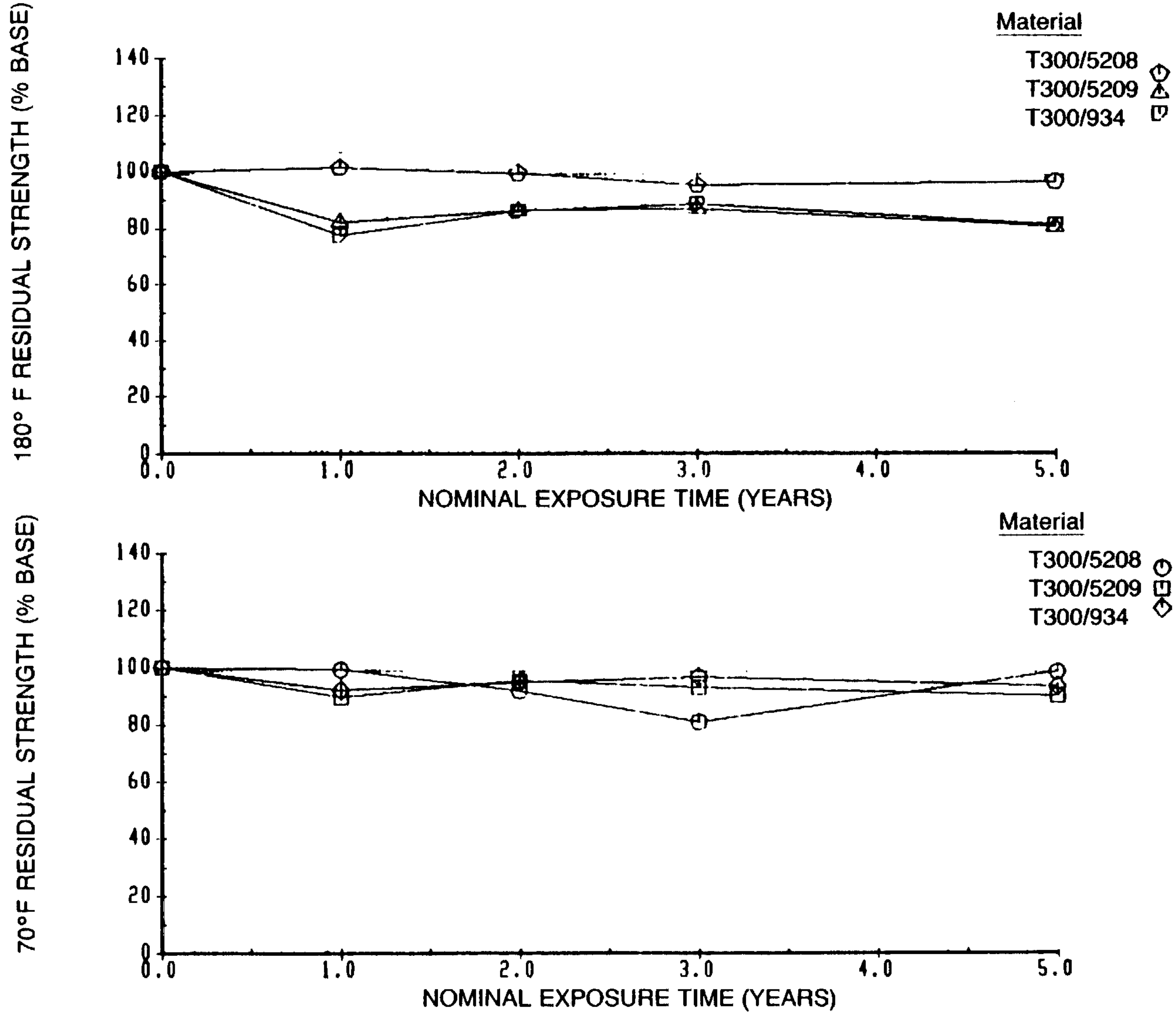

Figure 3-20. Short Beam Shear Strength Results for Nonsolar Ground Exposure at Edwards AFB, CA

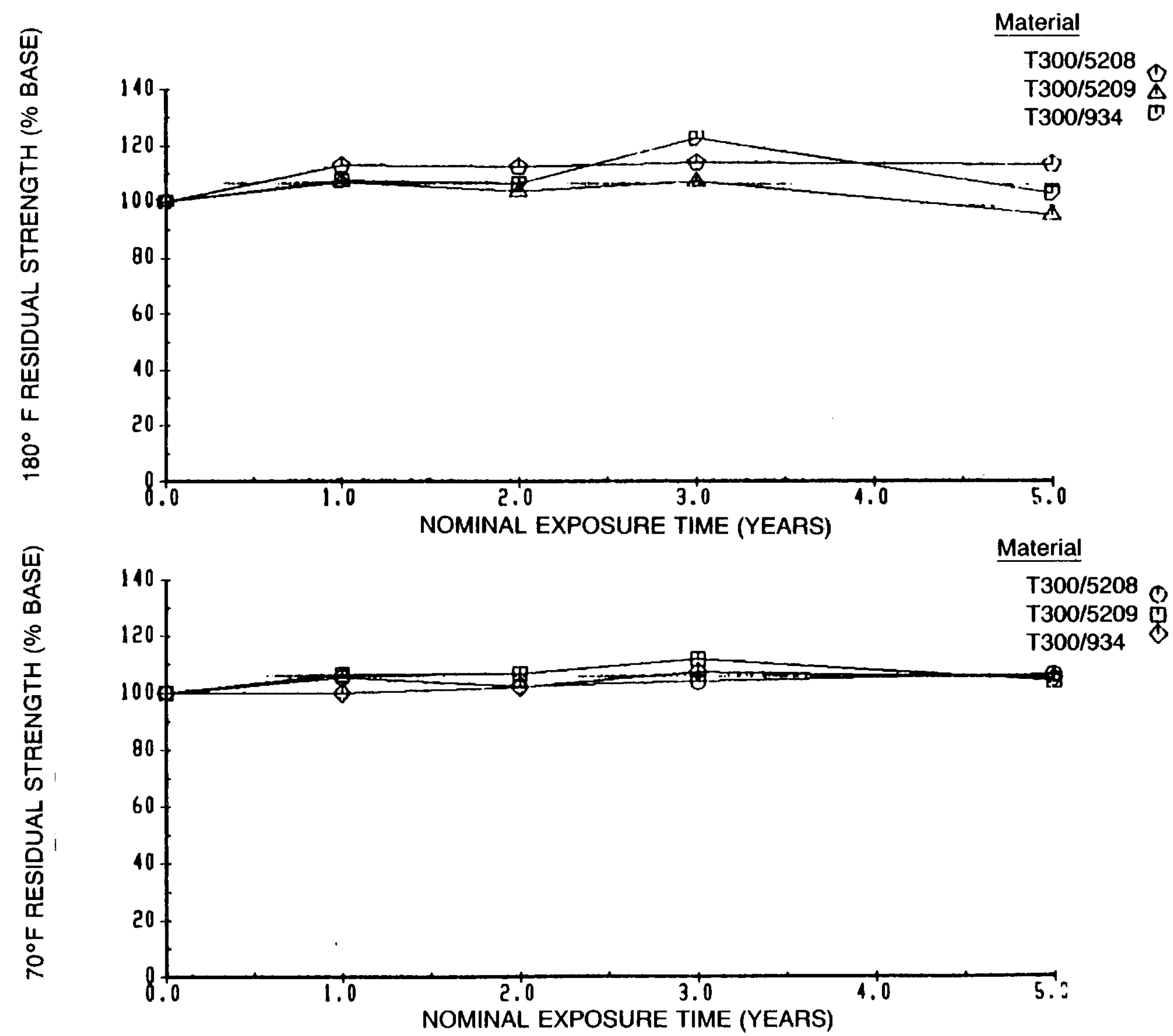

Figure 3-21. Flexure Strength Results for Nonsolar Ground Exposure at Edwards AFB, CA

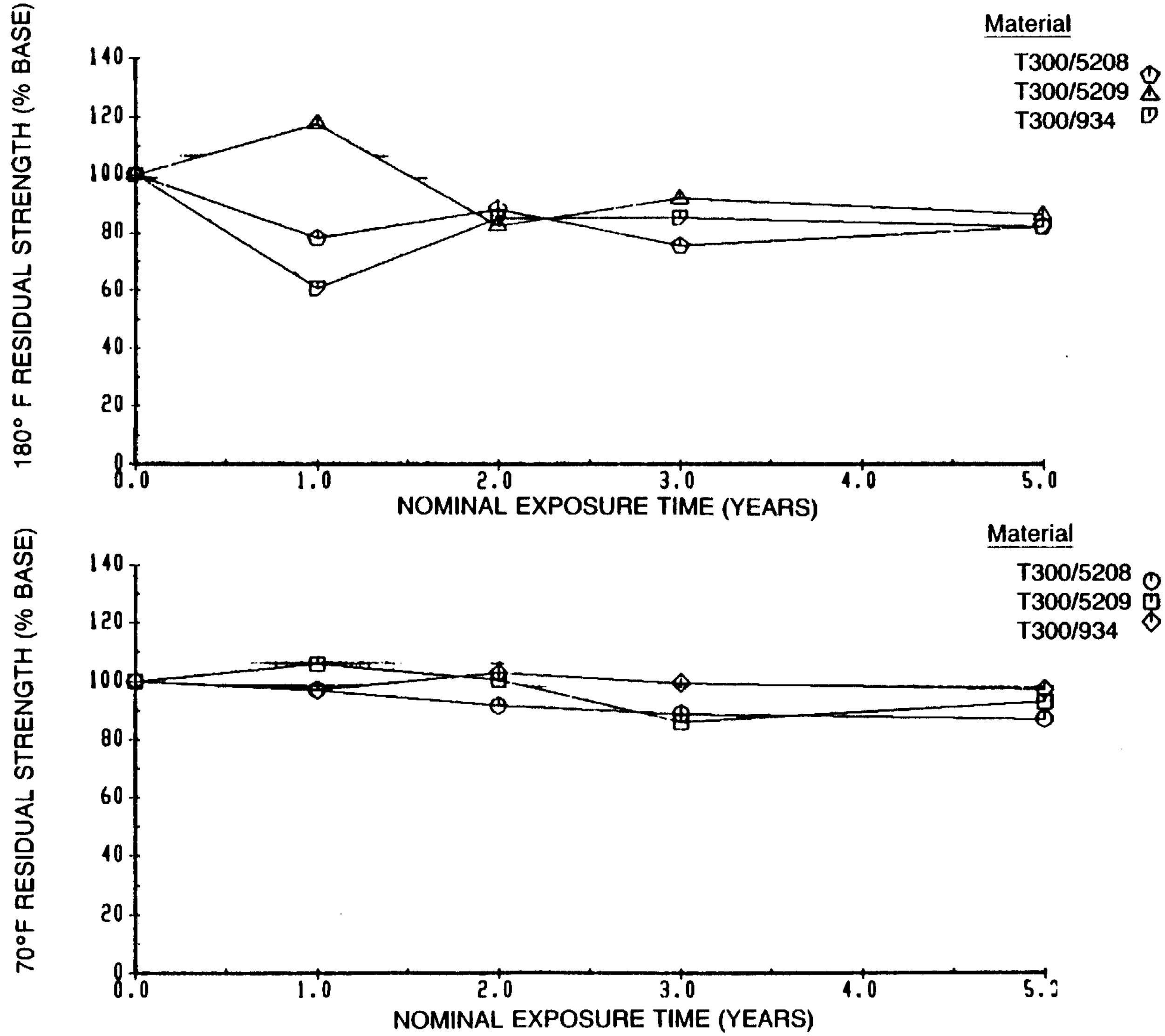

Figure 3-22. 0-deg Compression Strength Results for Nonsolar Ground Exposure at Edwards AFB, CA

