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THE INSULATION IRRADIATION TEST PROGRAM FOR THE COMPACT IGNITION TOKAMAK*

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ABSTRACT

The electrical insulation for the toroidal field coils of the Compact Ignition Tokamak (CIT) is expected to be exposed to radiation doses on the order of 10^{10} rad with ≈90% of the dose from neutrons. The coils are cooled to liquid nitrogen temperature and then heated during the pulse to a peak temperature > 300 K. In a program to evaluate the effects of radiation exposure on the insulators, three types of boron-free insulation were irradiated at room temperature in the Advanced Technology Reactor (ATR) and tested at the Idaho National Engineering Laboratory. The materials were Spaulrad-S, Shikishima PG5-1, and Shikishima PG3-1. The first two use a bismaleimide resin and the third an aromatic amine hardened epoxy. Spaulrad-S is a two-dimensional (2-D) weave of S-glass, while the others are 3-D weaves of T-glass. Flexure and shear/compression samples were irradiated to approximately 5×10^9 rad and 3×10^{10} rad with 35 to 40% of the total dose from neutrons. The shear/compression samples were tested in pairs by applying an average compression of 345 MPa and then a shear load. After static tests were completed, fatigue testing was done by cycling the shear load for up to 30,000 cycles with a constant compression. The static shear strength of the samples that did not fail was then determined. Generally, shear strengths on the order of 120 MPa were measured. The behavior of the flexure and shear/compression samples was significantly different; large reductions in the flexure strength were observed, while the shear strength stayed the same or increased slightly. The 3-D weave material demonstrated higher strength and significantly less radiation damage than the 2-D material in flexure but performed nearly identically when tested with combined shear and compression. The epoxy system was much more sensitive to fatigue damage than the bismaleimide materials. No swelling was measured; however, the epoxy samples did twist slightly. Shear tests of bonded samples without compression irradiated to the same dose levels are planned for 1990. ~~Irradiation and testing~~ at liquid nitrogen temperature are planned for 1991.

INTRODUCTION

The CIT is a proposed plasma device designed to produce significant fusion power through the deuterium-tritium reaction. The coils are to be constructed from a normally conducting alloy of copper. They are cooled to liquid nitrogen temperature

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before a discharge and then heated during the pulse to above room temperature. The turn-to-turn coil insulation is to be designed for a radiation dose of 10^{10} rad with ≈90% of the dose from neutrons. The initial design concept used unbonded 1-mm-thick sheets of insulation between plates, with high shear loads to be accommodated by surface roughness treatment and simultaneous high compressive loads developed from the coil centering forces.

Special fixtures were developed for testing small insulation sheet samples with both compression and interlaminar shear stress. Initial room temperature screening tests of 15 types of insulation sheet material from six vendors in combined compression and shear are described in ref. 1.

BIAXIAL TEST DEVICE

Two insulation samples, 12.7 × 12.7 × 1 mm^3, are tested simultaneously in the biaxial test device shown in Fig. 1. Each sample has a grit-blasted, 2-mm-thick Inconel backing piece on each side. These assemblies are placed on each side of a central steel block. The compressive load is applied first through the two outer steel blocks. This load is produced by a hydraulic piston and threaded rods suspended around the samples. The shear load is applied on the central block and reacted by vertical supports on the side blocks. An important feature of this configuration is that shear strain is not coupled to the compressive strain. If the shear strength integrity is lost, the sample will fail catastrophically. The shear stress can also be cycled with constant compression.

Figure 2 shows the average shear strength of Spaulrad-S vs compression measured in this test configuration. At 69-MPa compression, the failure mode was slipping with an effective coefficient of friction of 0.43. At compressions of 207, 345, and 414 MPa, the samples failed cohesively, usually in an interlaminar shear mode. No significant difference was found between the strength in the warp or fill direction. However, samples cut at 45° to the warp or fill direction showed greater strength (≈13%). At 345-MPa compression, the average shear strength was 118 MPa.

A nonlinear 2-D plane strain finite element stress analysis of this configuration was performed by H.W. Blake.[2] High compressive peaks and stress gradients were found near the upper and lower edges. The test method does appear to give good qualitative comparison between different materials. Nearly pure interlaminar shear failures were found with high compression of Spaulrad-S; the 3-D weave material from Shikishima produced more of a tearing failure.

