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AN EXPERIMENTAL EVALUATION OF THE IMPACT RESISTANCE OF RECOATED F-16A MONOLITHIC POLYCARBONATE FLAT SHEET

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F-16A coated monolithic polycarbonate forward canopies experiencing coating degradation are being reworked by the vendor by stripping the degraded coating and applying a new protective coating, thereby restoring the canopy for additional useful service life. The basic objective of the current investigation was to determine whether or not the impact resistance of monolithic polycarbonate flat sheet material for the F-16A forward canopy is degraded by the stripping and recoating process. The effects of laboratory storage and QUV weathering were also evaluated. Coupons (beams) were fabricated and subjected to QUV weathering, laboratory storage, and/or stripping/recoating (which was performed by the vendor). The coupons were then impact tested using either the falling weight beam test technique (ASTM F736-81) or a high rate (40,000 in/min center deflection rate) open loop servohydraulic (MTS) beam test technique. The primary conclusion of the investigation was that the strip and recoat process did not degrade the impact resistance of the polycarbonate relative to the impact resistance of new coated polycarbonate. In other words, the strip and recoat process
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MTS beam test

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restored the impact resistance of the reworked polycarbonate to its original newly-fabricated, newly-coated state, regardless of prior conditioning (QUV weathering or laboratory storage).

FOREWORD

The effort reported herein was performed by the University of Dayton Research Institute, Dayton, Ohio, under Contract No. F33615-84-C-3404, "Birdstrike Resistant Crew Enclosure Development Program." This work was administered by the Flight Dynamics Laboratory, Wright Laboratories, Wright-Patterson Air Force Base, Ohio, with administrative direction provided by Capt. Paul Kolodziejski and Lt. Duncan Dversdall, WL/FIVR. The work was performed during the period October 1984-March 1989.

Project supervision and technical assistance were provided through the Aerospace Mechanics Division of the University of Dayton Research Institute with Mr. Dale H. Whitford, Supervisor, and Mr. Blaine S. West, Head, Structures Group and Project Engineer. Mr. Michael P. Bouchard served as Principal Investigator. The author gratefully acknowledges the efforts of the following individuals from UDRI: Mr. Fred Pestian and Mr. Pete Muth for fabricating the test specimens, Mr. Tom Helmick and Mr. Cris Williams for performing the MTS beam tests, Mr. Chuck Griffin for performing the QUV weathering, and Mr. Kurt Ostdiek for helping perform the falling weight beam tests.

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INTRODUCTION

1.1 Background

The monolithic 0.75-inch-thick polycarbonate canopy of the F-16A fighter aircraft is protected by a thin coating on the inside and outside surfaces which enhance the canopy's resistance to moisture, ultraviolet radiation, and abrasion. In time, however, the coatings on in-service canopies tend to degrade via crazing, abrasion, erosion, peeling, and other phenomena. In the past, when the coating condition became intolerable, the canopies were discarded and replaced with new ones. In 1980, however, a process was developed by the vendor (Texstar, Inc.) to strip the degraded coating from a canopy so that the canopy can be recoated and placed back in service, thus saving much of the cost of manufacturing new replacement canopies.

In August 1984, the United States Air Force conducted birdstrike tests on recoated F-16A canopy assemblies to characterize the bird impact resistance of recoated canopies.[1] A subsequent investigation determined, in part, the effects of recoating on the impact resistance of samples obtained from the same birdstrike-tested canopies.[2] The chromatography tests conducted indicated no significant degradation of the polycarbonate molecular weight (MW) and molecular weight distribution (MWD) at the surface relating to the substrate due to the recoating process. Although MW and MWD directly affect impact resistance,[3,4] it could not be categorically concluded that degradation of the impact resistance had not occurred since such degradation could have occurred without affecting MW and MWD (for example, by physical aging[5]). Unfortunately, it was not possible to directly evaluate degradation of the impact resistance because of recoating using a mechanical test since no baseline of comparison (that is, a newly-manufactured coated canopy) was available.

The effort documented herein was therefore conducted as a separate and parallel task to evaluate directly via mechanical testing the effect of the recoating process on the impact resistance of polycarbonate sheet used for fabricating F-16A monolithic forward canopies. All specimen conditioning and testing was performed on flat sheet material in the laboratory to obtain better control of all pretest and test parameters.

1.2 Objectives

The objectives of this effort were to:

1. Determine whether or not the impact resistance of coated monolithic polycarbonate for F-16A forward canopies is degraded by the stripping and recoating process (including multiple strips and recoats on a single sample of material) used by the vendor.

2. Determine how artificial weathering using the QUV apparatus influences the impact resistance of F-16 coated monolithic polycarbonate.

3. Correlate test results for this investigation with test results for a similar study conducted using specimens fabricated from recoated F-16A canopies.[2]

4. Correlate falling weight and MTS test results obtained from this investigation.

1.3 Scope

Beam specimens were fabricated from flat sheet material that had been coated or recoated by the vendor. Prior to each recoating and/or test, the beams were subjected either to QUV weathering or laboratory storage. Both MTS and falling weight three-point beam tests were subsequently conducted.

SECTION 2
EXPERIMENTAL INVESTIGATION

2.1 Technical Approach

Table 2.1 presents the conditioning/test matrix for the investigation. Polycarbonate in flat sheet form was obtained from the vendor, who applied surface coatings in accordance with current F-16A monolithic polycarbonate canopy procurement specifications. Baseline impact resistance data were established by performing three-point MTS flexural beam tests on the material, both as-received and with the coating removed (specimen groups B and A, respectively). The remaining material was conditioned, either by storage in a controlled laboratory environment (groups C-F) or by weathering in the QUV apparatus (groups G-M), prior to testing. Some of this material (groups J-M) was also sent back to the vendor after conditioning to have the coating stripped and reapplied using the same techniques employed in stripping and recoating the F-16A forward canopies. Some material received multiple equivalent years of QUV weathering and/or strips and recoats prior to beam testing (groups H, I, K, L, and M). Falling weight three-point beam tests were performed for comparison to the MTS results for groups B-E and G-L.

2.2 Specimen Fabrication

Five flat sheets of press-polished polycarbonate, coated on both sides with C-254 coating (per current F-16A coated monolithic polycarbonate canopy practice) were received from the vendor. The nominal sheet dimensions were 10.5 inches x 32 inches x 0.75 inch thick. Arrows which pointed to the surface that was to be conditioned and

TABLE 2.1

CONDITIONING AND TEST MATRIX FOR F-16A (RE)COATED FLAT SHEET SPECIMENS

Specimen Group	Quantity	Test[a]	Conditioning[b]	Test	Conditioning	Test	Conditioning	Test
A[c]	3	M						
B	8	MF						
C	8	-	Lab, SR	MF				
D	8	-	Lab, SR	-	Lab, SR	MF		
E	8	-	Lab, SR	-	Lab, SR	-	Lab, SR	MF
F	3	-	Lab	-	Lab	-	Lab	M
G	8	-	QUV	MF				
H	8	-	QUV	-	QUV	MF		
I	8	-	QUV	-	QUV	-	QUV	MF
J	8	-	QUV,SR	MF				
K	8	-	QUV,SR	-	QUV,SR	MF		
L	8	-	QUV,SR	-	QUV,SR	-	QUV,SR	MF
M	3	-	QUV	-	QUV	-	QUV,SR	M

[a]M - MTS Beam Test
F - Falling Weight Beam Test

[b]Lab - Storage in Laboratory
QUV - QUV Weathering for 1 Equivalent Year
SR - Strip and Recoat

[c]Coating on test surface sanded off prior to test.

tested were engraved on the edges of the sheets. All conditioning, stripping, and recoating was accomplished on the flat sheets prior to fabrication of the beam specimens.

The geometry of both MTS and falling weight beam specimens was chosen, in conformance with ASTM Method F736-81[6], to be 10.5 inches long, 1.5 inches wide, and 0.75 inch thick (nominal flat sheet thickness). The width tolerance as ±0.010 inch while the length tolerance was +0.125 inch, -0 inch (the length dimension was not critical except that it had to be adequate to prevent the specimen from being pushed through the test supports). Figures 2.1-2.5 show the layouts of all beams from the parent sheets.

Fabrication of the beams was accomplished by first masking the flat surfaces of the sheets with Protex 8216-2L protective tape. The required beams were then band-sawed from the appropriate parent sheet. Each beam was machined to its final dimensions in the UDRI Machine Shop. The side of a sharp, eight-flute, 1.5-inch-diameter cutter was used for machining. The spindle speed was 900 rpm while the table feed was 6.5 in/min. An identifying code was then engraved at one end of each beam on the conditioned (test) surface (the same surface to which the arrow engraved on the edges pointed). The code was of the form "X-Y", where X was the specimen group designation (A, B, C, ..., M) and Y was a single-digit identifier used to distinguish specimens from the same group. The long edges of each beam were lightly sanded with 400-grit emery paper prior to testing to minimize any edge stresses.

Past discussions with the canopy vendor had revealed that fine-grit sanding was an acceptable method for removal of the test (tensile) surface coating of the group A specimens (sanding is part of the manufacturer's surface preparation prior to canopy recoating). The sanding procedure, which was developed under a previous test program,[2] is outlined in Table 2.2. The intent of the sanding was to remove the coating and leave

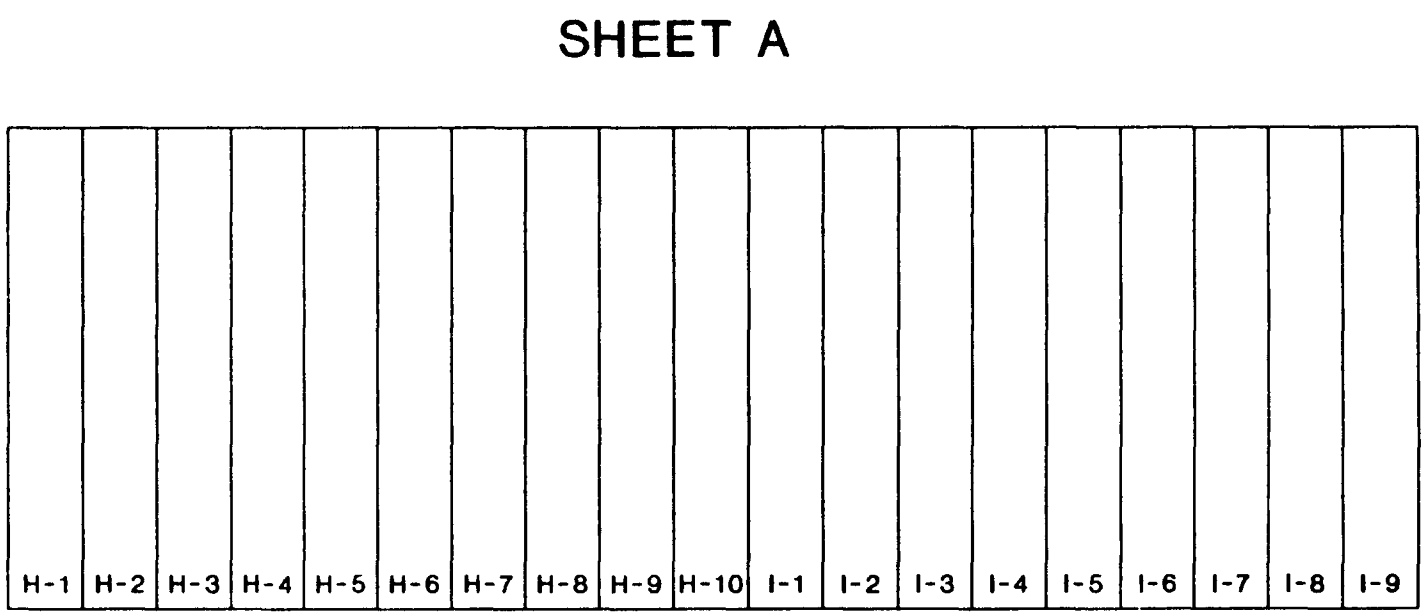


Figure 2.1. Layout for Beam Groups H and I.