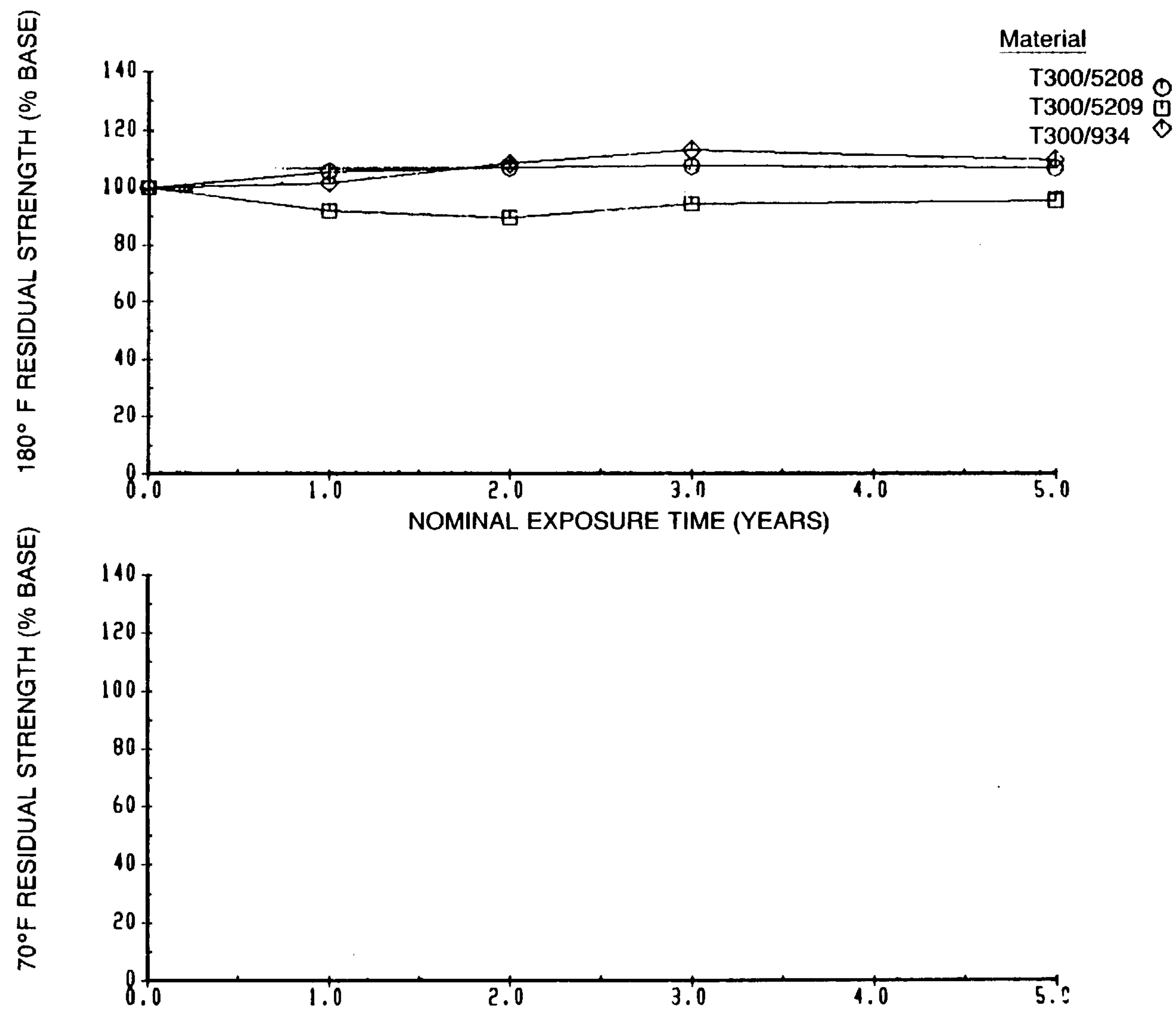

Figure 3-23. Stressed Tension Strength Results for Nonsolar Ground Exposure at Edwards AFB, CA

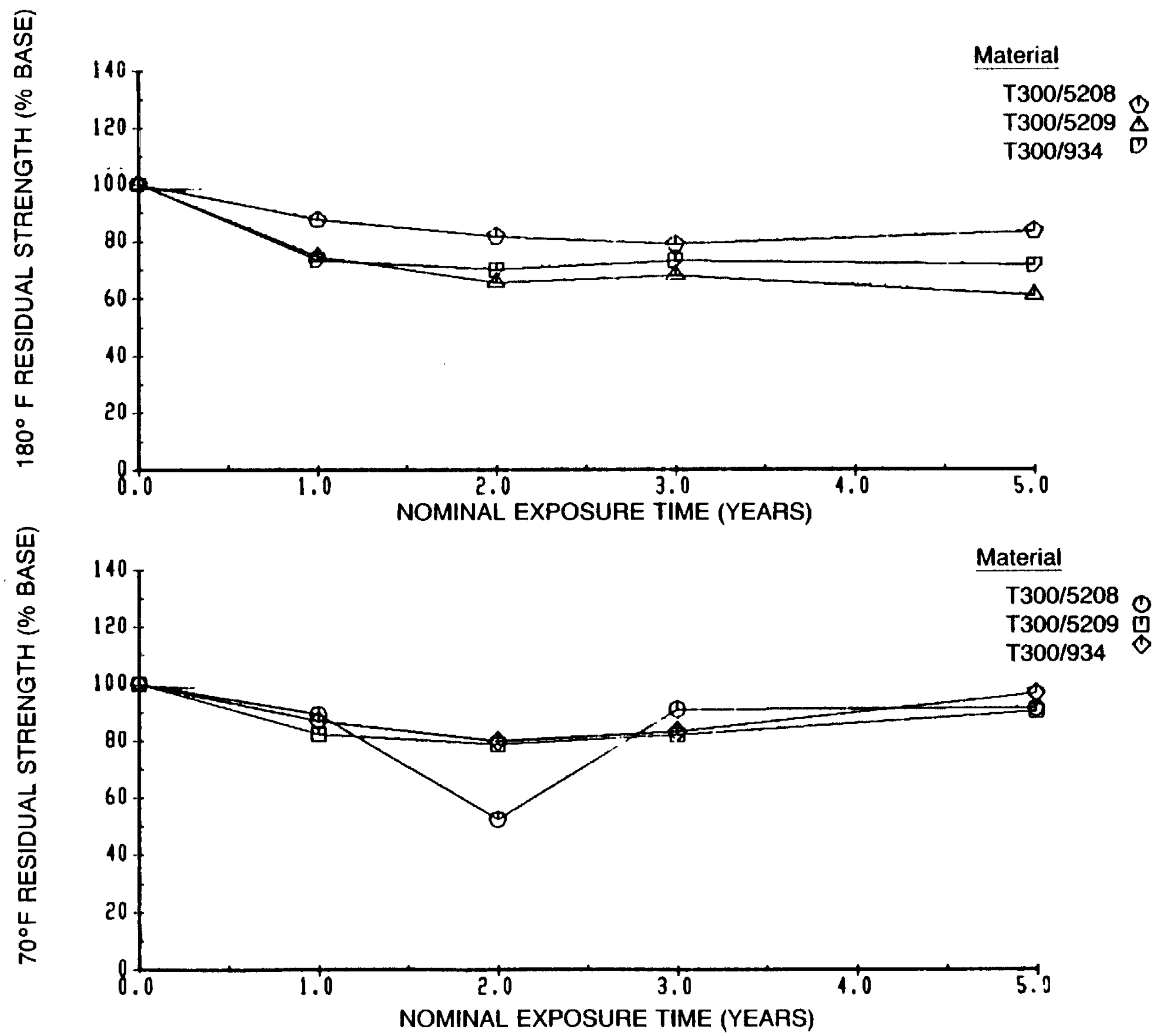

Figure 3-24. Short Beam Shear Strength Results for Solar Ground Exposure at Honolulu, HI

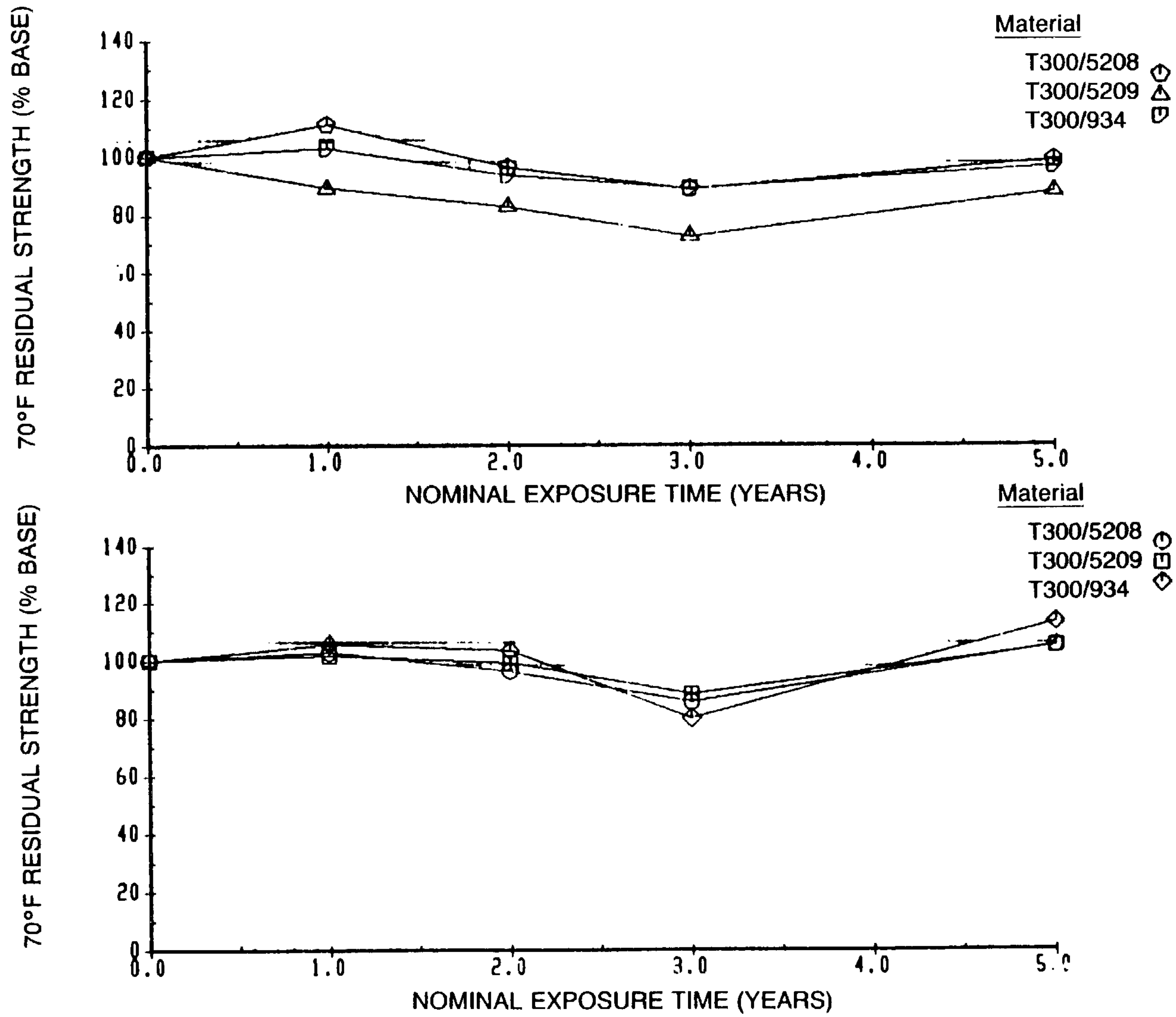

Figure 3-25. Flexure Strength Results for Solar Ground Exposure at Honolulu, HI

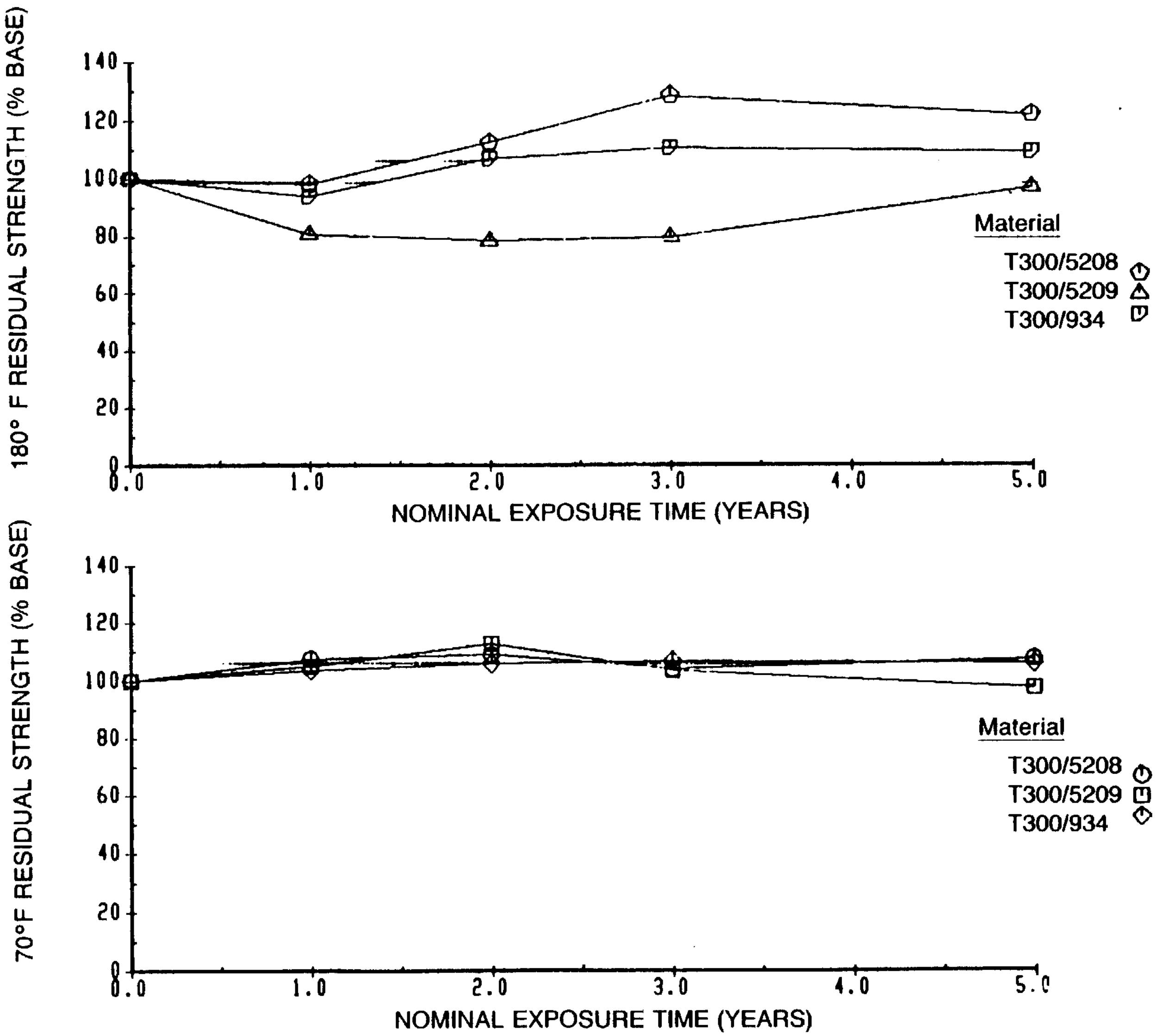

Figure 3-26. ±45-deg Tension Strength Results for Solar Ground Exposure at Honolulu, HI

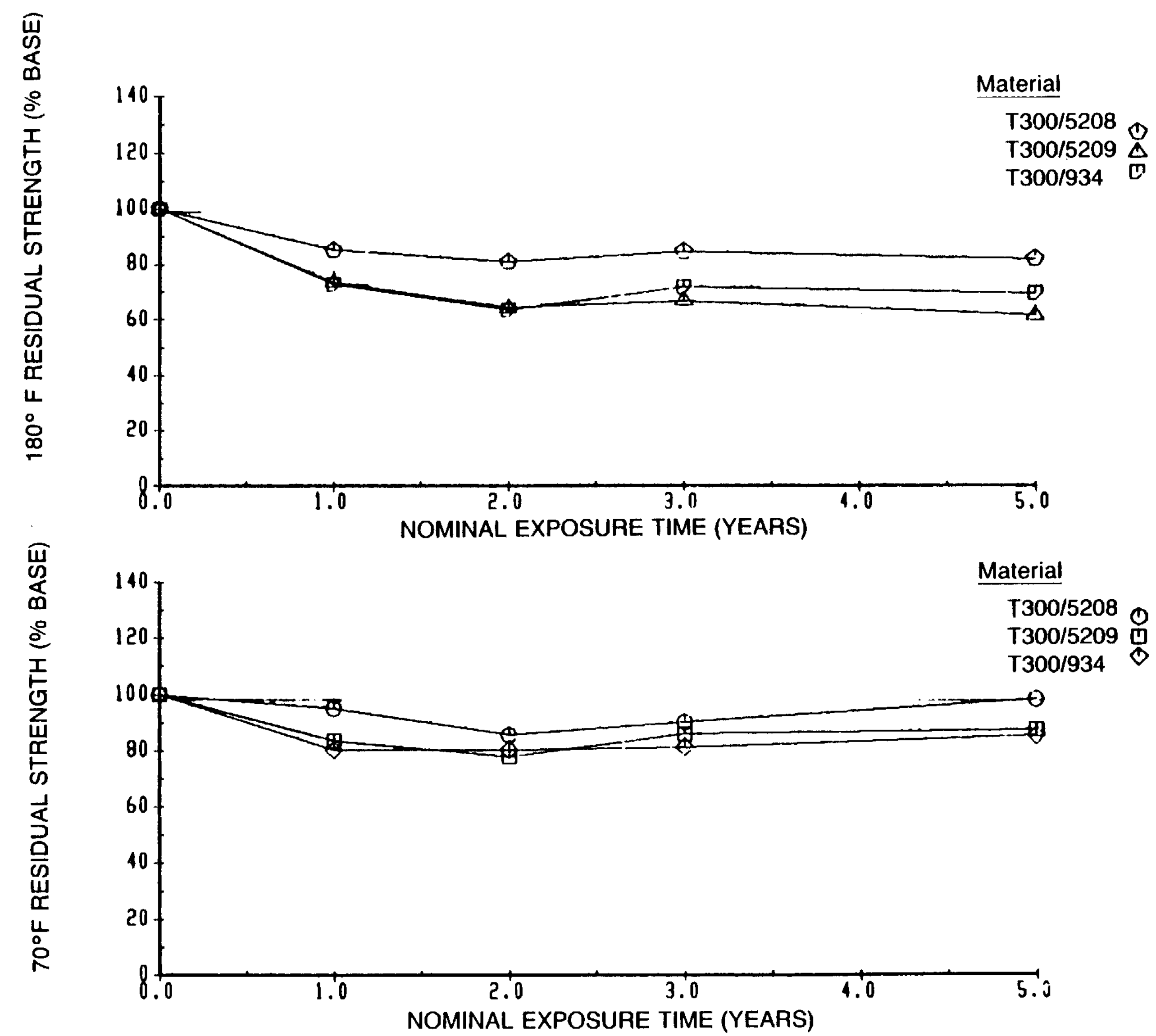

Figure 3-27. Short Beam Shear Strength Results for Nonsolar Ground Exposure at Honolulu, Hi

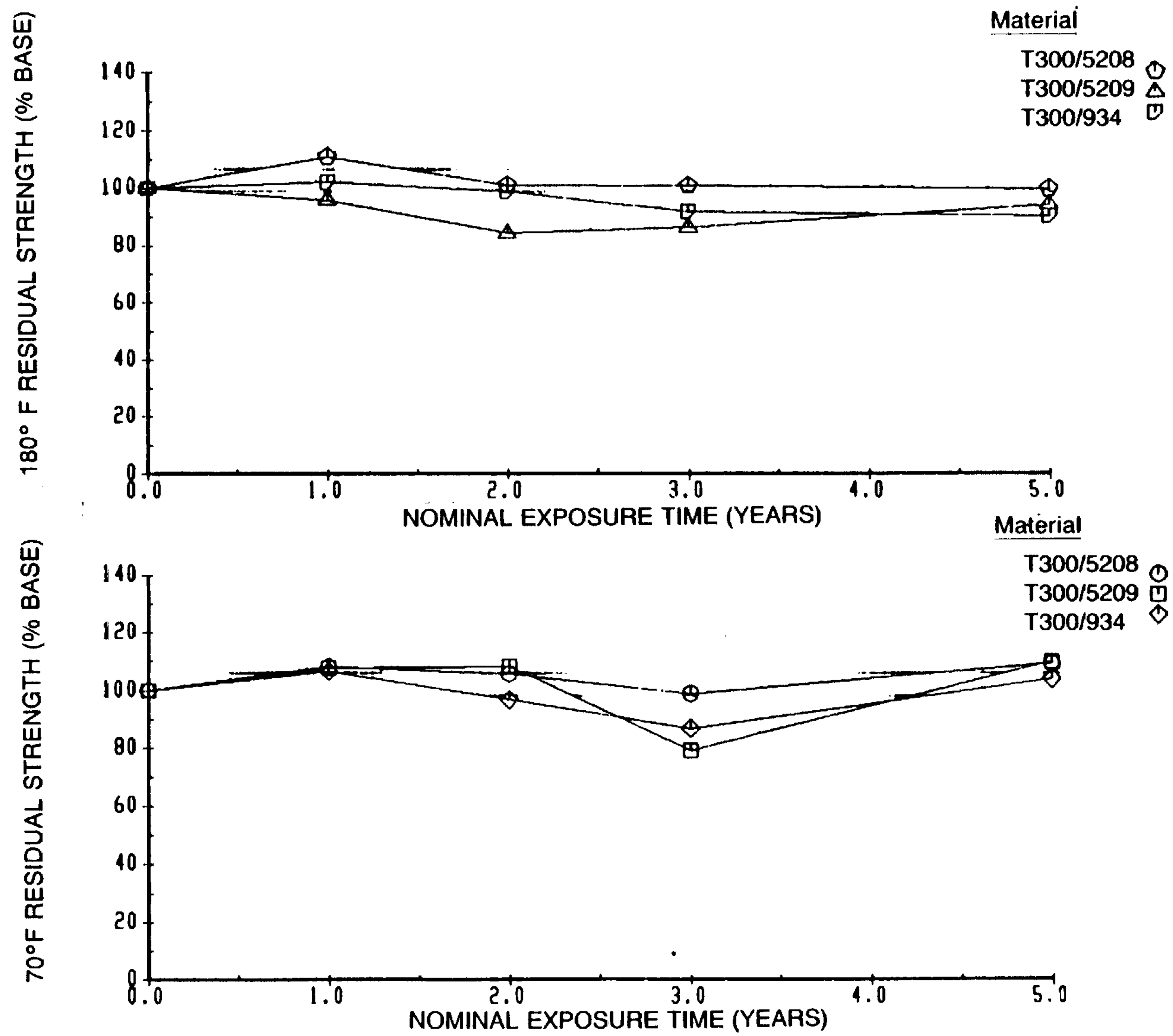

Figure 3-28. Flexure Strength Results for Nonsolar Ground Exposure at Honolulu, HI

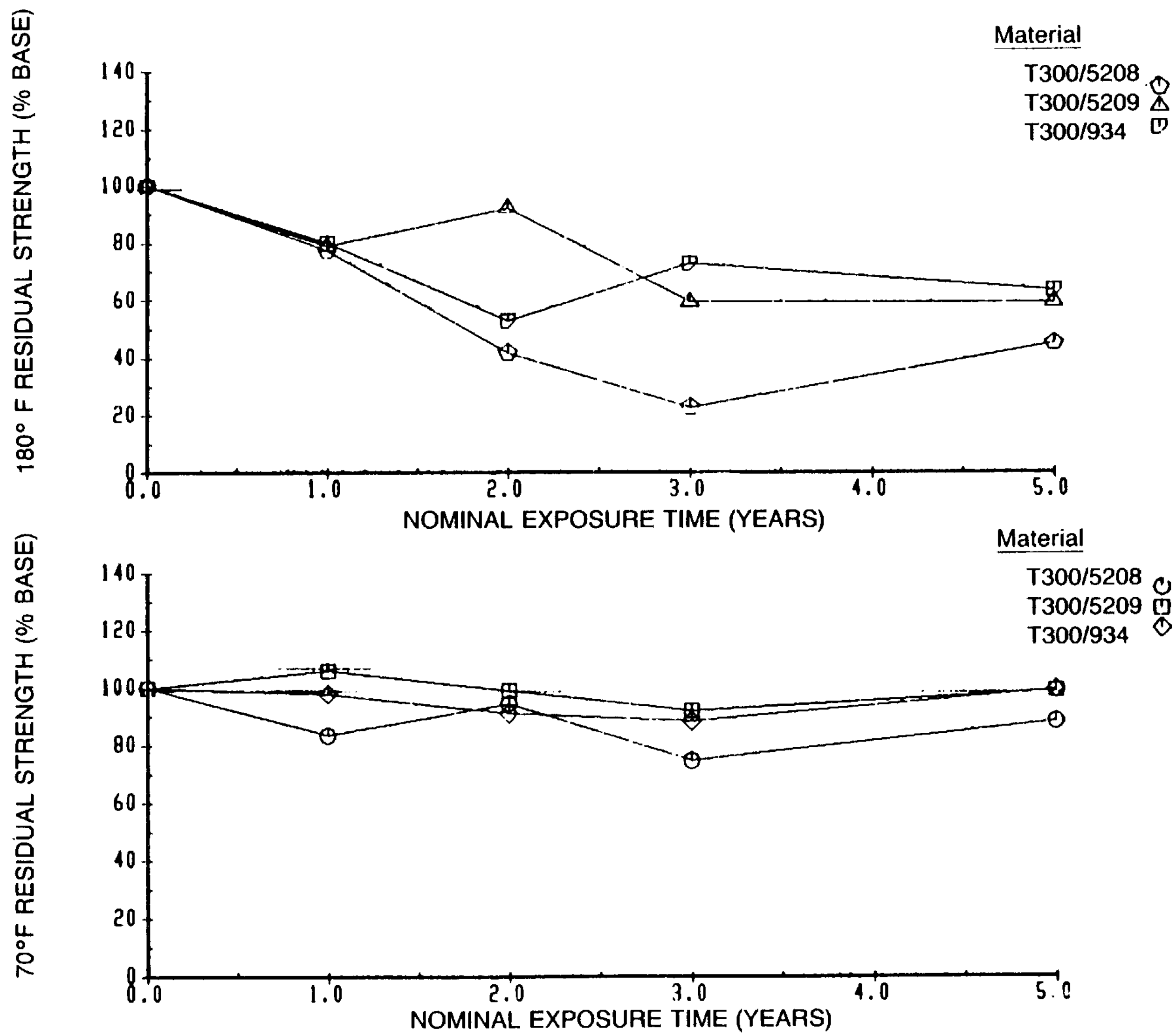

Figure 3-29. 0-deg Compression Strength Results for Nonsolar Ground Exposure at Honolulu, HI