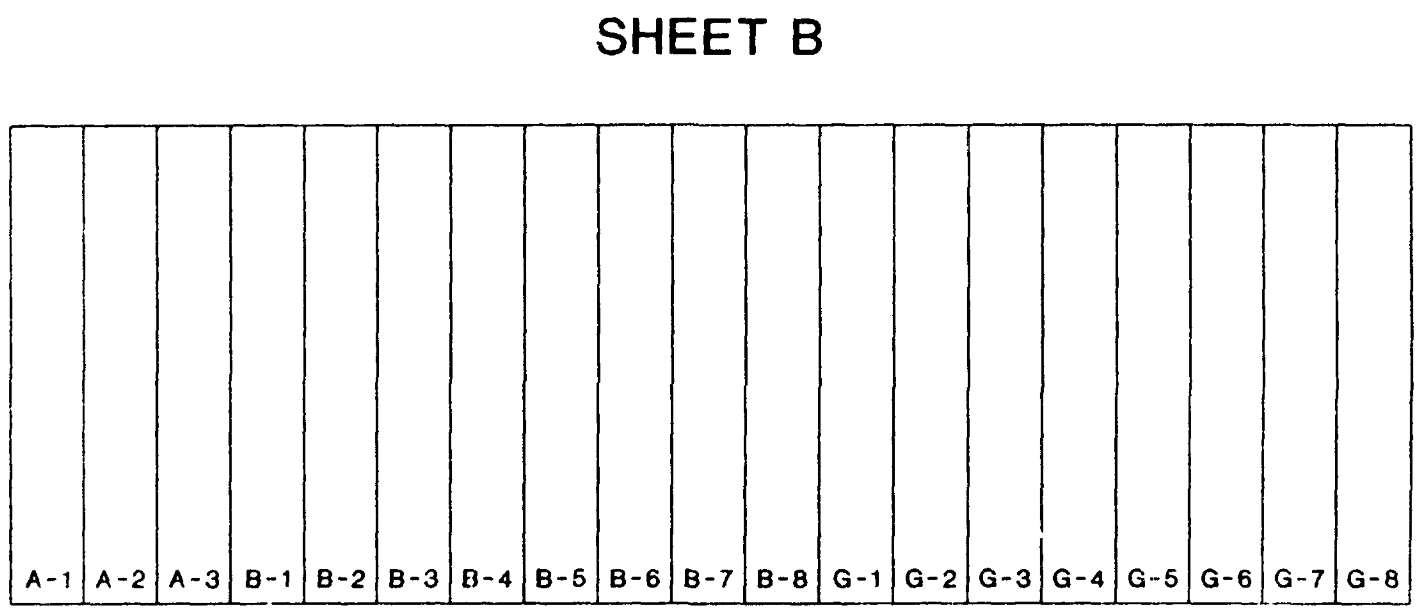


Figure 2.2. Layout for Beam Groups A, B, and G.

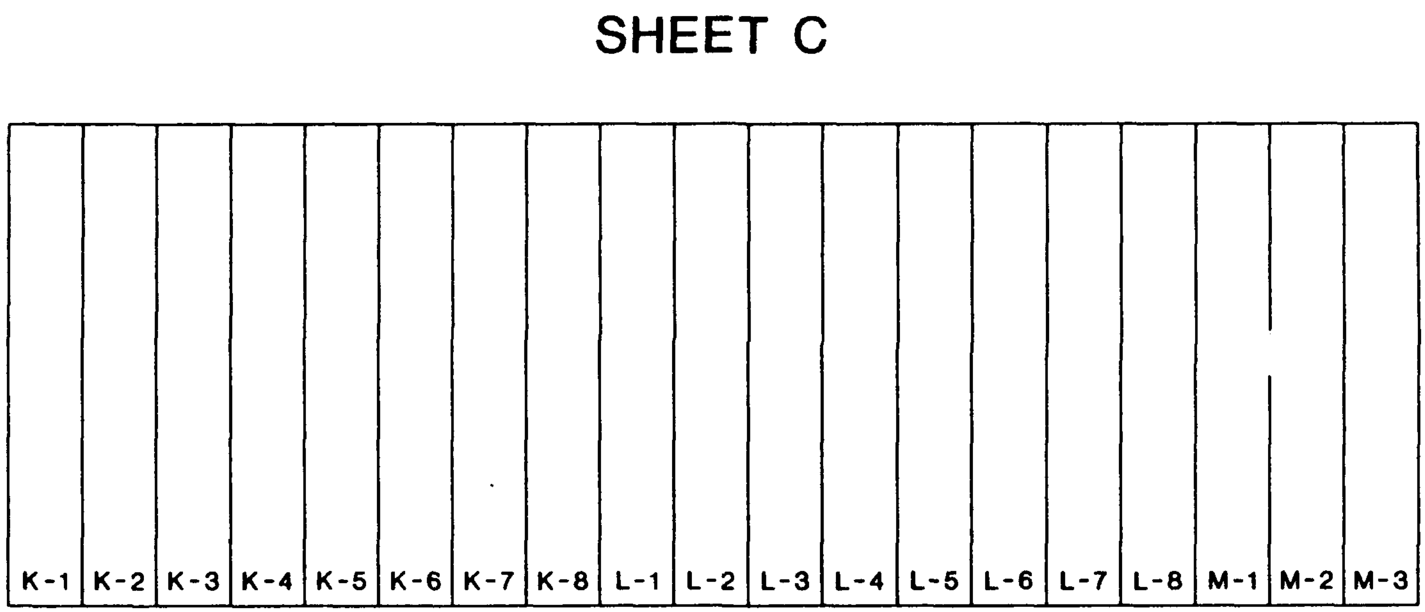


Figure 2.3. Layout for Beam Groups K, L, and M.

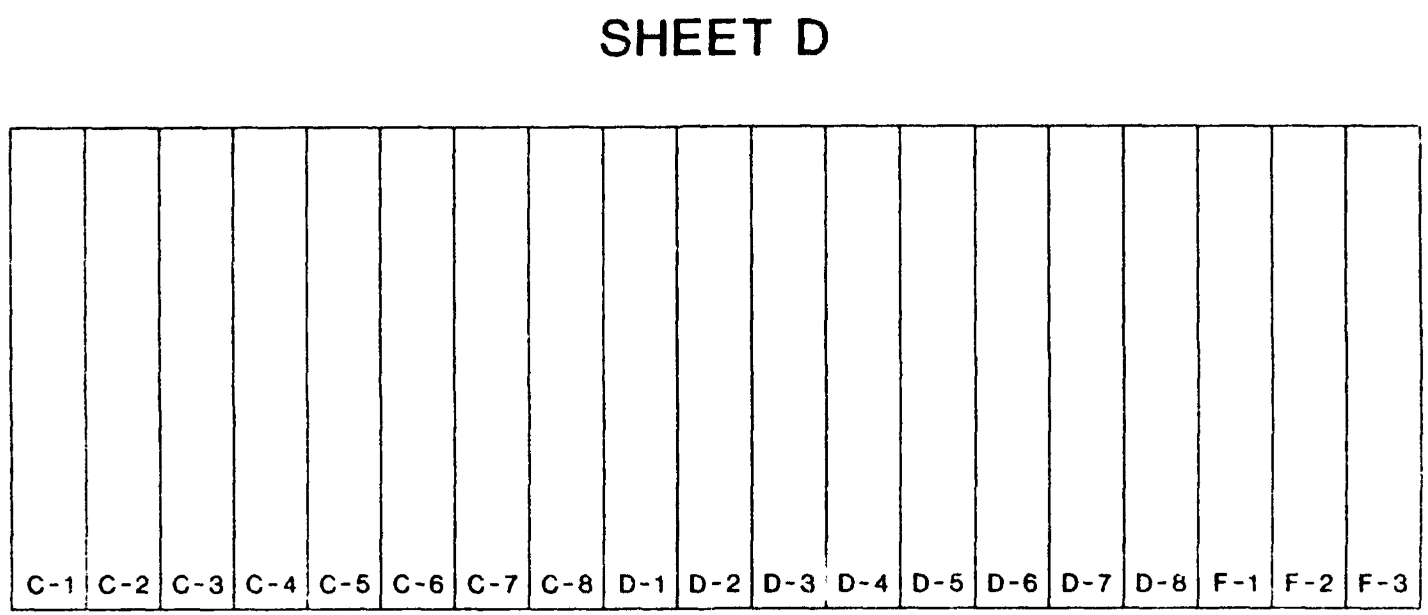


Figure 2.4. Layout for Beam Groups C, D, and F.

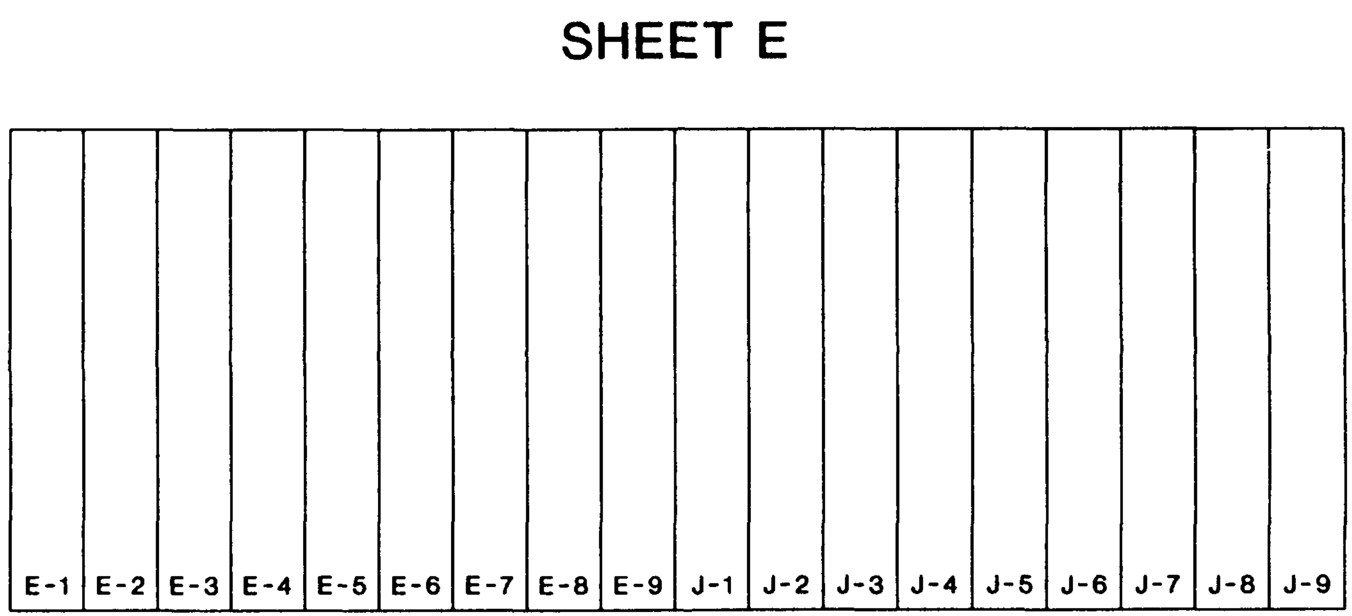


Figure 2.5. Layout for Beam Groups E and J.

TABLE 2.2

PROCEDURE FOR SANDING OFF INSIDE COATING

Step	Paper[a] or Solution[b]	Grit	Wet[c] or Dry	Sanding Direction	Comments
1	Paper	280	Wet	Longitudinal	Sand until coating removed[d], then until appearance uniform
2	Paper	400	Wet	Longitudinal	Sand until uniform appearance
3	Paper	600	Wet	Longitudinal	Sand until uniform appearance
4	Paper	0000	Dry	Longitudinal	Sand until uniform appearance
5	Solution	1 micron	Wet	Swirl	Sand until uniform appearance

Notes:

[a]Paper = emery

[b]Solution = suspension of 1 micron Al_2O_3 in H_2O (25-30g to 300 ml) rubbed with soft pad

[c]Wet = paper wetted before sanding

[d]Coating removal evident by following observations: when begin sanding, surface will turn hazy white due to scratching of coating. When sand completely through coating, surface will become more clear (transparent). More sanding will again cloud surface as polycarbonate is scratched.

a surface free of adverse stress concentrations from scratching by the various sanding mediums. The test surface was therefore not optical quality when sanding was complete, but scratches were very shallow and oriented along the length of the beam (transverse scratches could have caused high stress concentrations in the presence of bending stresses during testing[7]).

2.3 Specimen Conditioning

Specimen pretest conditioning consisted of laboratory storage and QUV weathering. For laboratory storage, the flat sheet material for specimen groups C-F was placed on edge in a box with a thin layer of packaging foam separating adjacent sheets to prevent scratching. The box was stored in a laboratory maintained at 73±4°F and 50±5% relative humidity. Figure 2.6 summarizes the laboratory storage schedule for each specimen group.

Artificial weathering of the specimens for groups G-M was accomplished using the QUV apparatus shown in Figure 2.7. The apparatus, which was manufactured by the Q-Panel Company of Cleveland, Ohio, consists of two banks of four fluorescent bulbs each, aligned parallel to two specimen racks. Closing in the underside of the unit is a shallow pan and water heater. The controls and air heater are located on top of the unit. Specimens are mounted such that their clearance from the bulbs is 2 inches. The bulbs are Q-Panel 48-inch fluorescent UVB-313, providing UV-B radiation with maximum output at 313 nanometers and a minimum output at 280 nanometers (1% of peak output).