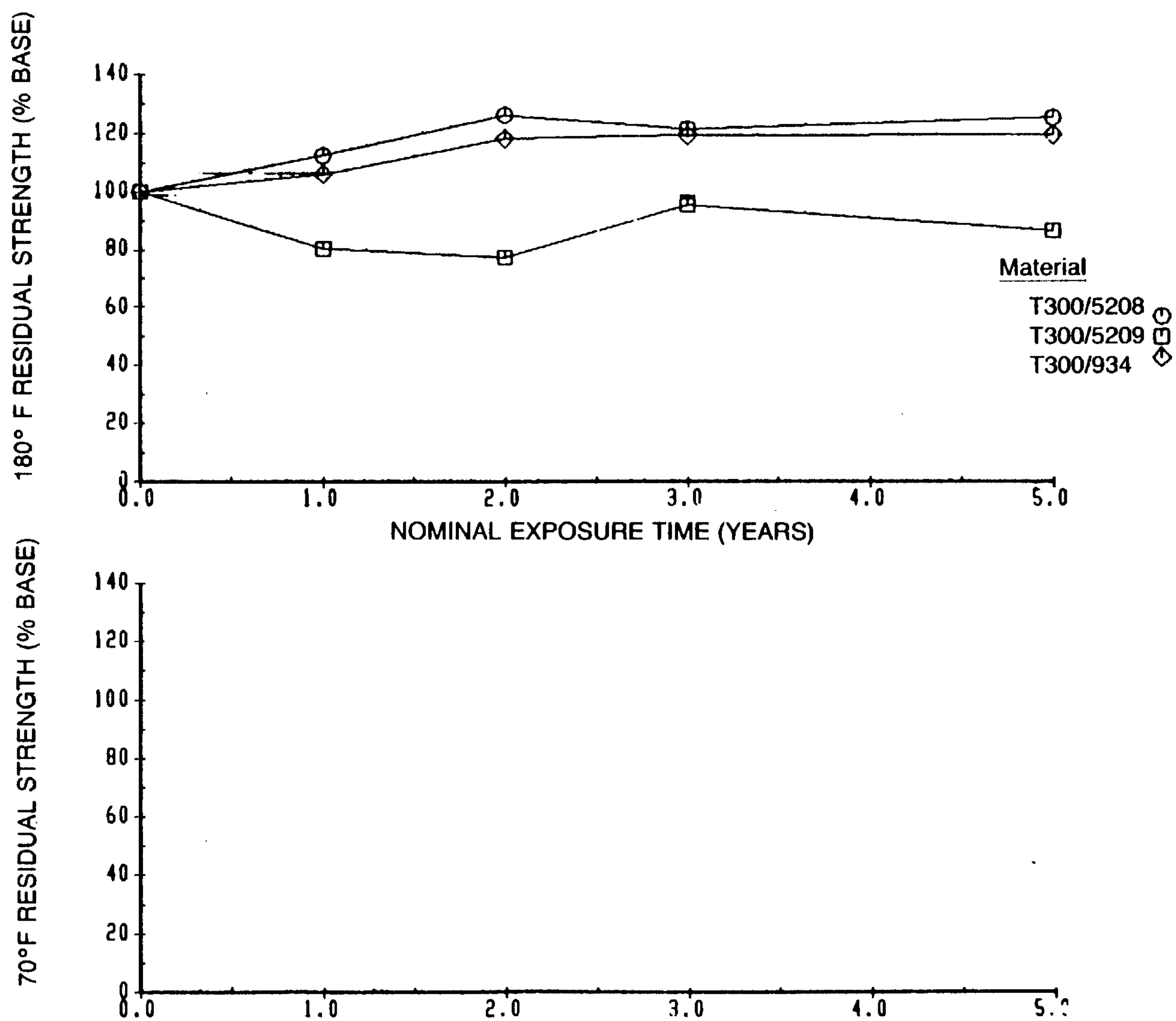

Figure 3-30. Stressed Tension Strength Results for Nonsolar Ground Exposure at Honolulu, HI

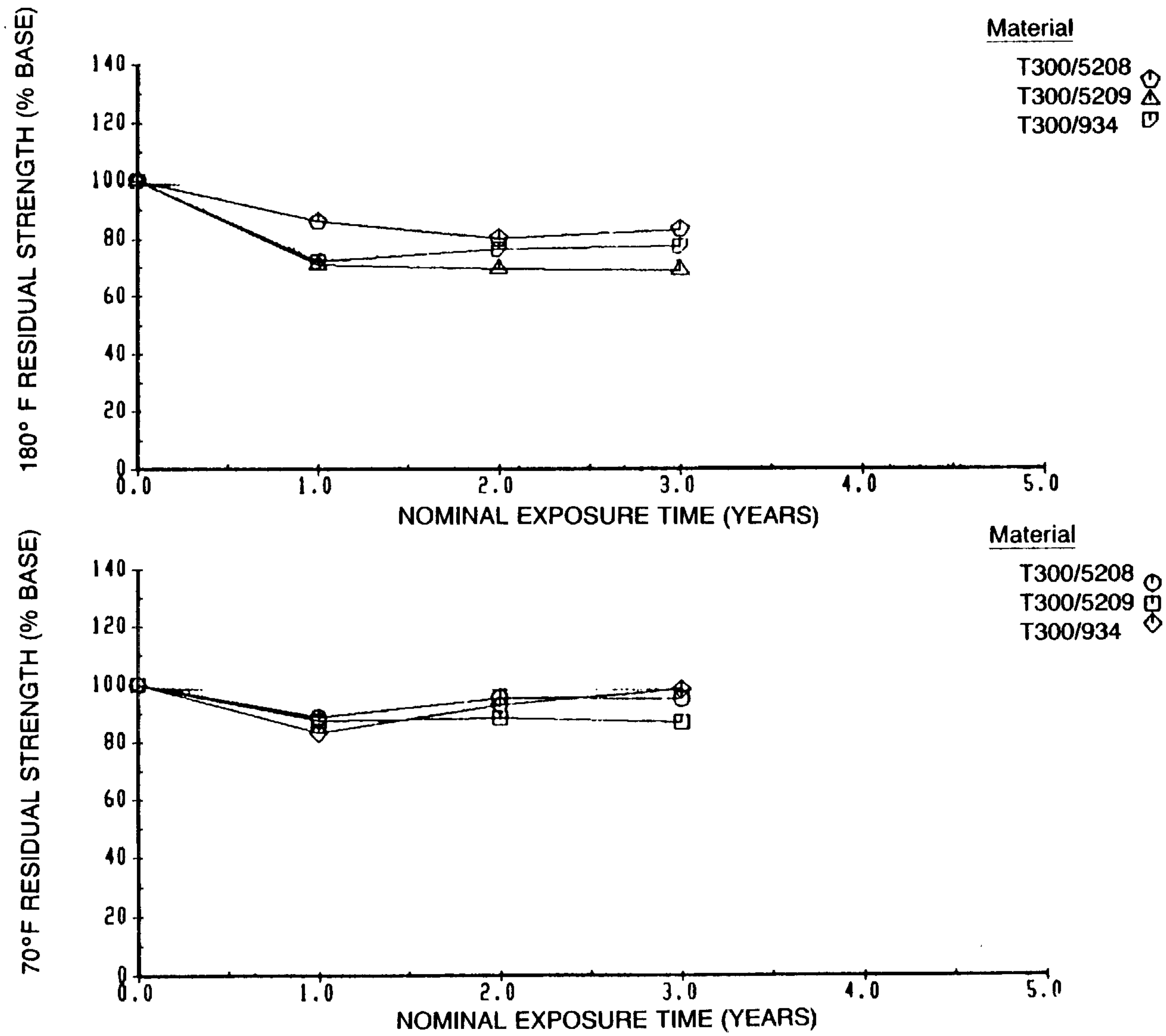

Figure 3-31. Short Beam Shear Strength Results for Solar Flight Exposure at Southwest Airlines

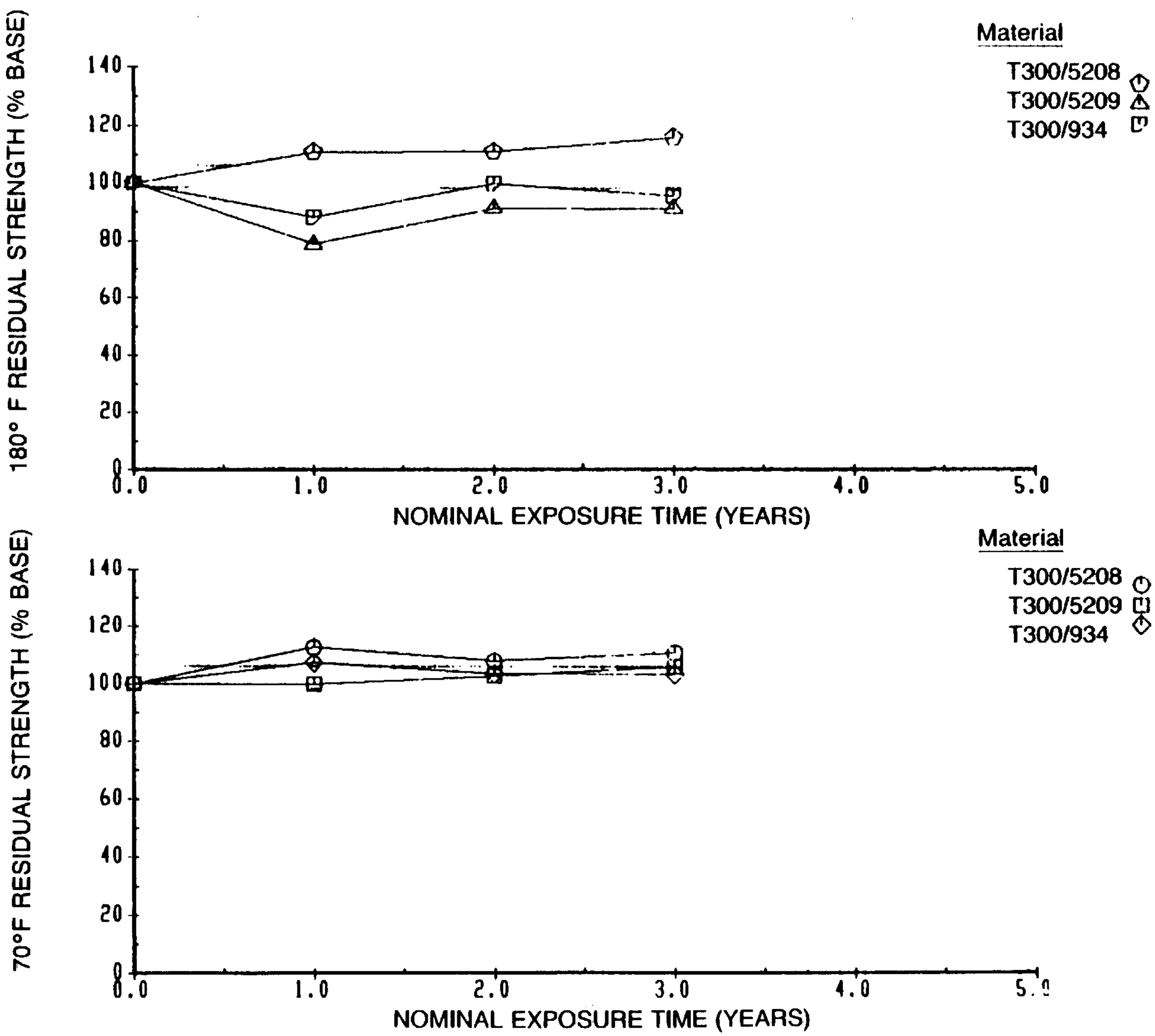

Figure 3-32. Flexure Strength Results for Solar Flight Exposure at Southwest Airlines

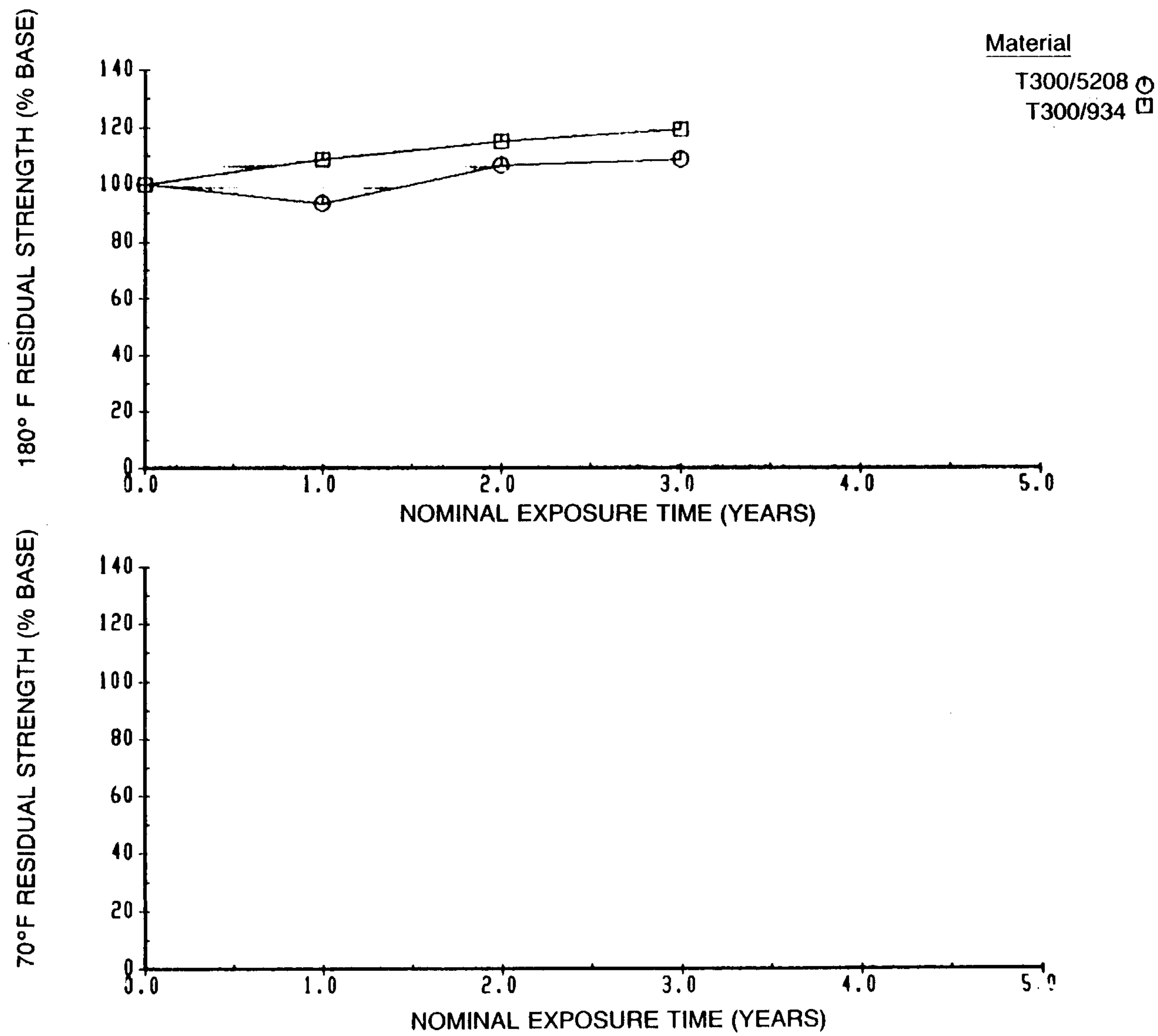

Figure 3-33. ± 45-deg Tension Strength Results for Solar Flight Exposure at Southwest Airlines