Functionally, the QUV tester provides continuous output of heat with alternating UV radiation and condensation. A cycle timer adjusts the starting and ending times for the condensation and ultraviolet conditionings. The timer was set for 7 hours of radiation

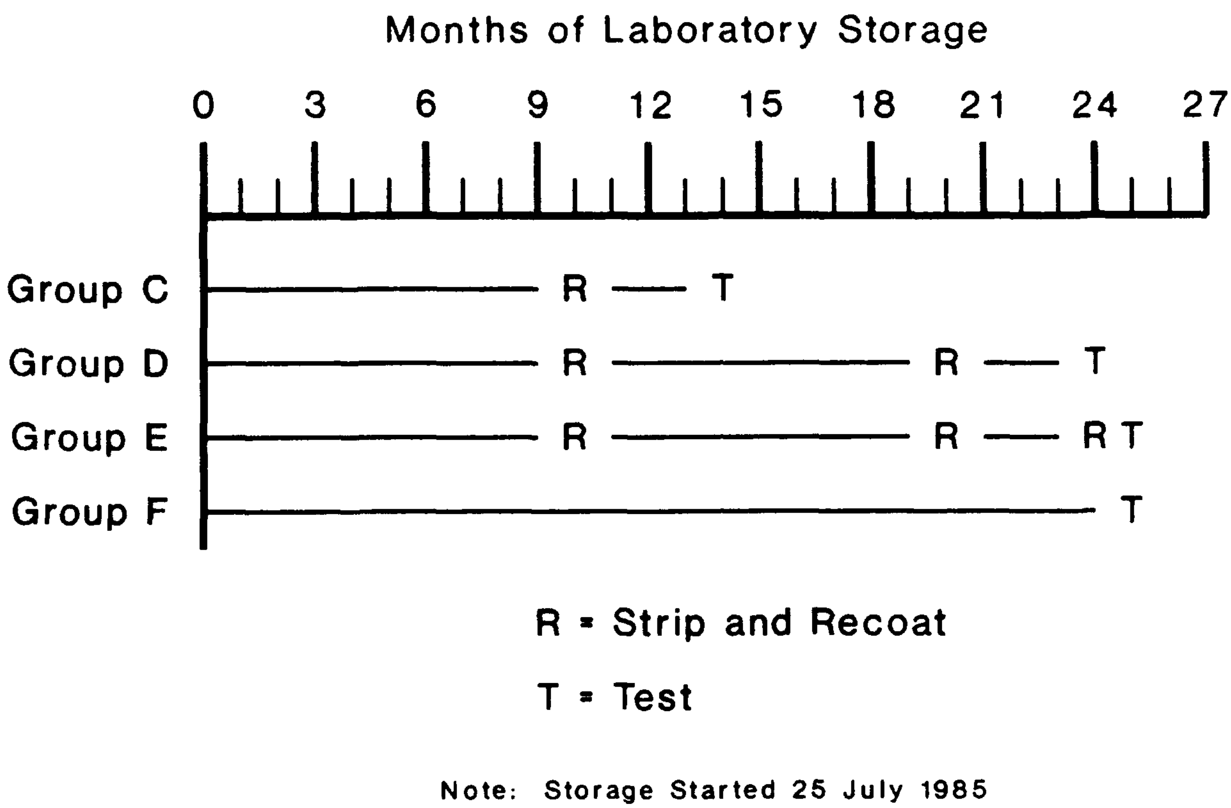
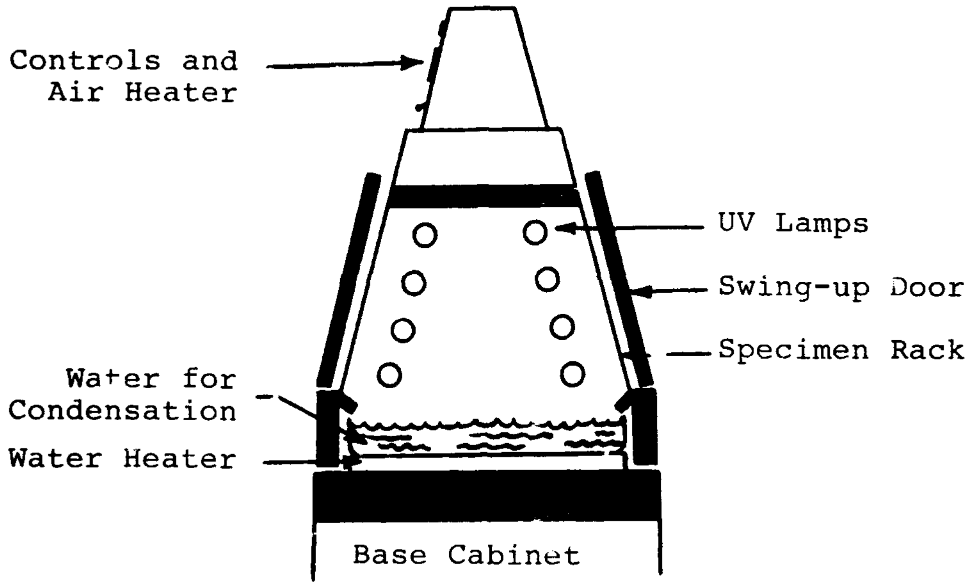


Figure 2.6. Schedule for Specimens Stored in Laboratory.



Schematic Cross Section

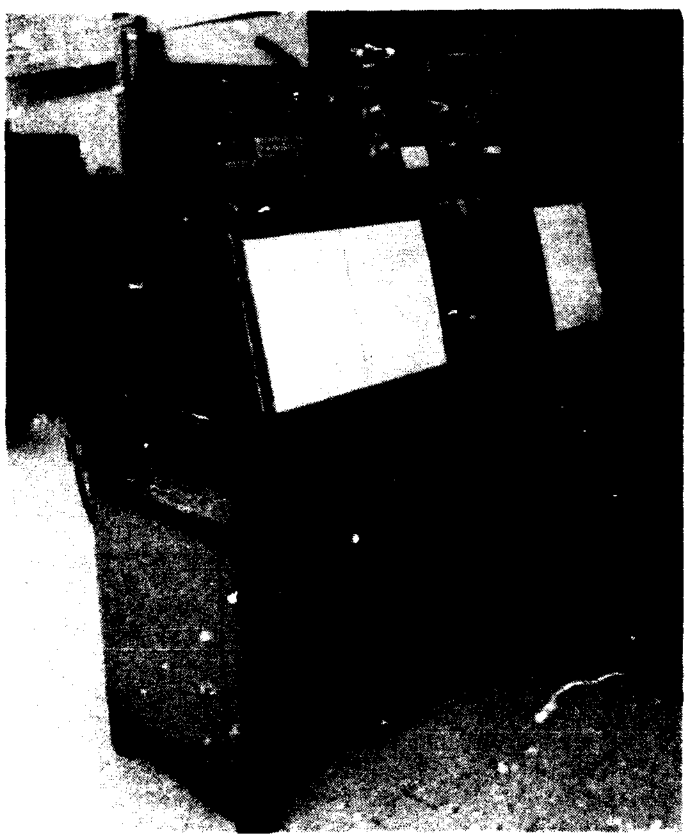


Figure 2.7. QUV Weathering Apparatus.

followed by 5 hours of condensation. This cycle was repeated as needed to fill the required total exposure duration. One equivalent year of QUV weathering was 192 hours of exposure (including both radiation and condensation hours). The cycle and exposure times had been computed under previous test programs based on weather data for Phoenix, Arizona.[8,9,10] The temperature during the entire exposure was 120±10°F.

All stripping and recoating was accomplished by the vendor. Both sides of the sheets were stripped and recoated with identical formulations of C-254 coating. As previously mentioned, the stripping process involves sanding of the coating, but the particular details of this process (and the recoating process) are proprietary to the canopy manufacturer.

2.4 MTS Beam Tests

All MTS beams were loaded in three-point bending with the conditioned surface in tension using a nominal 4.5-inch span in accordance with ASTM Method F736-81[6] and 0.75-inch-diameter supports and loading nose. The relatively short span specified in the falling weight method was chosen for the MTS tests to ensure that results could be correlated with falling weight tests (Section 2.5) and because a long span allows the highly ductile polycarbonate to push through the supports without failure (fracture). A high performance, high rate, open loop test system that included an axial load frame, load cell, displacement transducer, compressed nitrogen drive unit, and computer controller/recorder, manufactured by MTS Systems Corporation, was used for all testing. Figure 2.8 shows the test setup.

From Figure 2.8, it is apparent that the loading nose was not in contact with the specimen at the beginning of each test. Instead, it was located approximately 7 inches

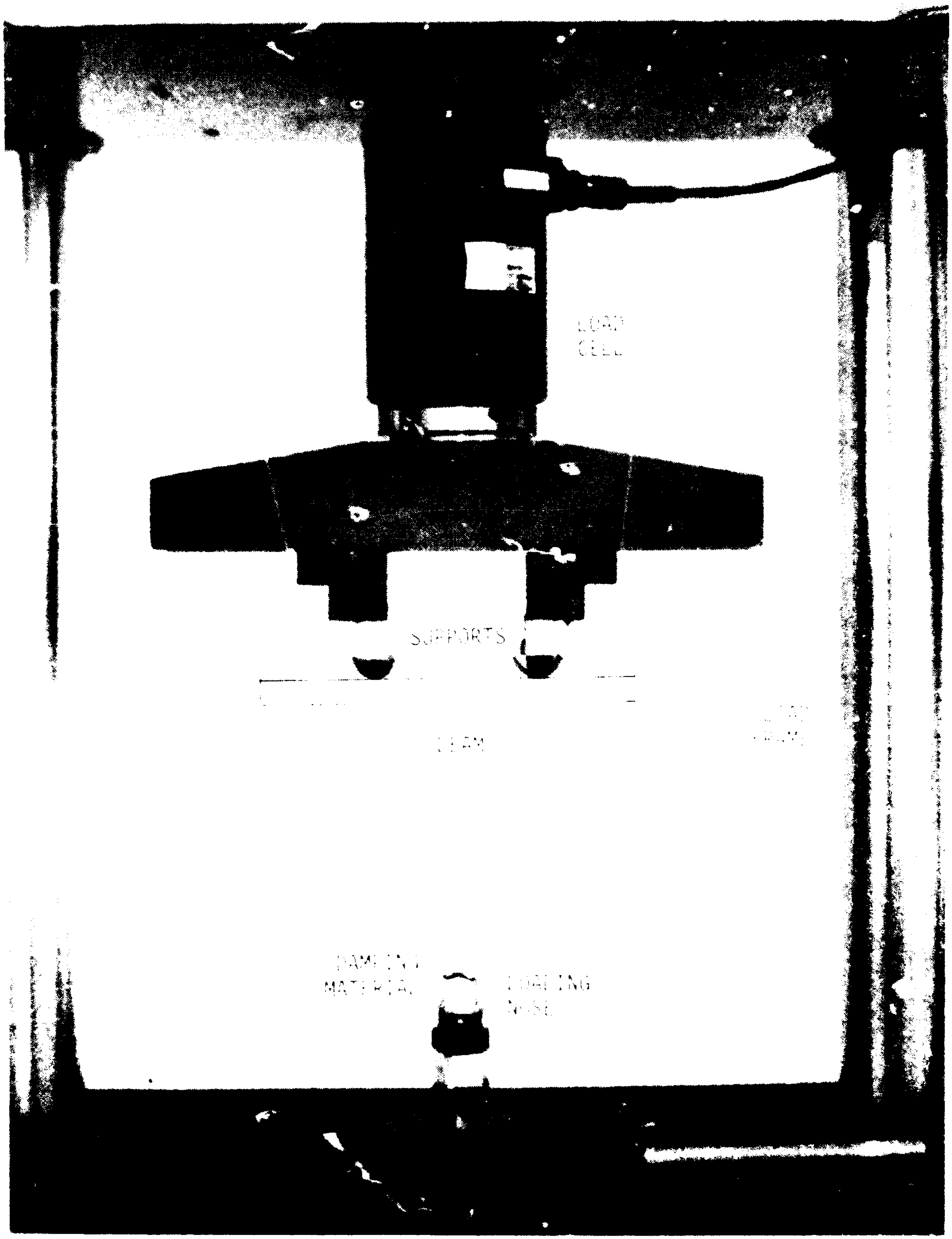


Figure 2.8. MLD Test Setup.

from the specimen to allow it to attain the desired deflection rate (loading velocity) of 40,000 in/min. Note that since the system was operated in open loop (no feedback control) configuration, this loading rate was not maintained during test, but decreased after loading nose impact. The open loop configuration was used because the high strain rates desired could not be obtained using the slower, closed loop configuration. The 40,000 in/min deflection rate resulted in a calculated initial strain rate in the beam of nearly 150 in/in/sec, characteristic of expected transparency strain rates during impact (UDRI has computed strain rates of 100-450 in/in/sec from a limited number of high-speed films of birdstrike tests on T-38 and F-111 windshields). Appendix A of Reference 2 details the strain rate calculation for beams subjected to three-point bending. The maximum displacement of the loading nose after impact with the specimen was limited to 3.5 inches, excluding any compression of the load nose pads and necking/compression of the specimen. A computer stored load and displacement data generated by transducers mounted in the loading nose assembly. Graphs of load versus displacement were obtained subsequent to testing by sending the data from the computer to an X-Y pen plotter. Based on earlier studies,[2] strong transient vibrations caused by the shock of loading nose impact were damped by wrapping Cabot Corporation's C1002-12 damping material around the loading nose and the supports. The thicknesses were 0.25 inch for the loading nose wrap and 0.125 inch for the support wrap.

2.5 Falling Weight Beam Tests

The falling weight beam specimens were tested in accordance with ASTM Method F736-81. The span was 4.5 inches and the diameter of the loading nose and supports was 0.25 inch. No damping material was required for these tests.

Figure 2.9 shows the UDRI Falling Weight Impact Test Apparatus used for the testing. It consisted of a supporting frame and concrete base; adjustable-span reaction

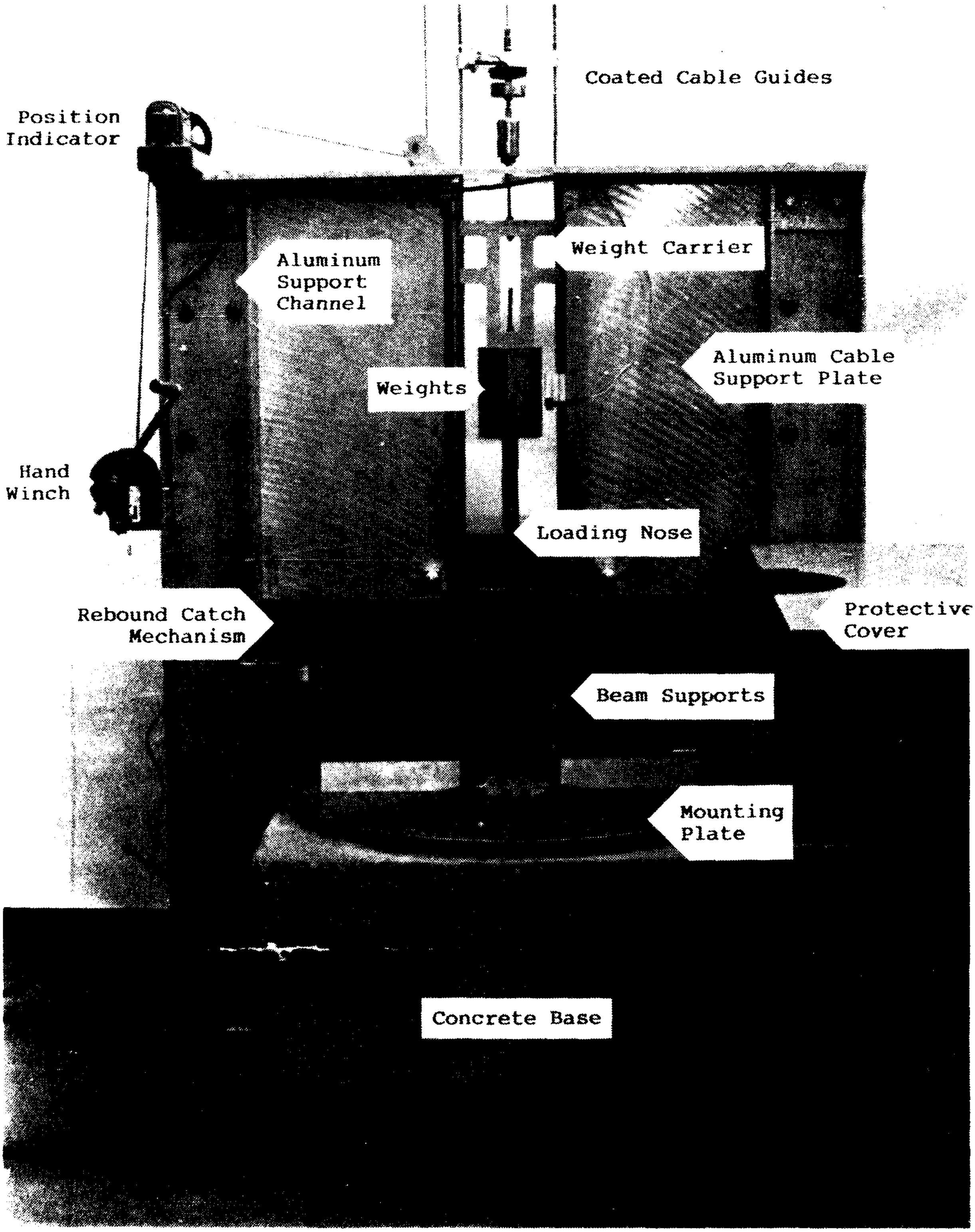


Figure 2.9. Falling Weight Test Apparatus.

supports; loading nose; detachable, interchangeable, and variable-mass drop weights; a two-cable system to guide the falling weight to the center of the specimen at a velocity approaching free fall; automatic release mechanism; and rebound catch mechanism.

The energy absorbed by the specimens was assumed to be the potential energy of the drop weight assembly relative to the test specimen, and was computed from

$$E = Wh$$

where

E = absorbed energy, in inch-pounds;

W = weight of loading nose, release mechanism, and drop weight, in pounds;

h = drop height, in inches.

Absorbed energies computed from the MTS load-displacement plots were used as a guide in selecting W and h for the falling weight tests.

The desired failure mode was a visible open crack on the tension surface of the specimen, as shown in Figure 2.10. The drop weight and height were varied from their initial values until this failure mode was achieved. The remaining specimens were then tested at the revised weight and height values to verify the threshold-of-failure energy.

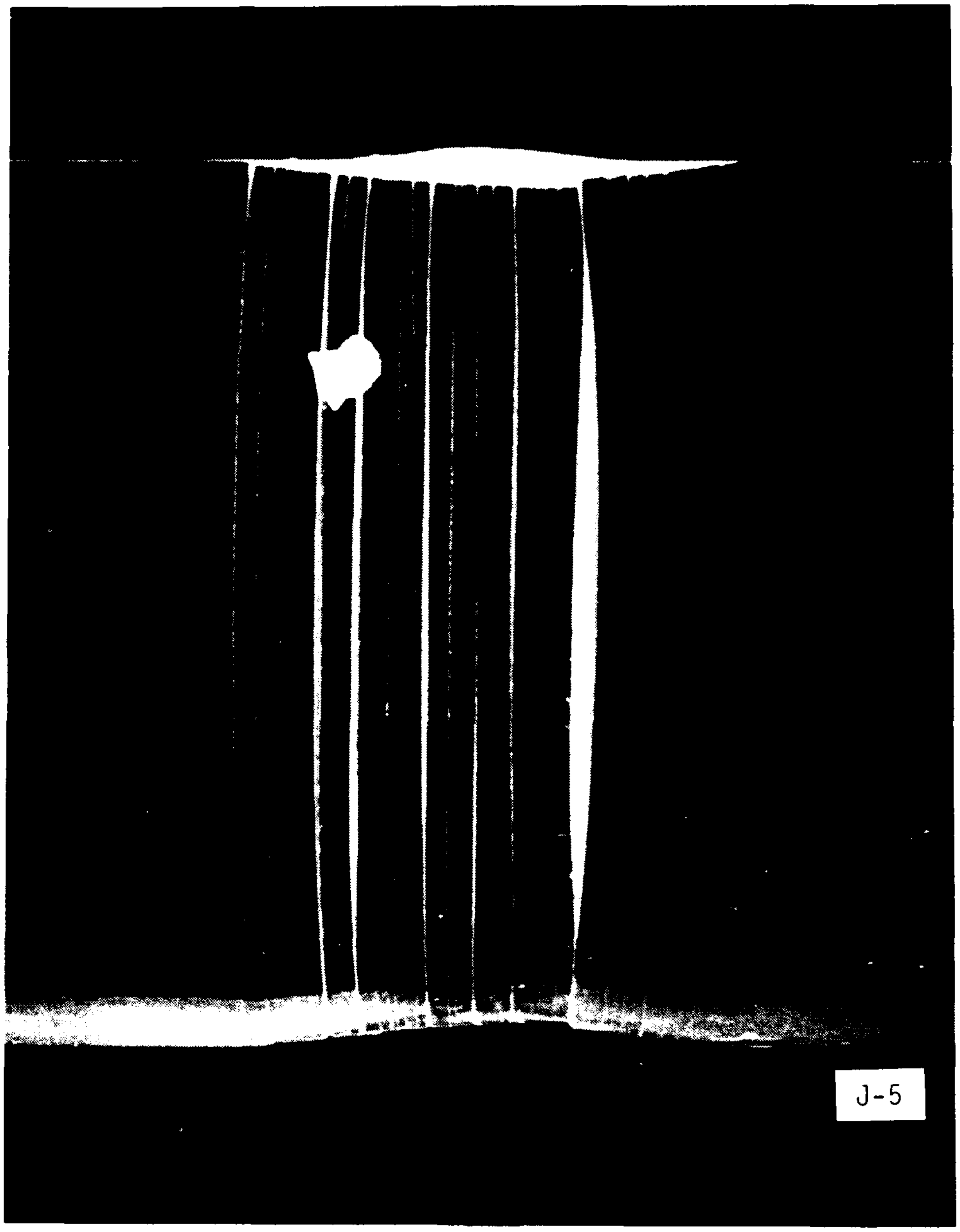


Figure 2.10. Threshold of Failure Cracking.

SECTION 3
RESULTS AND DISCUSSION

A total of 39 MTS beam tests and 52 falling weight beam tests were performed, with the results for each test being detailed in Appendices A and B. Figure 3.1 presents typical MTS load-displacement curves from which the data was derived. The data were obtained using the procedure documented in Appendix C of Reference 2. Tables 3.1 and 3.2 summarize the average values and standard deviations for each group of MTS and falling weight specimens. Figure 3.2 contains the same data as Tables 3.1 and 3.2, but in bar chart form for easier visualization and comparison of results. The height of the small "T" on top of the bars represents one standard deviation.

From Figure 3.2, the absorbed energy and maximum displacement show significant variation from one group to another, indicating that these quantities were sensitive to the various means of pretest conditioning that were employed. On the other hand, the peak load and flexural modulus show relatively little sensitivity to changes in pretest conditioning. Because of these trends, absorbed energy and maximum displacement are the data of primary interest in the evaluation of the recoated material which follows.

From Figure 3.2, it is also evident that the falling weight absorbed energies were generally much less than the MTS absorbed energies. The difference was primarily due to the fact that two different energies were being computed. For the falling weight test, the energy being computed was the failure energy, which was the energy required to produce a visible open crack in the specimen tension surface. For the MTS test, the computed energy accounted for all energy absorbed, which included the failure energy and