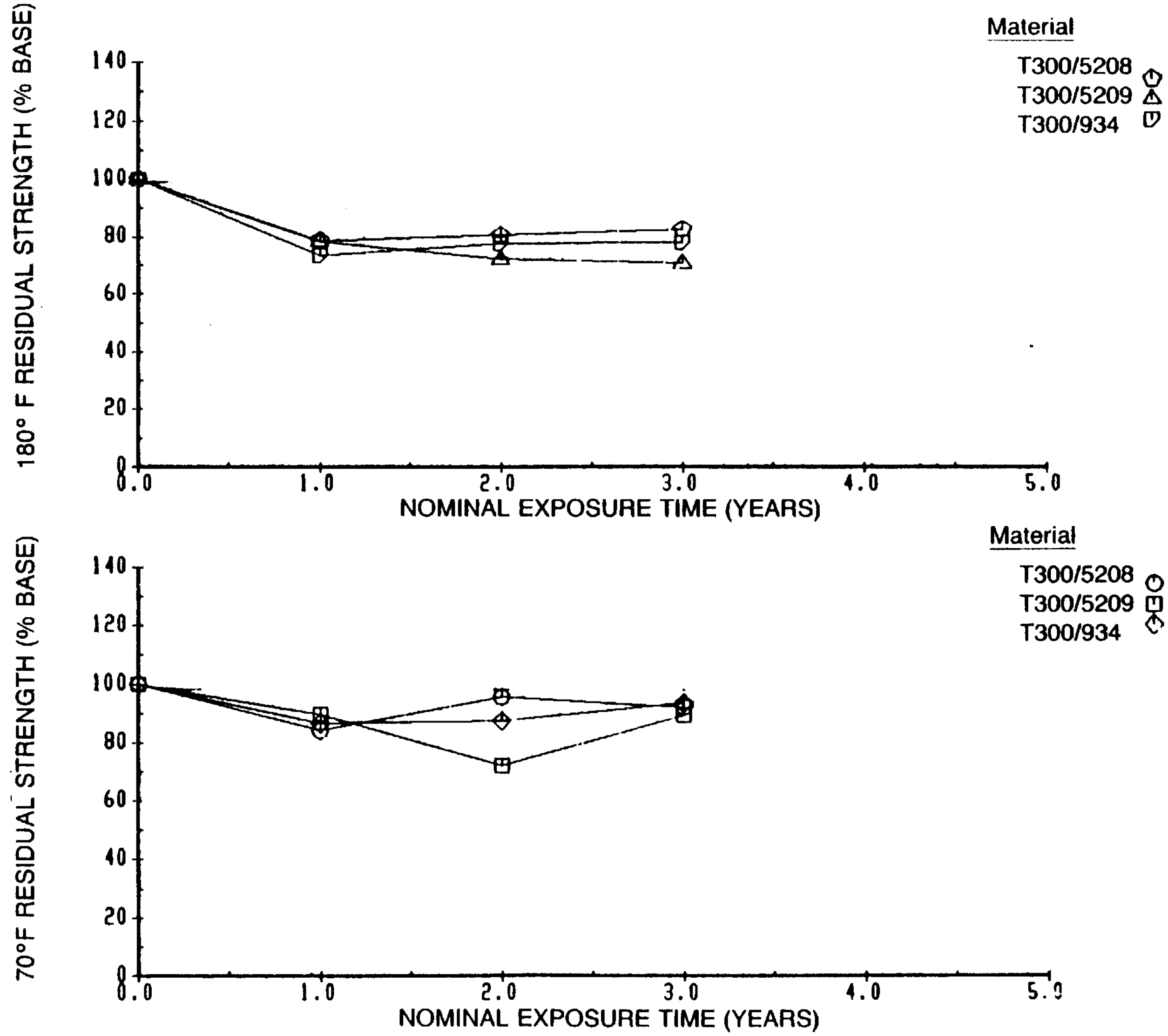

Figure 3-34. Short Beam Shear Strength Results for Nonsolar Flight Exposure at Southwest Airlines

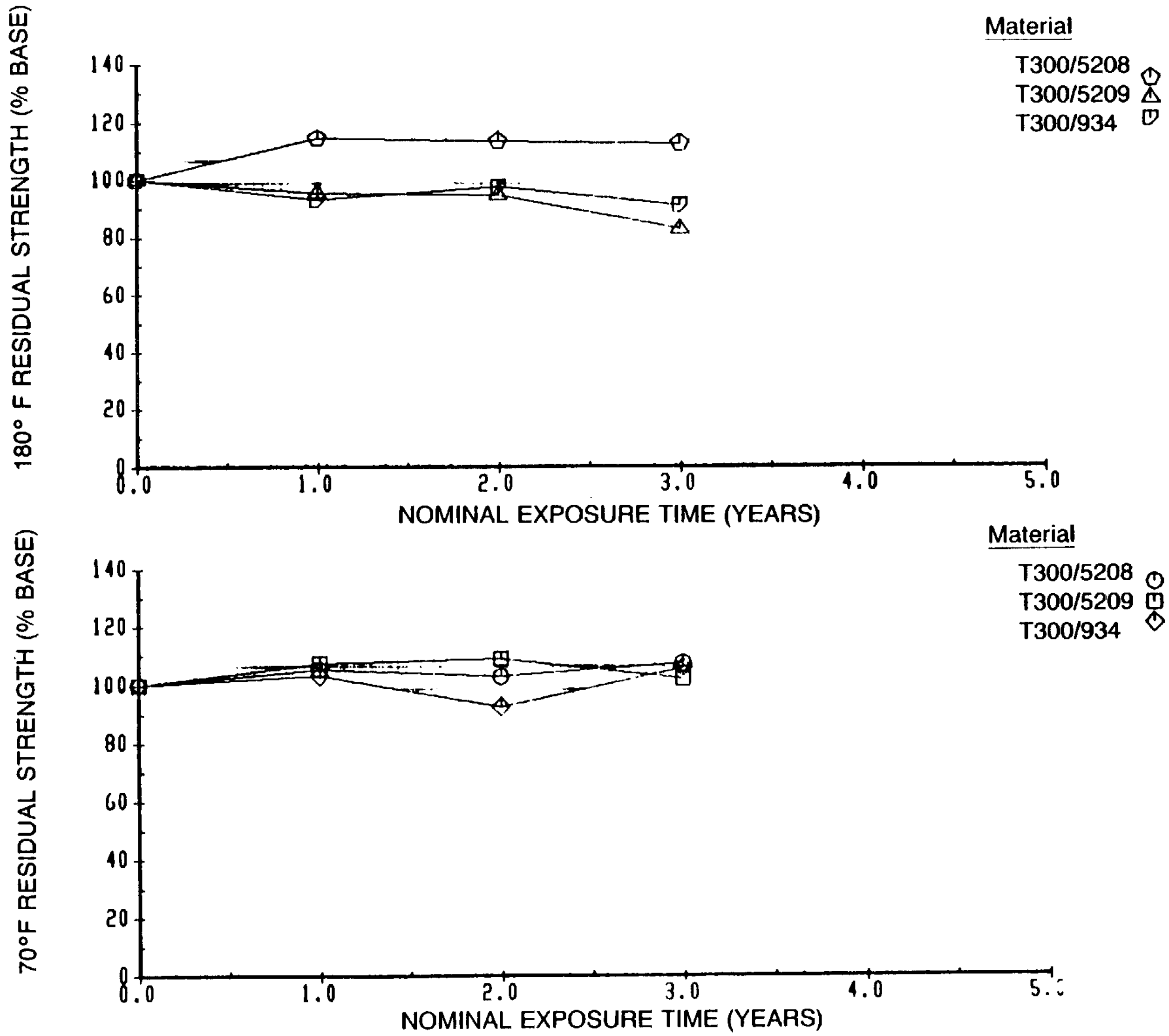

Figure 3-35. Flexure Strength Results for Nonsolar Flight Exposure at Southwest Airlines

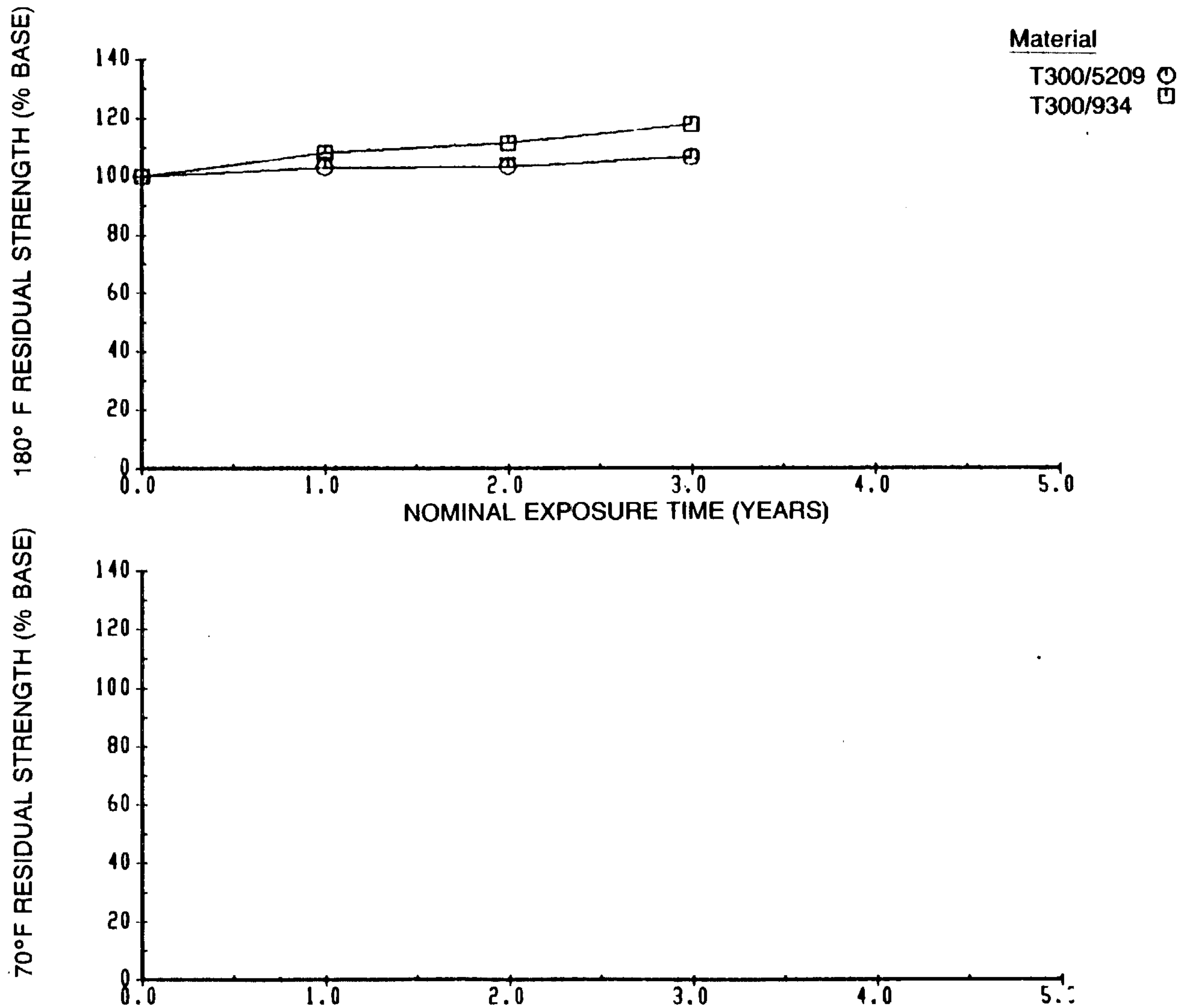

Figure 3-36. $\pm$ *45-deg Tension Strength Results for Nonsolar Flight Exposure at Southwest Airlines*