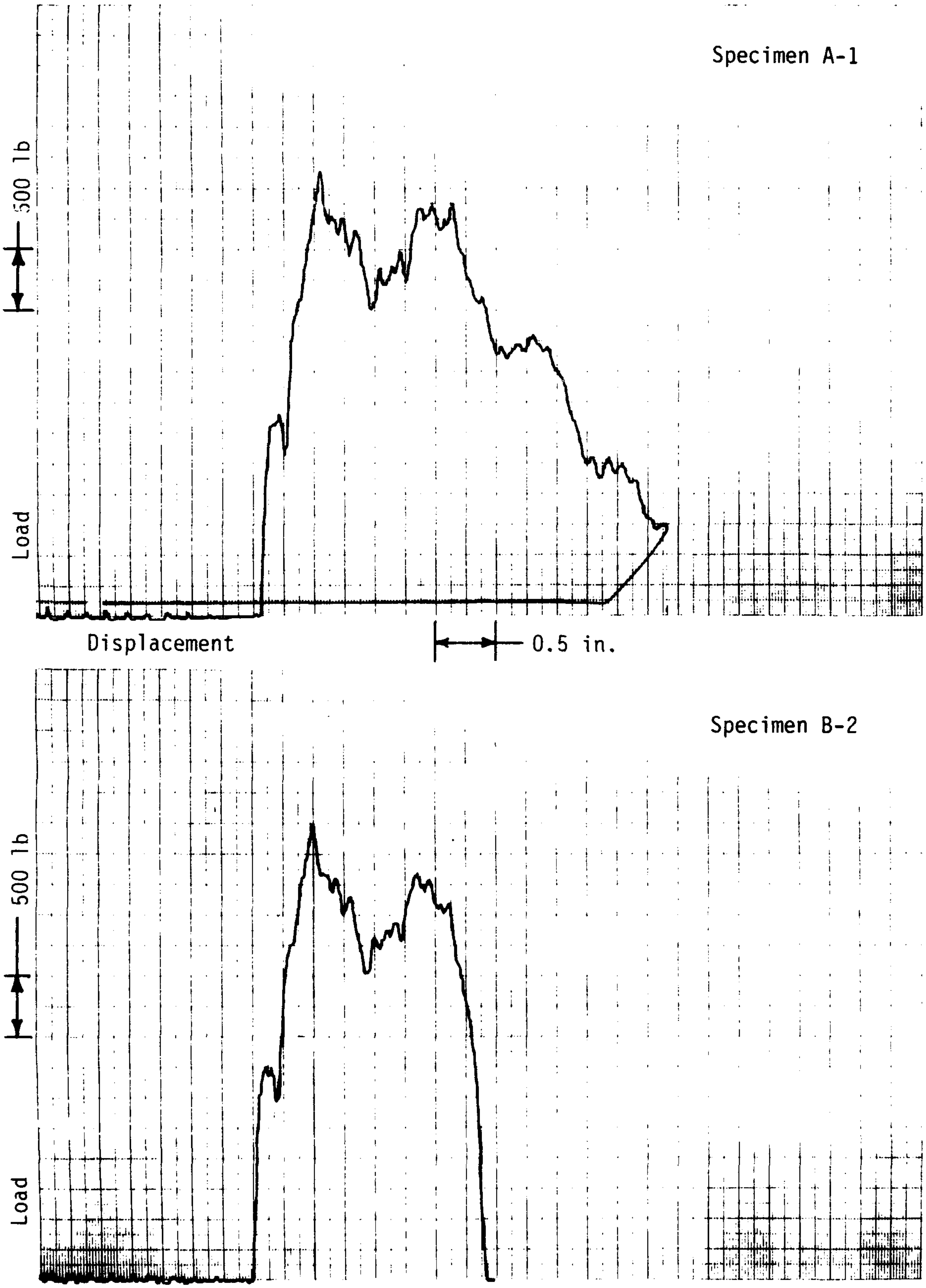


Figure 3.1. Typical MTS Load-Displacement Curves, 40,000 in/min Deflection Rate.

TABLE 3.1

SUMMARY OF MTS BEAM TEST RESULTS

Specimen Group	Peak Load (lb)	Displacement at Peak Load (in)	Flexural Modulus (ksi)	Absorbed Energy (in-lb)	Maximum Displacement (in)
A	3275	0.48	292.	7386	3.71
	223	0.	24.	227	0.02
B	3723	0.5	293.	5158	1.94
	91	0.01	27.	24	0.06
C	4375	0.57	384.	5643	2.74
	49	0.01	25.	593	0.23
D	3772	0.52	317.	4787	2.76
	73	0.01	26	412	0.21
E	4382	0.49	356	4951	1.78
	137	0.05	2	176	0.08
F	4168	0.49	319	4236	1.55
	125	0.02	11	465	0.16
G	4350	0.51	412	7073	2.88
	265	0.01	25	17	0.4
H	3912	0.51	306	7346	3.89
	122	0.01	27	174	0.13

TABLE 3.1 (continued)

Specimen Group	Peak Load (lb)	Displacement at Peak Load (in)	Flexural Modulus (ksi)	Absorbed Energy (in-lb)	Maximum Displacement (in)
I	4353	0.54	329	7522	3.69
	71	0.01	23	296	0.27
J	4478	0.56	346	5741	2.47
	38	0.01	21	958	0.69
K	3653	0.47	337	3678	2.09
	237	0.06	35	0	0.
L	4500	0.54	352	4168	1.51
	28	0.03	19	100	0.04
M	4487	0.55	327	4276	1.60
	28	0.02	20	569	0.20

Note: Computed strain rate for all tests was approximately 150 in./in./sec.

TABLE 3.2

SUMMARY OF FALLING WEIGHT TEST DATA

Specimen Group	Strain Rate [a] (in./in./sec.)	Failure Energy (in-lbs)
B	76	1560
C	92	<2420[b]
D	71	2510
E	56	1560
G	91	>2360[c]
H	84	6860
I	69	5710
J	84	2040
K	61	1820
L	59	1720

[a] Strain rate computed per Appendix A of Reference 2.

[b] Failure energy is less than the reported value.

[c] Failure energy is greater than the reported value.

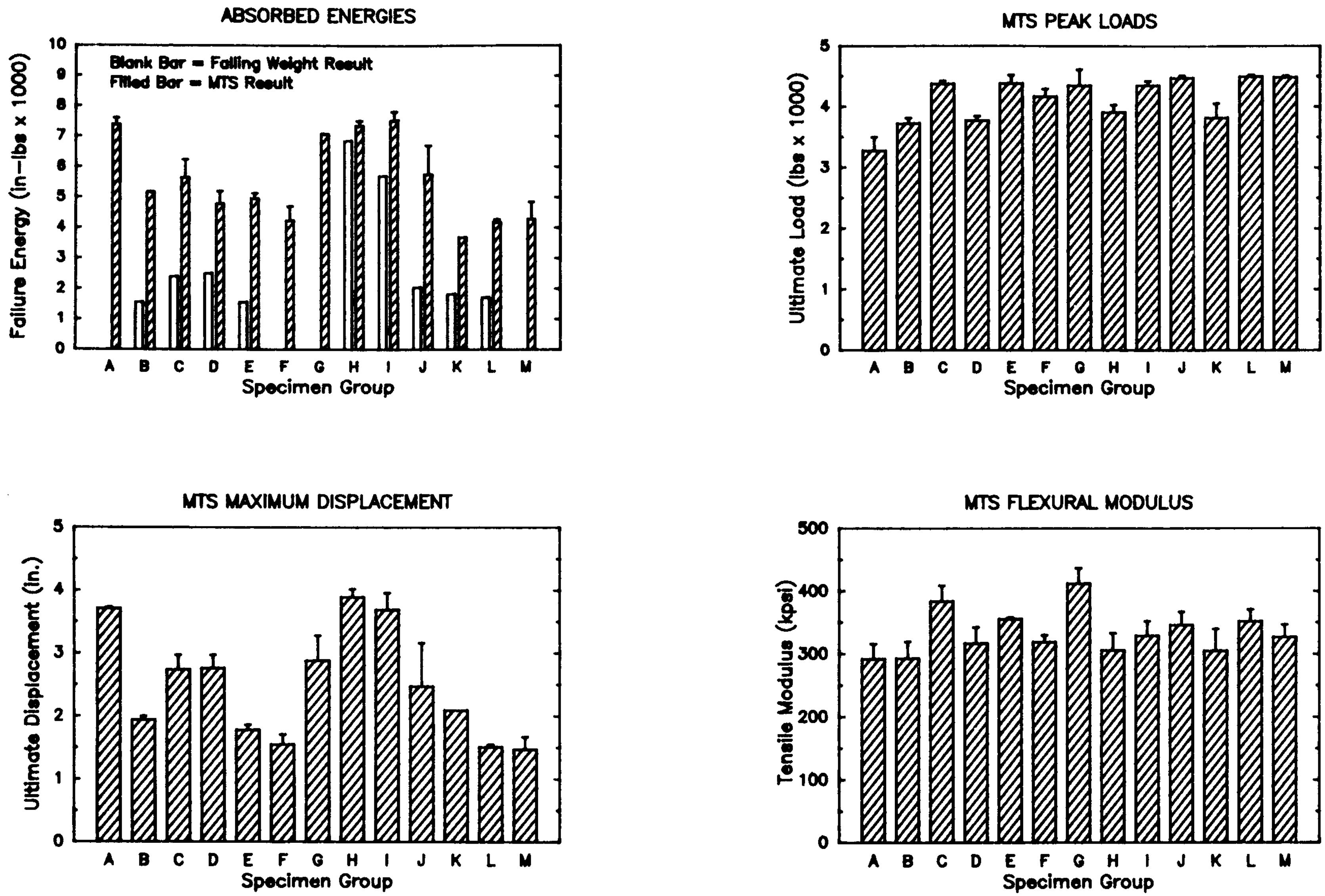


Figure 3.2. (Re)Coated F-16A Monolithic Polycarbonate Flat Sheet Beam Test Results.

any energy absorbed after initial cracking occurred. The results for groups H and I, which were exceptions to this general trend, are discussed in Section 3.3.

Another difference between MTS and falling weight results was in the computed strain rate values. The MTS value (150 in/in/sec) was 1.6-2.7 times greater than the falling weight values (56-92 in/in/sec). The difference occurred because the falling weight drop heights were not high enough to achieve impactor velocities which would produce values comparable to the MTS values.

3.1 Baseline Results

Figure 3.3 presents the average test results for the as-received and stripped baseline cases. The absorbed energy and maximum displacement for the as-received coated specimens (Group B) were markedly decreased compared to the stripped specimens (Group A). The absorbed energy decreased from 7390 *in-lb to 5160 in-lb* (a 43% decrease) while the maximum displacement decreased from 3.71 in to 1.94 in (a 91% decrease). The data indicate that the newly applied coating reduced the impact resistance of the uncoated polycarbonate sheet. This reduction in impact resistance because of the coating was consistent with the findings of previous research conducted on F-16A coated monolithic polycarbonate material.[2,11]

3.2 Results for Laboratory Storage With and Without Stripping/Recoating

Figure 3.4 presents the average test results for those specimens subjected to laboratory storage and, for three cases, stripping and recoating. Also presented for comparison are the baseline results. Specimen group F, which retained its original coating and which received the longest storage time, 25 months, experienced no significant loss in impact resistance. The absorbed energy was similar to the coated baseline (Case B)

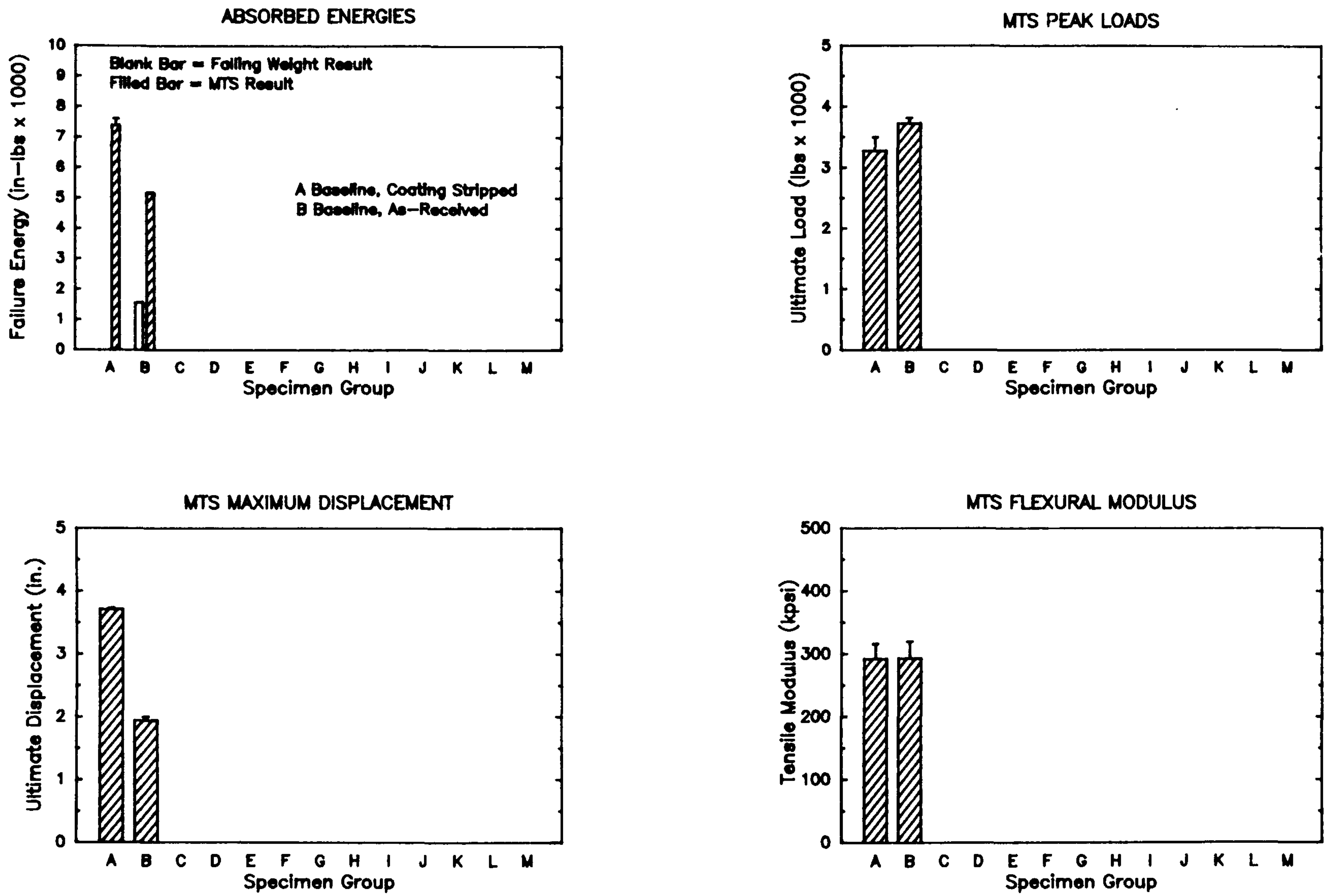


Figure 3.3. Baseline Flat Sheet Beam Test Results.

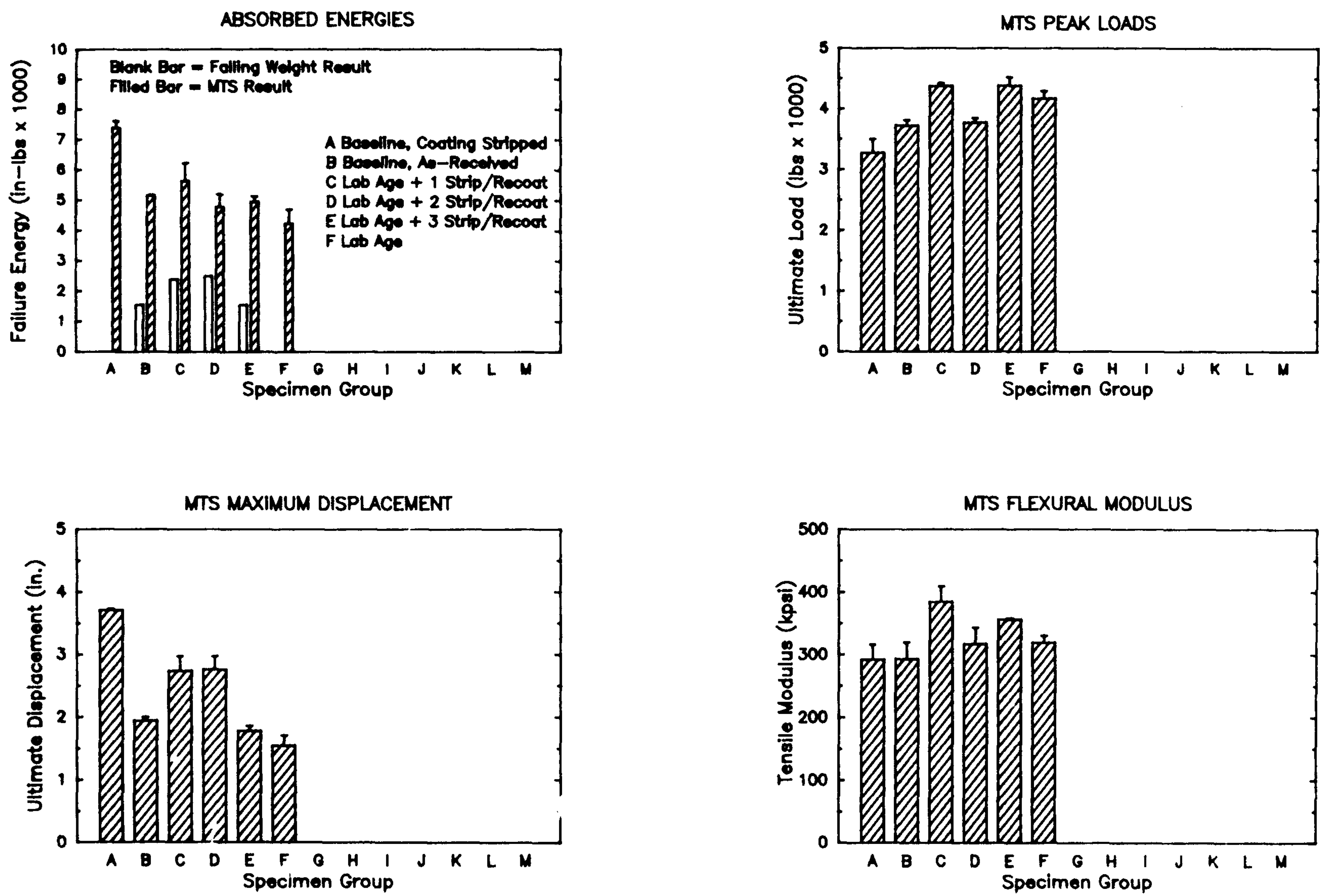


Figure 3.4. Flat Sheet Beam Test Results for Specimens Stored in Laboratory and Stripped/Recoated.

results while the maximum displacement was greater than or equal to the Case B results (but not up to the maximum displacement of the Case A stripped specimens). The results therefore indicate that 24 months storage in the controlled laboratory environment did not degrade the impact resistance of the coated polycarbonate sheet. The results also indicate that the stripping and recoating process, in conjunction with the laboratory storage, did not degrade the impact resistance, even for samples which were stripped and recoated three times.

3.3 QUV Weathering Results

Figure 3.5 presents the average test results for those specimens subjected to QUV weathering. Also presented for comparison are the baseline results. The absorbed energies and maximum displacements were similar to those for the stripped (Case A) baseline specimens even though all samples receiving QUV weathering were coated. The results show that the QUV weathering alleviated the embrittling effect of the coating, restoring the impact resistance of the coated polycarbonate to levels obtained by uncoated polycarbonate. (However, as discussed in Section 3.5, there was a significant decrease in coating adhesion owing to the QUV weathering.) Nearly all of the increase in absorbed energy was obtained in the first equivalent year of weathering, with only slight increases occurring thereafter. Note finally that the falling weight energies were approaching the values of the MTS energies. The specimens for these groups experienced extensive ductile deformation prior to cracking. Therefore little energy was absorbed after cracking, so that the falling weight and MTS energies nearly coincided. These same trends (in QUV effects on coated monolithic F-16A polycarbonate impact resistance and on MTS versus falling weight absorbed energies) have been noted in other studies conducted on F-16 coated monolithic polycarbonate material.[2,10]

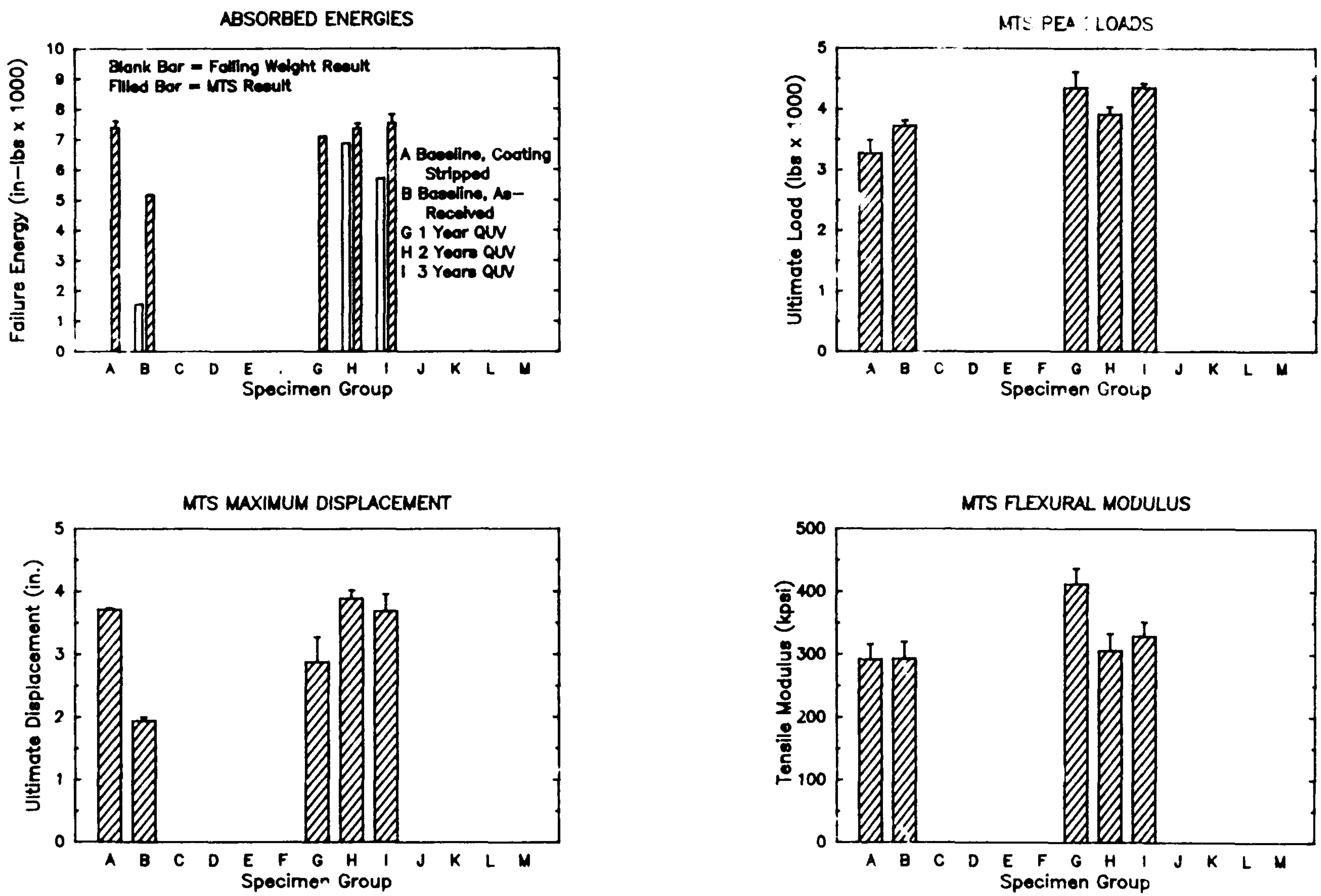


Figure 3.5. Flat Sheet Beam Test Results for Specimens Weathered in QUV.

3.4 Results for QUV Weathering With Stripping/Recoating

Figure 3.6 presents the average test results for those specimens subjected to QUV weathering and subsequent stripping and recoating. Three groups (J, K, and L) were stripped and recoated after each equivalent year of QUV weathering while one group (M) was recoated after 3 equivalent years of QUV weathering. The MTS absorbed energy and maximum displacement data for groups J, K, and L show fairly significant differences, for unknown reasons. Even so, these data, along with the falling weight data, indicate that the impact resistances for these groups, and also for group M, were similar to the baseline coated impact resistance. Therefore there appears to have been no degradation of impact resistance because of the combined QUV weathering and stripping/recoating processing. Note that the increase in impact resistance because of QUV weathering discussed in Section 3.3 was not evident in the results for groups J, K, L, and M because stripping and recoating followed all weathering for these groups. The stripping and recoating process thus appears to have restored the weathered specimens to "like-new" condition from the standpoint of impact resistance.

Finally, there was no significant difference in impact resistance between the specimens which were stripped and recoated after each of 3 equivalent years (group L) and those which were stripped and recoated after completing 3 continuous equivalent years of QUV weathering (group M). Thus the accumulation of several strip and recoats did not degrade the impact resistance relative to either the baseline results or to the results for specimens receiving only a single strip and recoat. These results for multiple strips/recoats agree with those of Section 3.2.