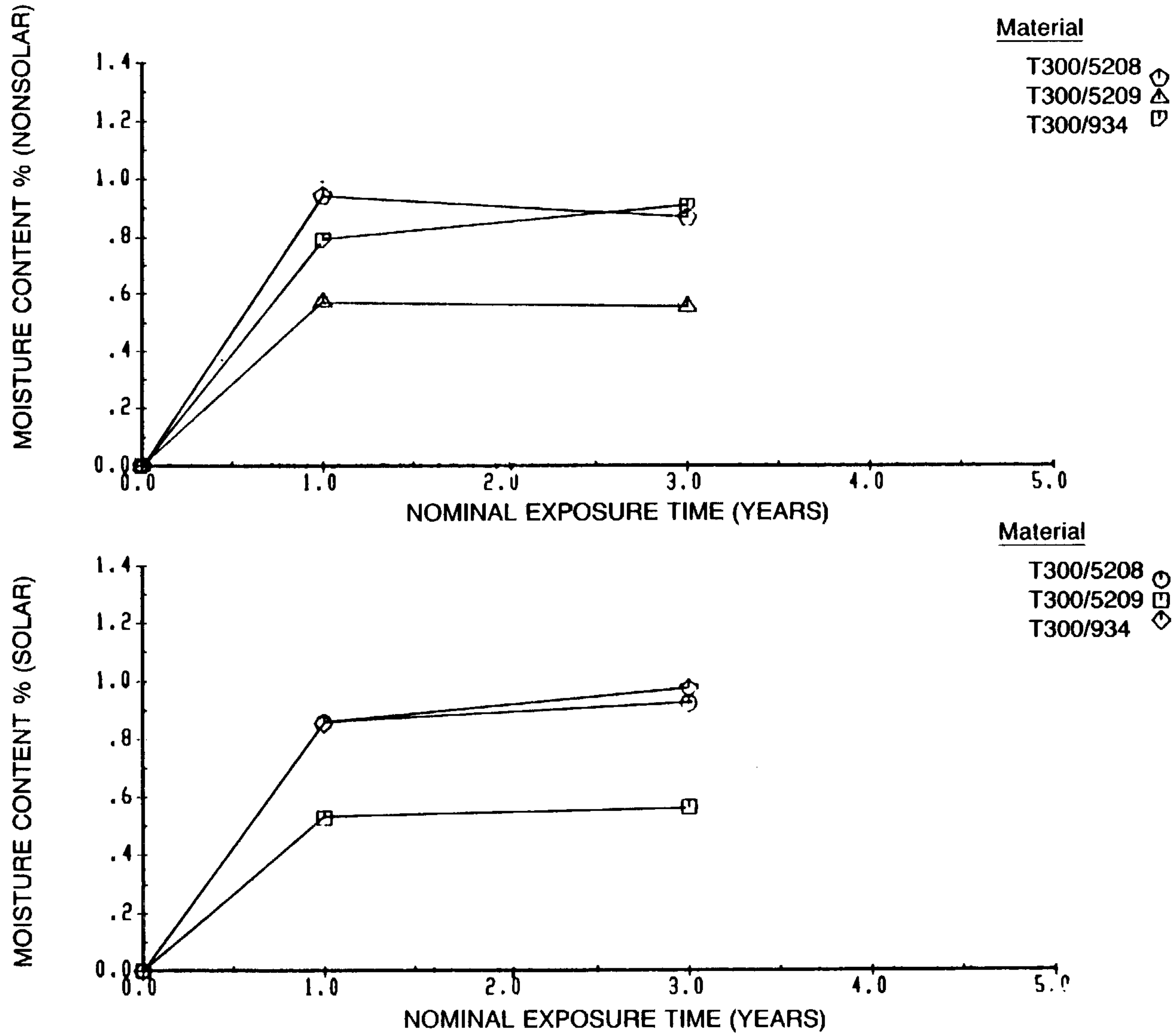

Figure 3-37. Moisture Content Results for Solar and Nonsolar Ground Exposure at Southwest Airlines

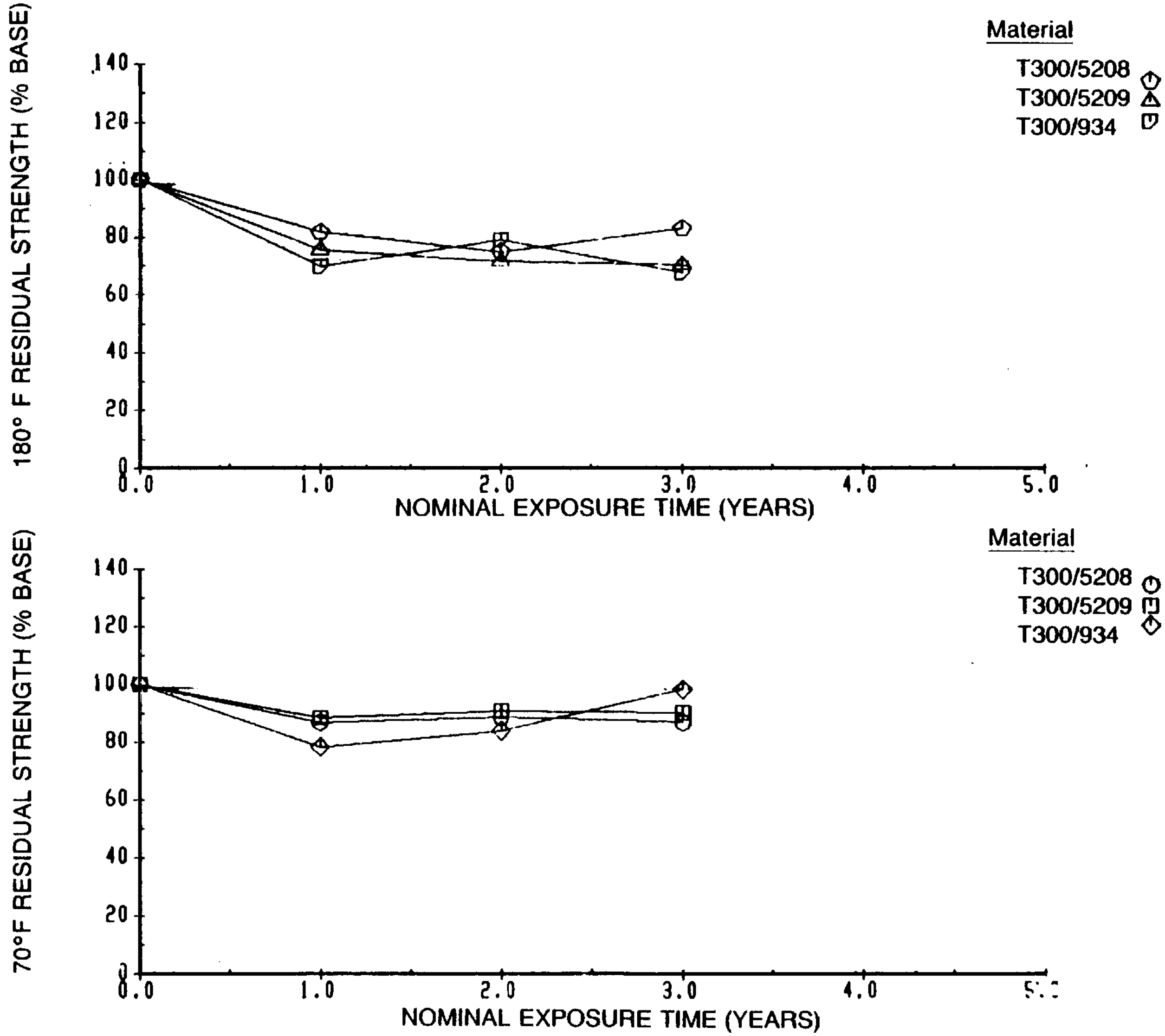

Figure 3-38. Short Beam Shear Strength Results for Interior Exposure at Southwest Airlines

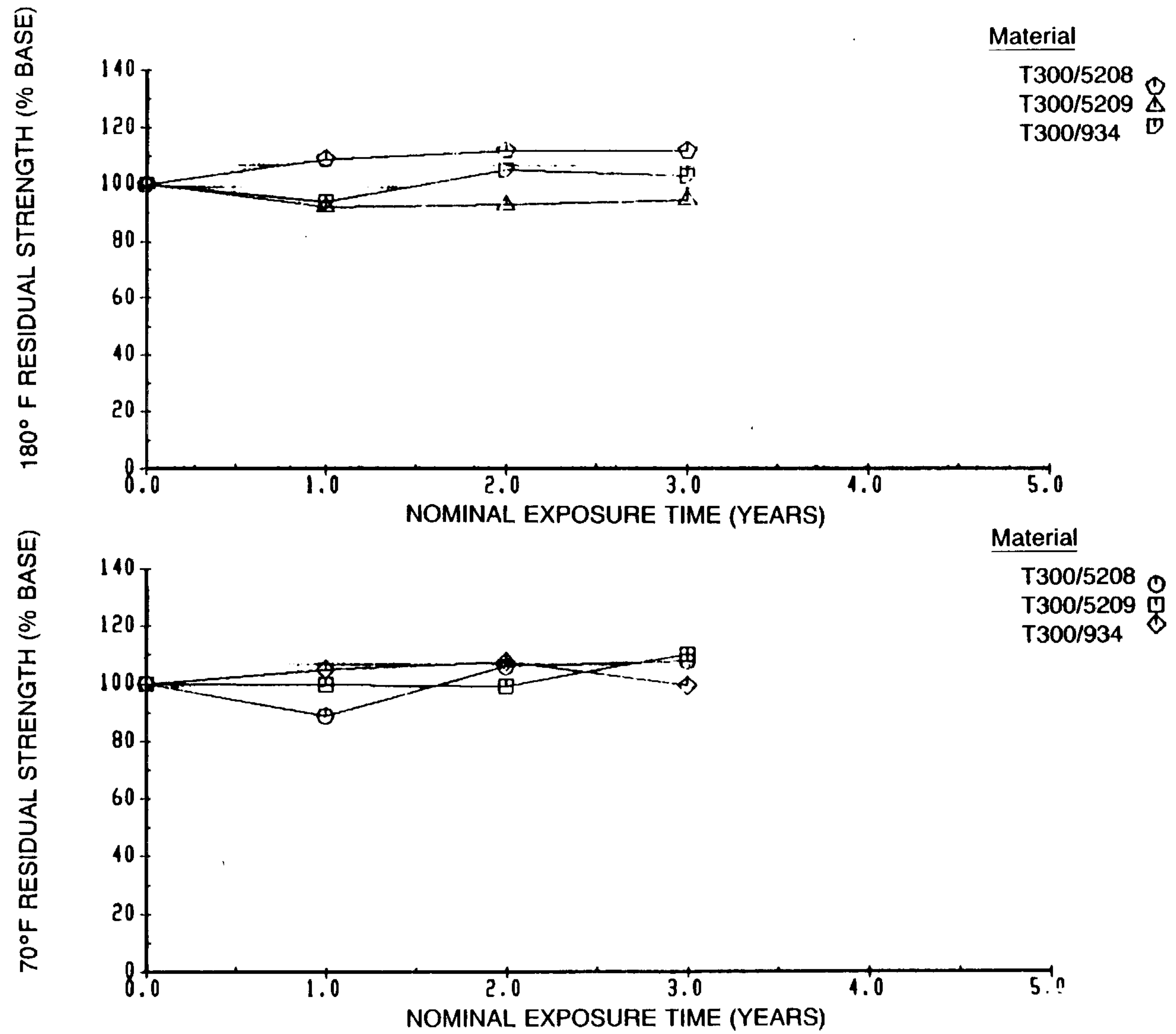

Figure 3-39. Flexure Strength Results for Interior Exposure at Southwest Airlines

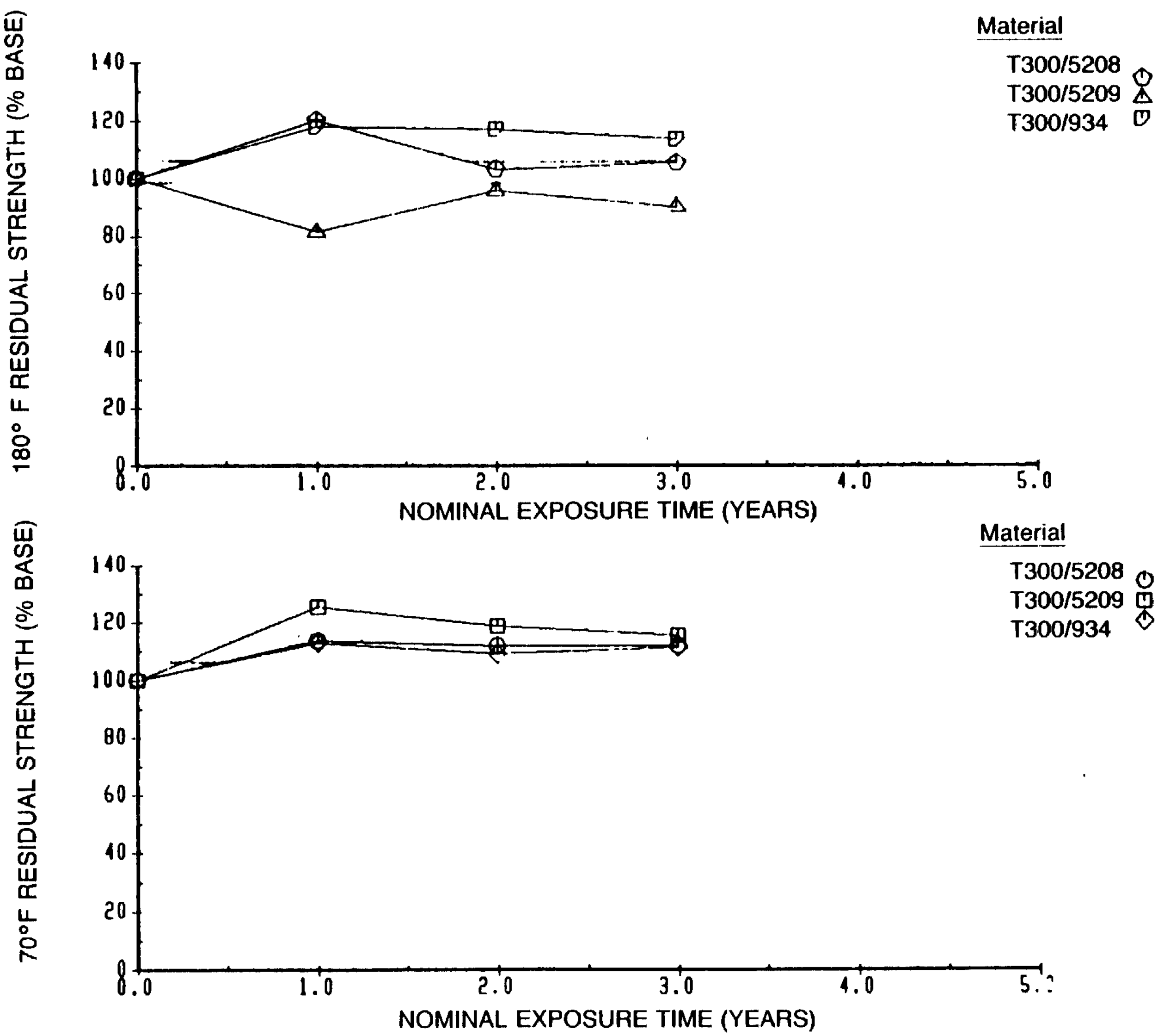

Figure 3-40. ±*45-deg Tension Strength Results for Interior Exposure at Southwest Airlines*