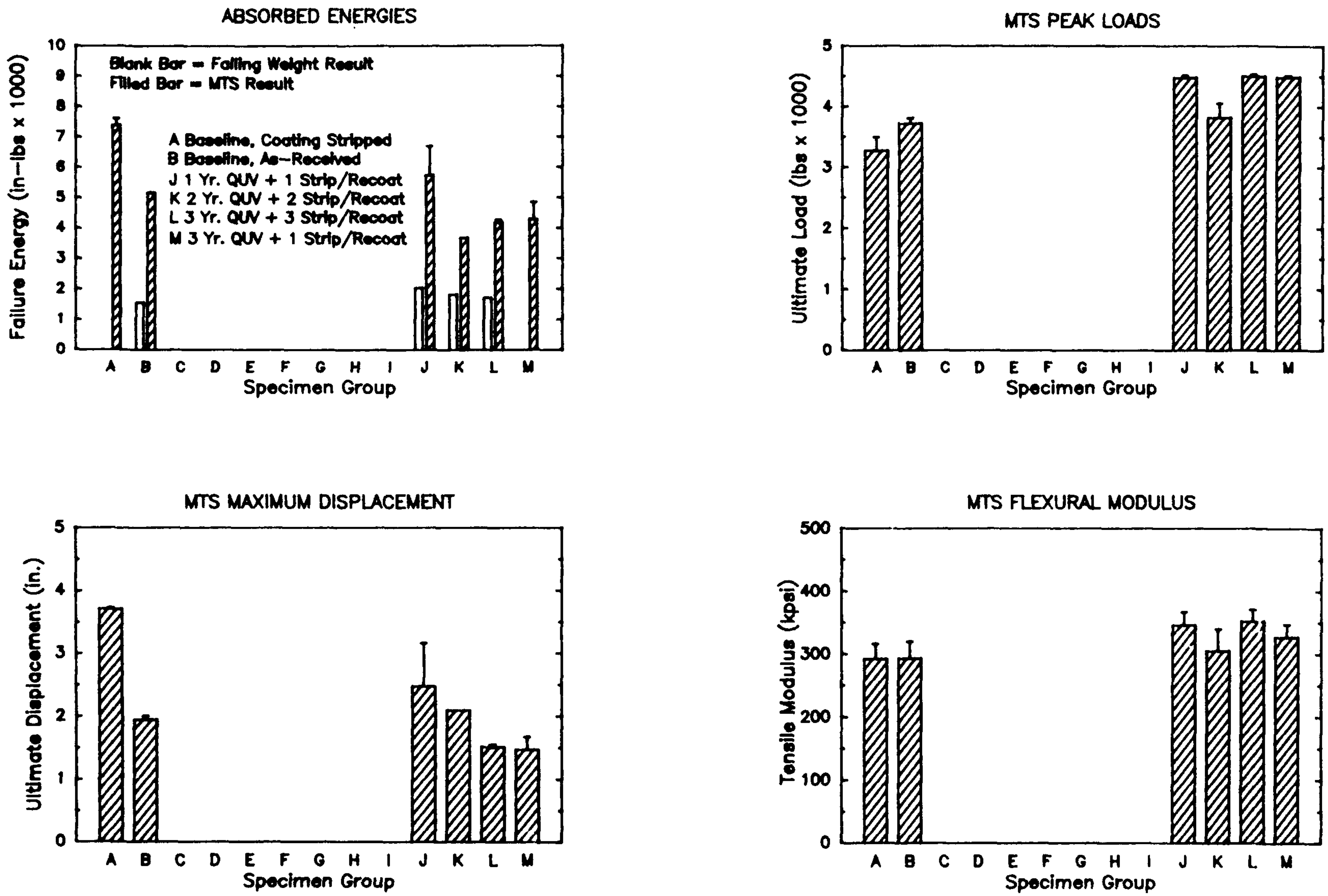


Figure 3.6. Flat Sheet Beam Test Results for Specimens Weathered in QUV and Stripped/Recoated.

3.5 Comparison With Recoated Canopy Specimen Results

Reference 2 includes discussion of MTS and falling weight three-point beam tests performed on F-16A forward monolithic polycarbonate canopies that had been recoated and, in some cases, had been subjected to additional service life after recoating. Table 3.3 summarizes the recoated canopy specimen groups and service history. Commercially-available uncoated Lexan served as a baseline for these tests. Figure 3.7 presents a bar chart summary of the MTS test results. The results are directly comparable to Figures 3.2-3.6 since all test conditions were similar.

Comparing stripped baseline results (group A) from Figure 3.1 with the results for stripped specimens (groups 166, 320, 512, 408, and 525) from Figure 3.7 reveals excellent agreement in MTS absorbed energies and maximum displacements. The absorbed energy and maximum displacement for the group A flat sheet specimens was 7386 in-lb and 3.71 in, respectively, compared to 6711-7600 in-lb and 3.68-3.86 in for the canopy specimens. The magnitudes of the peak loads and flexural moduli of the flat sheet and canopy specimens were also similar. As with the flat sheet specimens, the flexural moduli of the canopy specimens showed no correlation with pretest conditioning (service life). The canopy specimen peak load showed some correlation with service life (no correlation was evident for the flat sheet specimens), with the peak load for the newly recoated canopy specimens (groups 166 and 320) being approximately 25% less than the peak loads for the canopy specimens which had received service life after recoating (groups 512, 408) or original coating.

Comparing the test data for the newly coated flat sheet specimens (group B) with the newly recoated canopy specimens (groups 166 and 320) shows a considerable difference in impact resistance. The canopy specimen energies were 86% less than the flat sheet energies (720 in-lb versus 5160 in-lb) while the maximum displacements were

TABLE 3.3

HISTORY OF RECOATED F-16A CANOPY BEAMS

(From Reference 2)

Specimen Group*	Months of Service Before Recoating	Canopy Recoated?	Months of Service After Recoating
Lexan	0	No	-
166	51	Yes	0
320	41	Yes	0
512	16	Yes	17
408	11	Yes	22
525	35	No	-

*Number indicates serial number of canopy. "Lexan" denotes commercial-grade, uncoated polycarbonate used as a baseline.

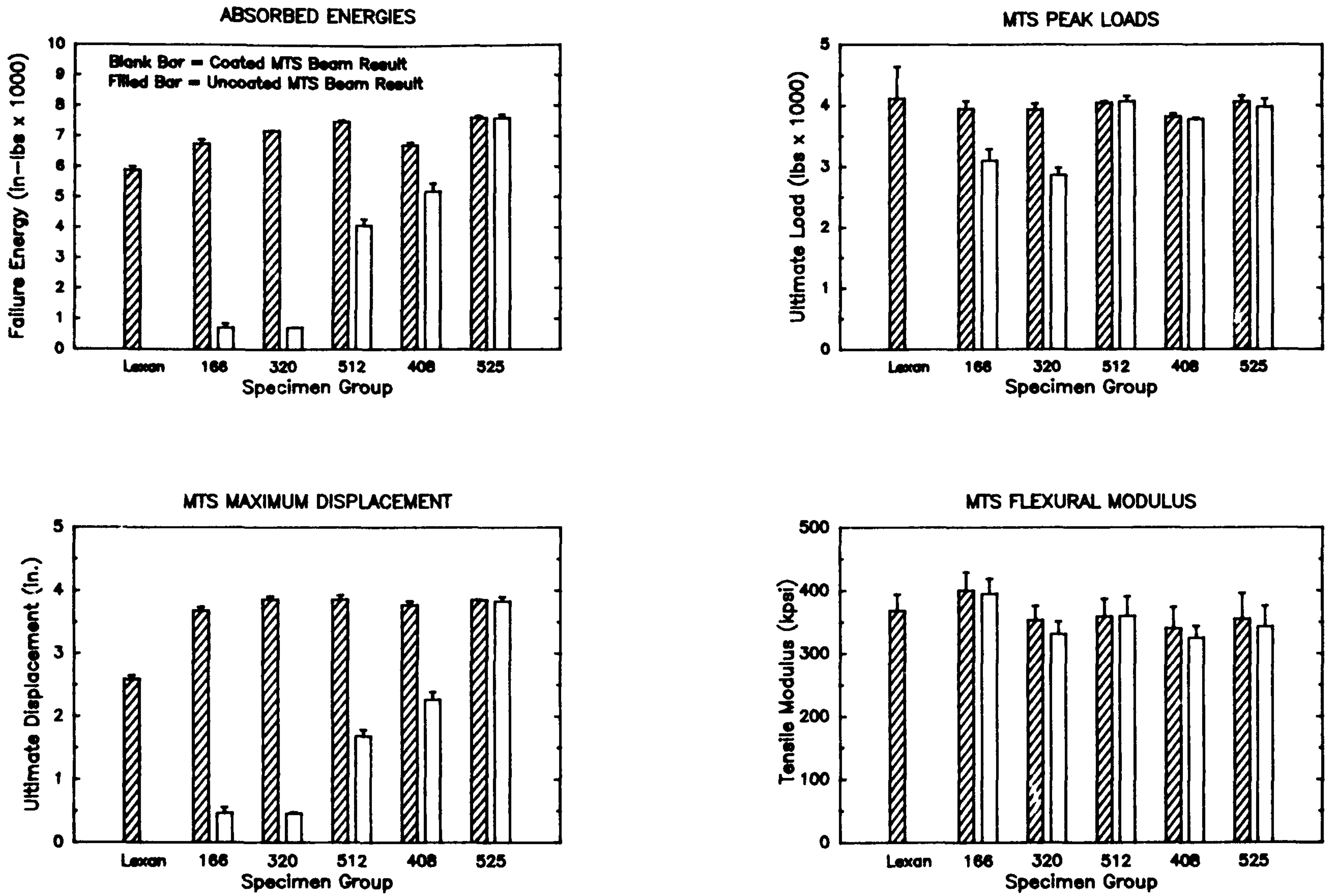


Figure 3.7. Recoated F-16A Monolithic Canopy Beam Test Results (Reference 2).

76% less (0.46 in versus 1.94 in). The small differences in specimen thickness and test span (10% at most) could not account for these sharp differences. The data appear to indicate that the differences were due to differences in the C-254 coatings that were applied to both the flat sheets and canopies. It is known that various formulations of the C-254 coating can be produced which can adjust the coating hardness. It appears that the flat sheet material received a softer coating formulation than the canopies. Despite the differences in the resulting data, the data trends for the flat sheet and canopy coated specimens were the same (i.e., absorbed energy and maximum displacement for uncoated/stripped material is greater than those of a newly coated material, and increasing weathering/service life duration results in increasing absorbed energy and maximum displacement).

The absorbed energy and maximum displacement for the coated canopy specimens show increasing impact resistance with increasing service life. The impact resistance reached the same level as the stripped canopy specimens for canopy 525 after 35 months of service life following the application of the initial coating. Note that for the flat sheet coated samples, the impact resistance reached levels comparable to the stripped specimens after only 1 equivalent year of QUV weathering. One equivalent year of QUV weathering was therefore possibly equivalent to 3 years of service life of canopy 525 in terms of achieving similar effects on impact resistance. (As discussed above, the flat sheet coating was apparently softer than that applied to the canopies, so that not as much coating degradation was required to reach impact resistance levels typical of uncoated material. Therefore it is possible that 1 equivalent year of QUV could equal less than 3 years of canopy 525 service life.) With respect to impact resistance of coated monolithic polycarbonate, the QUV cycle times and duration for 1 equivalent year of weathering may have been too severe to simulate the effects of 1 actual year of canopy service life. The severe effects of QUV weathering on impact and craze resistance have been noted in previous studies.[9,10]

Figures 3.8 and 3.9 present failure modes for the flat sheet and canopy beams, respectively. The baseline stripped (B) and Lexan (L) baseline beams showed excellent ductile deformation, although the Lexan beams cracked deeply for unknown reasons. The newly coated (A) and recoated (M and 166) beams showed little permanent deformation prior to fracture into two pieces. The beams with the original coating and subsequent QUV weathering (I) or service life (525) showed excellent ductile deformation. All of the QUV beams (G, H, and I) showed excellent ductility, although the G beams all fractured into two pieces, two of the H beams fractured into two pieces, and only one of the I beams fractured into two pieces. None of the canopy 525 beams fractured into two pieces. Yield lines in the coatings of the flat sheet and canopy beams were similar. The newly coated beams had coarsely-spaced transverse yield lines which penetrated deep into the polycarbonate substrate as a result of testing. With increasing service life or QUV weathering, the lines became more closely spaced and shallow, giving a hazy appearance to the test surface. For the 2 and 3-year flat-sheet beams with the original coating and QUV weathering (H and I) and the canopy beams with the original coating and service life (525), the coating adhesion was reduced significantly, so that the yield lines did not penetrate the polycarbonate substrate and the coating was easily removed by scratching by a fingernail. In summary, the failure modes of both the flat sheet and canopy beams (1) compared favorably, (2) indicated that increasing QUV weathering or service life resulted in increased ductile deformation during testing, and (3) indicated reduced coating adhesion with increasing QUV weathering or service life.

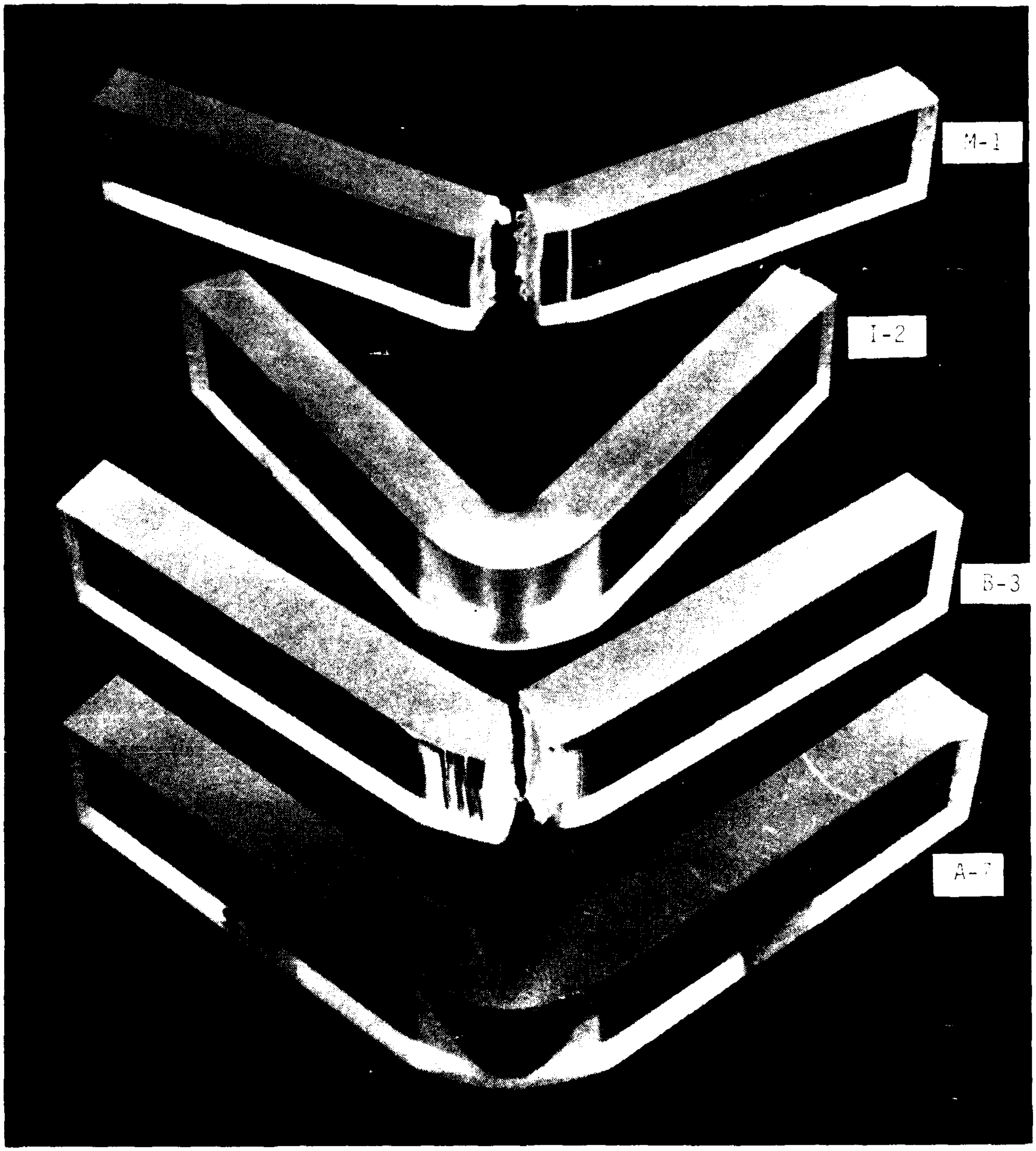


Figure 3.8. Typical Failure Modes for the Flat Sheet Beams.

Figure 3.9. Typical Failure Modes for the [illegible].

SECTION 4
CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

As a result of this investigation, it was determined that the strip and recoat process did not degrade the impact resistance of the coated polycarbonate material relative to the baseline coated material. From the standpoint of impact resistance, the process restored the polycarbonate to its original newly-fabricated, newly-coated state, regardless of previous conditioning (laboratory storage or QUV weathering). Other conclusions are noted below.

1. Changes in pretest conditioning caused noticeable changes in absorbed energy and maximum displacement of the beam specimens, so that these quantities provided an accurate characterization of the impact resistance of the conditioned polycarbonate. Peak load and flexural modulus showed little-to-no correlation with changes in pretest conditioning.

2. The impact resistance of the new coated polycarbonate flat sheet was significantly less than that of new uncoated polycarbonate material (30% reduction in absorbed energy and 50% reduction in maximum displacement).

3. Laboratory storage of up to 24 months did not change the impact resistance of the coated polycarbonate.

4. QUV weathering increased the impact resistance of the coated polycarbonate up to levels comparable to the uncoated (stripped) polycarbonate. Virtually all of the increase was accomplished in the first equivalent year of weathering.

5. The falling weight energies were generally much less than the MTS energies since the falling weight energies included only the energy required to produce a visible, open crack, while the MTS energies also included the energy absorbed after initial cracking. The falling weight and MTS energies were very similar after QUV weathering, however, since such specimens experienced considerable deformation before cracking (that is, not much additional energy was absorbed after cracking).

6. The QUV weathering produced effects on F-16 coated polycarbonate that were similar to the effects resulting from service life (increased impact energy and maximum displacement, decreased coating adhesion and yield line depth, and increased ductility). However, the cycle times and/or duration for one equivalent year of QUV weathering appeared to be too severe.

4.2 Recommendations

As a result of this investigation, it is recommended that further tests be conducted to better establish the relationship between QUV duration and service life duration for F-16A coated monolithic polycarbonate. The current investigation shows that the QUV weathering produced effects on impact resistance that were similar to the effects produced by service aging, but that the definition for an equivalent year of QUV weathering was too severe. The additional testing would redefine the QUV equivalent year so that it better simulated the effects of a calendar year of F-16 canopy service life (based on canopies 408 and 525).

MTS tests would be conducted on beams fabricated from F-16A canopies 166 and 320 (recoated with no subsequent service life) which had been subjected to QUV weathering for various lengths of time. The MTS results as well as failure mode observations would be correlated with the existing results for canopies 408 and 525, which exp r nced 27 and 39 months of service life, respectively, after coating/recoating. The hours of QUV weathering which produced results similar to 27 and/or 39 months of service life would thus be established. From this relationship, the duration of QUV weathering which produced impact resistance results similar to those for 1 year of service life (that is, service life typical of that for canopies 408 and 525) could easily be computed, thus defining a revised equivalent year for the QUV weathering apparatus. Such a definition would only be appropriate for F-16A monolithic polycarbonate canopies coated with C-254 which experience service lives similar to those for canopies 408 and 525. Further testing would be needed to establish the QUV equivalent year for other coatings, canopy outer ply materials, and/or service histories.

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APPENDIX A

MTS BEAM TEST RESULTS

	Peak Load (lb)	Displacement at Peak Load (in)	Flexural Modulus (ksi)	Absorbed Energy (in-lb)	Maximum Displacement (in)
A-1	3530	0.48	311	7632	3.73
A-2	3160	0.48	265	7344	3.70
A-3	3130	1.29*	301	7183	3.70
Avg.	3275	0.48	292	7386	3.71
St. Dev.	223	0.	24	227	0.02
B-1	3805	0.49	266	5134	1.90
B-2	3740	0.50	295	5181	1.93
B-3	3625	0.50	319	5160	1.99
Avg.	3723	0.50	293	5158	1.94
St. Dev.	91.2	0.01	27	24	0.06
C-1	3190*	0.33*	877*	1241*	1.19*
C-4	4410	0.57	366	5223	2.57
C-7	4340	0.56	401	6062	2.94
Avg.	4375	0.565	384	5643	2.74
St. Dev.	49	0.01	25	593	0.23
D-1	3830	0.52	304	5242	2.99
D-4	3795	0.52	300	4682	2.68
D-7	3690	0.53	347	4438	2.60
Avg.	3772	0.52	317	4787	2.76
St. Dev.	73	0.01	26	412	0.21
E-1	4305	0.43	358	5132	1.72
E-4	4540	0.53	355	4940	1.76
E-6	4300	0.51	354	4780	1.87
Avg.	4382	0.49	356	4951	1.78
St. Dev.	137	0.05	2.1	176	0.08

MTS BEAM TEST RESULTS (continued)

	Peak Load (lb)	Displacement at Peak Load (in)	Flexural Modulus (ksi)	Absorbed Energy (in-lb)	Maximum Displacement (in)
F-1	4310	0.50	331	3939	1.46
F-2	4075	0.47	318	3997	1.45
F-3	4120	0.49	309	4771	1.73
Avg.	4168	0.49	319	4236	1.55
St. Dev.	125	0.02	11	465	0.16
G-1	4620	0.56	393	7065	2.57
G-4	4340	0.56	402	7062	2.74
G-7	4090	0. 58	440	7093	3.34
Avg.	4350	0.57	412	7073	2.88
St. Dev.	265	0.01	25	17	0.40
H-4	3775	0.50	321	7344	3.74
H-7	4010	0.52	275	7173	3.92
H-9	3950	0.50	323	7520	4.00
Avg.	3912	0.51	306	7346	3.89
St. Dev.	122	0.01	27	174	0.13
I-2	4435	0.55	331	7863	3.94
I-5	4310	0.54	305	7363	3.72
I-7	4315	0.54	351	7340	3.41
Avg.	4353	0.54	329	7522	3.69
Std. Dev.	71	0.01	23	296	0.27

MTS BEAM TEST RESULTS (continued)

	Peak Load (lb)	Displacement at Peak Load (in)	Flexural Modulus (ksi)	Absorbed Energy (in-lb)	Maximum Displacement (in)
J-1	4450	0.56	366	6642	2.81
J-4	4460	0.55	325	4734	1.68
J-7	4520	0.57	346	5846	2.93
Avg.	4478	0.56	346	5741	2.47
St. Dev.	38	0.01	21	958	0.69
K-1	2080*	0.03*	375	862*	0.98*
K-4	3820	0.51	305	3678	2.09
K-7	3485	0.42	330	930*	0.46*
Avg.	3683	0.47	337	3678	2.09
St. Dev.	237	0.06	35	0	0.
L-1	3200*	0.33*	593*	1089*	0.98*
L-6	4480	0.56	365	4238	1.53
L-8	4520	0.52	338	4097	1.48
Avg.	4500	0.54	352	4168	1.51
St. Dev.	28	0.03	19	100	0.04
M-1	4495	0.55	338	3884	1.47
M-2	4455	0.53	304	4016	1.49
M-3	4510	0.56	338	4929	1.83
Avg.	4487	0.55	327	4276	1.60
St. Dev.	28	0.02	20	569	0.20

*Anomalous - data not averaged.

APPENDIX B

FALLING WEIGHT TEST RESULTS

Specimen	Drop Height (ft)	Weight (lb)	Energy (ft-lb)	Failure Mode[a]
B-4	10.67	35.16	275	P
B-5	6.54	35.16	230	P
B-6	9.62	10.4	100	D
B-7	12.50	10.4	130	F
C-2	18.5	10.93	202	P
C-3	19.0	10.93	208	P
C-5	19.0	10.93	208	P
C-6	21.0	10.93	230	P
C-8	20.0	10.93	219	P
D-2	6.83	19.01	130	D
D-3	9.0	19.01	172	D
D-5	13.0	19.01	247	P
D-6	11.0	19.01	209	F
D-8	11.0	19.01	209	P[b]
E-2	6.83	18.98	130	F
E-3	8.0	18.98	152	F
E-5	10.0	18.98	190	P
E-7	9.0	18.98	171	FP
E-8	5.0	18.98	95	D
E-9	6.0	18.98	114	D

FALLING WEIGHT TEST RESULTS (continued)

Specimen	Drop Height (ft)	Weight (lb)	Energy (ft-lb)	Failure Mode[a]
G-2	12.0	10.93	131	D
G-3	13.0	10.93	142	D
G-5	18.0	10.93	197	D
G-6	16.0	10.93	175	D
G-8	15.0	10.93	164	D
H-2	10.5	19.01	200	D
H-3	13.0	19.01	247	D
H-5	16.0	19.01	304	D
H-6	15.0	26.93	404	D
H-8	17.0	29.93	509	D
H-10	14.0	45.25	634	P
I-1	10.0	45.25	453	D
I-3	15.0	45.25	679	P
I-4	12.0	45.25	543	P
I-6	11.0	45.25	498	P
I-8	9.0	45.25	407	D
I-9	10.0	45.25	453	P[b]
J-2	18.25	10.93	199	F
J-3	17.5	10.99	198	F
J-5	16.75	10.99	197	F
J-6	18.04	10.93	192	F
J-8	18.08	10.93	184	F
J-9	15.5	10.99	170	F

FALLING WEIGHT TEST RESULTS (continued)

Specimen	Drop Height (ft)	Weight (lb)	Energy (ft-lb)	Failure Mode[a]
K-2	11.0	19.01	209	P
K-3	9.0	19.01	172	F
K-5	8.0	19.01	152	F
K-6	7.0	19.01	133	D
K-8	10.0	19.01	190	P
L-2	8.0	19.01	152	F
L-3	7.0	19.01	133	D
L-4	10.0	19.01	190	P
L-5	6.0	19.01	114	D
L-7	7.5	19.01	143	F

[a]P = Penetration (deep cracking-to-complete fracture)

F = Failure threshold (crack initiation)

D = Ductile (no cracking)

[b]Edge-initiated Failure

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