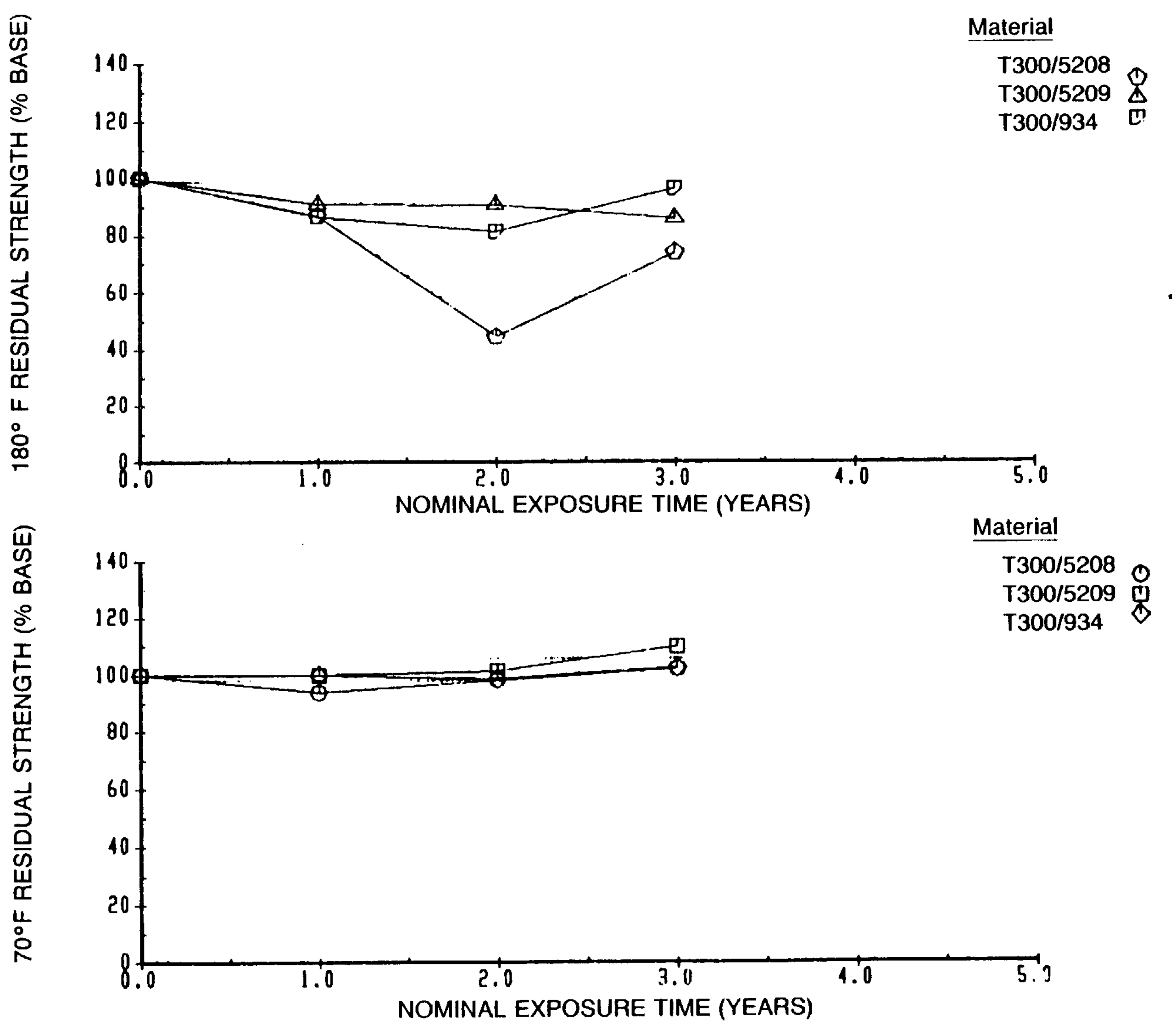

Figure 3-41. 0-deg Compression Strength Results for Interior Exposure at Southwest Airlines

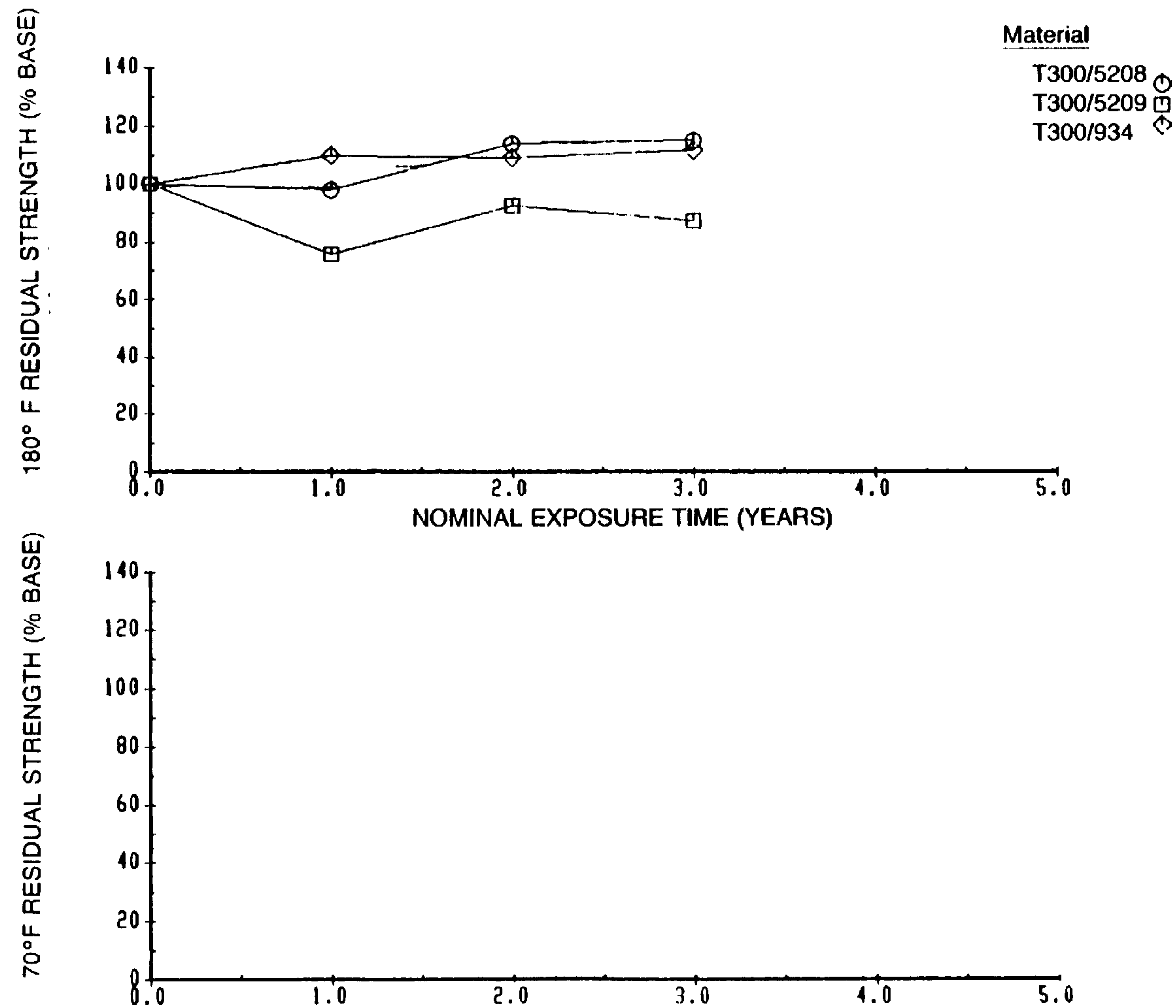

Figure 3-42. Stressed Tension Strength Results for Interior Exposure at Southwest Airlines

*Table 3-1. Termination Dates for Flight Exposure of Specimens***

Nominal exposure, yr	1	2	3	5	7	10
Aloha Airlines	3-14-80	3-27-81	3-18-83	6-01-90	2-14-87	2-18-89
Air New Zealand	11-25-80	10-20-81	6-1-86	3-23-86	10-20-88	8-16-89
Southwest Airlines	6-21-81	11-19-83*	3-31-83*	11-19-88	3-30-90	6-22-90

*This report contains data for these exposures.

**Materials T300/5208
T300/5209
T300/934

*Table 3-2. Termination Dates for Ground Rack Exposure of Specimens***

Nominal exposure, yr	1	2	3	5	7	10
NASA-Dryden	2-11-80	10-14-80	10-30-81	12-2-83	10-9-86	3-11-89
Honolulu	3-13-80	2-19-81	2-9-82	2-9-84*	6-16-86	2-9-89
Wellington	12-1-80	10-27-81	9-14-82	4-4-85	7-4-86	7-4-89
Dallas	6-21-81	7-13-82*	6-6-83*	4-18-85	4-18-87	4-18-90

*This report contains data for these exposures.

**Materials T300/5208
T300/5209
T300/934

Table 3-3. T300/5208 Baseline and Effect of Temperature Results

Specimen	Strength, MPa (ksi)		
	Room Temperature	49°C (120°F)	82°C (180°F)
0-deg short beam shear	108.2 (15.70)	99.5 (14.44)	85.0 (12.33)
Flexure	1679.0 (243.63)	1649.0 (239.17)	1559.0 (226.16)
±45-deg tension	158.4 (22.98)	147.7 (21.43)	134.2 (19.46)
0-deg compression	1706.0 (247.44)	1561.6 (226.49)	1199.7 (174.01)
0-deg tension	1448.0 (210.02)		1543.8 (223.91)
Quasi-isotropic tension	335.6 (48.68)	324.6 (47.09)	340.4 (49.39)
90-deg compression	197.4 (28.63)	204.9 (29.73)	186.4 (27.04)
Quasi-isotropic compression	1048.9 (152.14)	919.5 (133.37)	867.6 (125.84)
Tg, °C (°F)	214 (417)		

Table 3-4. T300/5209 Baseline and Effect of Temperature Results

Specimen	Strength, MPa (ksi)		
	Room Temperature	49°C (120°F)	82°C (180°F)
0-deg short beam shear	91.1 (13.22)	80.9 (11.74)	63.5 (9.22)
Flexure	1699.0 (246.48)	1606.0 (232.97)	1443.0 (209.30)
±45-deg tension	173.2 (25.10)	180.7 (26.21)	178.1 (25.83)
0-deg compression	1657.0 (240.35)	1551.8 (225.07)	1206.0 (174.94)
0-deg tension	1723.0 (249.94)		1543.8 (223.91)
Quasi-isotropic tension	354.7 (51.45)	330.3 (47.91)	344.3 (49.93)
90-deg compression	209.6 (30.40)	179.6 (26.05)	158.5 (23.00)
Quasi-isotropic compression	573.5 (83.19)	538.8 (78.16)	475.5 (68.97)
Tg, °C (°F)	128 (262)		

Table 3-5. T300/934 Baseline and Effect of Temperature Results

Specimen	Strength, MPa (ksi)		
	Room Temperature	49°C (120°F)	82°C (180°F)
0-deg short beam shear	106.1 (15.39)	99.1 (14.38)	86.2 (12.51)
Flexure	1770.0 (256.78)	1730.0 (250.94)	1626.0 (235.85)
±45-deg tension	160.2 (23.23)	152.3 (22.09)	158.9 (23.06)
0-deg compression	1738.0 (252.08)	1624.4 (235.60)	1554.0 (225.42)
Quasi-isotropic tension	386.8 (56.11)	371.3 (53.86)	324.9 (47.13)
90-deg compression	190.8 (27.68)	193.1 (28.01)	173.5 (25.17)
Quasi-isotropic compression	900.2 (130.56)	856.4 (124.22)	816.4 (118.41)
Tg, °C (°F)	205 (401)		

*Table 3-6. Summary of Results—Dallas, Nominal 2-yr Solar Specimens**

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percent of baseline)**	SBS Flexure ±45-deg tension	91.47 110.96 110.05	90.02 108.35 110.88	91.26 103.10 116.74
Elevated temperature residual strength data (percent of baseline)**	SBS Flexure ±45-deg tension	85.75 109.59 125.48	72.86 83.76 83.11	80.17 100.40 116.26
Weight change data Percent gain + Percent loss −	SBS Flexure ±45-deg tension	0.490 0.351 0.304	0.451 0.028 0.222	0.527 0.364 0.276
Weight loss during dryout	SBS dryout	0.96	0.65	0.97

Notes:

* These specimens exposed for 816 days.

** Residual strength data base on baseline tests at the respective temperatures.

*Table 3-7. Summary of Results—Dallas, Nominal 3-yr Solar Specimens**

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percent of baseline)**	SBS Flexure ±45-deg tension	95.70 107.20 113.10	91.50 101.70 106.10	88.10 101.70 116.40
Elevated temperature residual strength data (percent of baseline)**	SBS Flexure ±45-deg tension	84.30 113.80 123.20	68.80 87.00 88.00	74.60 91.10 118.10
Weight change data Percent gain + Percent loss –	SBS Flexure ±45-deg tension	0.285 0.343 0.190	0.222 –0.226 0.126	0.364 0.128 0.163
Weight loss during dryout	SBS dryout	0.94	0.58	1.00

Notes:
* These specimens exposed for 1144 days.
** Residual strength data base on baseline tests at the respective temperatures.

*Table 3-8. Summary of Results—Dallas, Nominal 2-yr Nonsolar Specimens**

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percent of baseline)**	SBS Flexure Compression	94.08 107.76 89.98	90.12 101.66 108.16	88.75 98.98 95.75
Elevated temperature residual strength data (percent of baseline)**	SBS Flexure Stressed tension Compression	82.73 103.05 130.71 34.79	68.58 78.47 85.52 76.02	74.98 92.72 120.18 79.44
Weight change data Percent gain + Percent loss –	SBS Flexure Stressed tension	0.585 0.473 0.231	0.557 0.304 0.181	0.610 0.477 0.484
Weight loss during dryout	SBS dryout	0.90	0.73	1.02

Notes:

* These specimens exposed for 816 days.

** Residual strength data base on baseline tests at the respective temperatures.

*Table 3-9. Summary of Results—Dallas, Nominal 3-yr Nonsolar Specimens**

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percent of baseline)**	SBS Flexure Compression	93.80 108.70 97.60	92.00 102.00 105.50	84.10 108.50 98.70
Elevated temperature residual strength data (percent of baseline)**	SBS Flexure Stressed tension Compression	77.60 109.90 118.80 51.20	67.20 87.70 91.60 70.01	74.00 92.70 114.40 69.00
Weight change data Percent gain + Percent loss –	SBS Flexure Stressed tension	0.449 0.306 0.197	0.324 0.051 0.184	0.536 0.221 0.191
Weight loss during dryout	SBS dryout	1.17	0.57	0.98

Notes:

* These specimens exposed for 1144 days.

** Residual strength data base on baseline tests at the respective temperatures.

*Table 3-10. Summary of Results—Wellington, Nominal 3-yr Solar Specimens**

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percent of baseline)**	SBS Flexure ±45-deg tension	86.30 105.00 109.30	88.10 99.80 121.84	93.30 106.50 115.80
Elevated temperature residual strength data (percent of baseline)**	SBS Flexure ±45-deg tension	80.40 103.10 106.00	67.70 89.60 86.40	73.70 95.00 115.30
Weight change data Percent gain + Percent loss −	SBS Flexure ±45-deg tension	— 0.701 0.388	0.490 0.396 0.425	0.745 0.612 0.294
Weight loss during dryout	SBS dryout	0.89	0.77	0.99

Notes:

* These specimens exposed for 1163 days.

** Residual strength data base on baseline tests at the respective temperatures.

*Table 3-11. Summary of Results—Wellington, Nominal 3-yr Nonsolar Specimens**

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percent of baseline)**	SBS Flexure Compression	94.00 105.40 86.50	87.10 104.70 100.20	91.80 107.60 93.40
Elevated temperature residual strength data (percent of baseline)**	SBS Flexure Stressed tension Compression	82.40 96.10 129.40 73.00	69.20 80.50 81.40 76.60	73.60 91.60 118.80 69.60
Weight change data Percent gain + Percent loss –	SBS Flexure Stressed tension	— 0.701 0.388	0.490 0.396 0.425	0.745 0.612 0.294
Weight loss during dryout	SBS dryout	1.11	0.62	1.10

Notes:

* These specimens exposed for 1163 days.

** Residual strength data base on baseline tests at the respective temperatures.

*Table 3-12. Summary of Results—Edwards, Nominal 5-yr Solar Specimens**

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percent of baseline)**	SBS Flexure ±45-deg tension	98.20 103.13 109.85	86.16 105.22 117.87	85.52 105.19 105.74
Elevated temperature residual strength data (percent of baseline)**	SBS Flexure ±45-deg tension	98.18 107.98 102.15	78.07 103.32 95.39	82.90 107.94 97.28
Weight change data Percent gain + Percent loss –	SBS Flexure ±45-deg tension	0.082 –0.187 -0.318	0.049 0.095 -0.233	0.171 0.265 -0.208
Weight loss during dryout	SBS dryout	***	***	***

Notes:
* These specimens exposed for 1822 days.
** Residual strength data base on baseline tests at the respective temperatures.
*** Not available.

*Table 3-13. Summary of Results—Edwards, Nominal 5-yr Nonsolar Specimens**

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percent of baseline)**	SBS Flexure Compression	98.27 106.49 86.95	89.92 103.97 93.12	93.22 105.17 97.20
Elevated temperature residual strength data (percent of baseline)**	SBS Flexure Stressed tension Compression	96.33 113.33 106.87 82.26	80.54 95.35 95.42 86.36	81.34 113.12 109.75 82.28
Weight change data Percent gain + Percent loss –	SBS Flexure Stressed tension	0.181 -0.040 0.063	0.038 -0.123 0.056	0.227 -0.719 -1.194
Weight loss during dryout	SBS dryout	***	***	***

Notes:
* These specimens exposed for 1822 days.
** Residual strength data base on baseline tests at the respective temperatures.
*** Not available.

*Table 3-14. Summary of Results—Honolulu, Nominal 5-yr Solar Specimens**

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percent of baseline)**	SBS Flexure ±45-deg tension	91.30 105.31 107.49	90.30 104.85 97.64	96.66 113.54 105.92
Elevated temperature residual strength data (percent of baseline)**	SBS Flexure ±45-deg tension	83.53 98.77 121.80	61.30 88.09 96.63	71.59 96.80 108.93
Weight change data Percent gain + Percent loss –	SBS Flexure ±45-deg tension	*** *** ***	*** *** ***	*** *** ***
Weight loss during dryout	SBS dryout	***	***	***

Notes:
* These specimens exposed for 1826 days.
** Residual strength data base on baseline tests at the respective temperatures.
*** Not available.

*Table 3-15. Summary of Results—Honolulu, Nominal 5-yr Nonsolar Specimens**

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percent of baseline)**	SBS Flexure Compression	98.27 109.05 88.34	87.48 109.87 98.93	85.24 103.69 99.31
Elevated temperature residual strength data (percent of baseline)**	SBS Flexure Stressed tension Compression	82.16 99.45 125.60 45.33	61.91 94.05 86.81 59.65	69.91 90.03 119.52 63.85
Weight change data Percent gain + Percent loss −	SBS Flexure Stressed tension	*** *** ***	*** *** ***	*** *** ***
Weight loss during dryout	SBS dryout	***	***	***

Notes:
* These specimens exposed for 1826 days.
** Residual strength data base on baseline tests at the respective temperatures.
*** Not available.

*Table 3-16. Summary of Results—Southwest Airlines, Nominal 2-yr Solar Specimens**

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percent of baseline)**	SBS Flexure	95.41 107.97	88.42 102.58	92.85 103.41
Elevated temperature residual strength data (percent of baseline)**	SBS Flexure ±45-deg tension SBS dryout	80.26 111.15 106.66 —	69.54 91.35 — —	76.30 100.00 114.95 —
Weight change data Percent gain + Percent loss –	SBS Flexure ±45-deg tension	0.585 0.692 0.325	0.441 0.356 —	1.027 0.705 0.405
Weight loss during dryout	SBS dryout	***	***	***

Notes:
* These specimens exposed for 881 days, 8334 hours.
** Residual strength data base on baseline tests at the respective temperatures.
*** Not available.

*Table 3-17. Summary of Results—Southwest Airlines, Nominal 3-yr Solar Specimens**

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percent of baseline)**	SBS Flexure	95.00 110.70	87.00 105.90	98.00 103.20
Elevated temperature residual strength data (percent of baseline)**	SBS Flexure ±45-deg tension SBS dryout	83.20 115.80 108.90 99.86	69.10 91.00 — 103.68	77.40 95.30 119.30 90.94
Weight change data Percent gain + Percent loss −	SBS Flexure ±45-deg tension	0.335 0.354 0.559	0.451 0.214 —	−0.025 −0.186 0.548
Weight loss during dryout	SBS dryout	0.92	0.56	0.97

Notes:

* These specimens exposed for 1128 days, 10,790 hours.

** Residual strength data base on baseline tests at the respective temperatures.

*Table 3-18. Summary of Results—Southwest Airlines, Nominal 2-yr Nonsolar Specimens**

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percent of baseline)**	SBS Flexure	95.53 102.71	72.12 108.94	87.37 92.38
Elevated residual strength data (percent of baseline)**	SBS Flexure ±45-deg tension SBS dryout	80.65 113.32 103.42 —	72.12 94.51 — —	77.61 97.76 111.40 —
Weight change data Percent gain + Percent loss –	SBS Flexure ±45-deg tension	0.620 0.657 0.252	0.401 1.127 —	0.701 0.511 0.372
Weight loss during dryout	SBS dryout	***	***	***

Notes:
* These specimens exposed for 881 days, 8334 flight hours.
** Residual strength data base on baseline tests at the respective temperatures.
*** Not available.

*Table 3-19. Summary of Results—Southwest Airlines, Nominal 3-yr Nonsolar Specimens**

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percent of baseline)**	SBS Flexure	92.20 107.30	89.30 101.90	93.40 105.70
Elevated residual strength data (percent of baseline)**	SBS Flexure ±45-deg tension SBS dryout	82.40 112.40 106.60 108.55	70.70 82.70 — 102.53	78.10 90.90 117.80 90.83
Weight change data Percent gain + Percent loss −	SBS Flexure ±45-deg tension	−0.379 0.870 0.244	0.437 0.445 —	−0.221 −0.122 0.301
Weight loss during dryout	SBS dryout	0.86	0.56	0.91

Notes:
* These specimens exposed for 1128 days, 10,790 flight hours.
** Residual strength data base on baseline tests at the respective temperatures.

*Table 3-20. Summary of Results—Southwest Airlines, Nominal 2-yr Interior Specimens**

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percent of baseline)**	SBS Flexure ±45-deg tension Compression	88.54 105.70 111.98 98.06	90.76 99.04 118.95 101.46	83.95 107.54 109.14 98.68
Elevated residual strength data (percent of baseline)**	SBS Flexure ±45-deg tension Stressed tension Compression	75.05 111.92 103.84 114.03 44.45	71.77 93.00 95.92 92.76 90.68	79.14 105.09 117.22 109.26 81.30
Weight change data Percent gain + Percent loss −	SBS Flexure ±45-deg tension	0.421 0.398 −0.510	0.201 −0.628 0.263	0.523 0.361 0.270

Notes:
* These specimens exposed for 884 days, 8334 flight hours.
** Residual strength data base on baseline tests at the respective temperatures.

*Table 3-21. Summary of Results—Southwest Airlines, Nominal 3-yr Interior Specimens**

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percent of baseline)**	SBS	86.90	90.30	98.20
	Flexure	107.70	110.20	99.20
	±45-deg tension	112.00	115.50	111.30
	Compression	102.20	110.20	102.50
Elevated residual strength data (percent of baseline)**	SBS	83.00	70.40	67.60
	Flexure	111.80	94.60	103.10
	±45-deg tension	105.30	90.10	113.60
	Stressed tension	114.90	87.30	111.60
	Compression	73.90	85.90	96.30
Weight change data Percent gain + Percent loss −	SBS	0.491	0.465	0.625
	Flexure	0.339	0.219	0.346
	±45-deg tension	0.351	0.343	0.373

Notes:

* These specimens exposed for 1128 days, 10,790 flight hours.

** Residual strength data base on baseline tests at the respective temperatures.

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16. Abstract

A study is being conducted to determine the effects of environmental exposure on composite materials. The environments considered are representative of those experienced by commercial jet aircraft. Initial results have been compiled for the following material systems: T300/5208, T300/5209, and T300/934. Future results will include AS-1/3501-6 and Kevlar 49/F161-188. Specimens were exposed on the exterior and interior of 737 airplanes of three airlines, and to continuous ground-level exposure at four locations. In addition, specimens were exposed in the laboratory to conditions such as: simulated ground-air-ground, weatherometer, and moisture.

Residual strength results are presented for specimens exposed for up to five years at five ground-level exposure locations and on airplanes from one airline.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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