MATERIALS

Three types of insulation sheet material, nominally 1 mm thick, were chosen for irradiation testing. Table I summarizes their properties. PG5-1 and PG3-1 were produced with a 3-D glass weave, which has been reported to have good radiation resistance and improved shear strength.[3] Spaulrad-S has also been previously tested after irradiation and shown to be resistant to radiation damage.[4,5] All three materials used boron-free glass, which has been shown to be much less sensitive to damage from thermal neutrons than E-glass with boron.[6]

Table I. Rad-I test materials

	Material		
	Spaulrad-S	PG5-1	PG3-1
Manufacturer	Spaulding[a]	Shikishima[b]	Shikishima
Resin	Bismaleimide (Kerimid 601)	Bismaleimide triazine	Bisphenol-A
Hardener	None	None	Aromatic amine
Fiber			
Material	S-2 glass	T-glass	T-glass
Preparation	Silane	Epoxy silane	Epoxy silane
Form	Fabric	3-D weave	3-D weave
Resin, wt %	26	33	29
Glass, vol. %			
Warp direction		57	57
Fill direction		34	34
Thickness direction		9	9

[a] Spaulding Composite Company, Tonawanda, N.Y.
[b] Shikishima Canvas Co., Ltd., Shiga, Japan.

IRRADIATION TEST FACILITY

Irradiation and testing were performed by EG&G at INEL. The ATR was used for the irradiation. Two aluminum sample capsules were fabricated with an inside diameter of 23.6 mm. Each capsule contained 18 shear/compression samples ($12.7 \times 12.7 \times 1$ mm^3) and 6 flexure specimens ($50 \times 5 \times 1$ mm^3) of each material. The samples were packed with aluminum foil and powder to limit the peak temperature to <340 K. Each capsule also contained four packs of six flux wire monitors. The capsule lengths were chosen to limit the pressure due to outgassing to <1.6 MPa, based on the outgassing rates in ref. 7 (2.5×10^{-3} cm^3/g·Gyfor e poxy at STP; 0.06×10^{-3} cm^3/g·Gy for polyimide at STP) and expected dose levels of 1 and 5×10^{10} rad.

To minimize the gamma heating fraction, a cylindrical lead shield with an aluminum liner was fabricated to surround the sample capsules. The 41-mm radial thickness was as large as would fit in the 127-mm-diam "I-hole" planned for the experiment while allowing for water cooling. The shield and capsules were placed so that one capsule was near the top of the core and the other was at the midplane. The upper capsule was removed after one 14-day fuel cycle; the second, after two 14-day cycles.

RADIATION DOSE AND FLUENCE ESTIMATES

Table II gives the calculated radiation doses for the top and midplane capsules. The calculations assume that all energy deposited in the resin stays in the resin. The Monte Carlo dose calculation described in ref. 1 was redone after the flux wire measurements, resulting in higher gamma doses and slightly lower neutron doses. The fast neutron fluences (>1 MeV) based on flux wire measurements are also given in Table II. Details are reported in refs. 7 and 8.

Table II. Sample dose and fluence levels

Resin	Dose (10^{10} rad)			Fast fluence (10^{18} neutrons/cm^2)
	Gamma	Neutron	Total	
Top				
Spaulding	0.34	0.20	0.54	0.5
PG 5-1	0.33	0.20	0.53	0.5
PG 3-1	0.28	0.21	0.49	0.5
Midplane				
Spaulding	2.18	1.27	3.45	2.53
PG 5-1	2.10	1.27	3.37	2.53
PG 3-1	1.79	1.34	3.13	2.53

TEST RESULTS

Flexure Strength

Six flexure specimens (51 × 5 × 1 mm^3) of each material were tested with a 25-mm span for a control group and a group from each capsule. The extreme fiber fracture stress results are shown in Fig. 3; the averages are as follows.

Material	Fracture stress (MPa)		
	Control	Top capsule	Midplane capsule
Spaulrad	675	531 (–21%)	362 (–46%)
PG 5-1	946	831 (–12%)	723 (–24%)
PG 3-1	697	548 (–21%)	699 (+0%)

The stresses were calculated based on the measured thickness after irradiation. The PG 3-1 samples were warped and the measured thickness increased 5%, which may account for some of the 21% reduction.

Shear Strength with Compression

Six 12.7 × 12.7 × 1 mm^3 shear/compression samples were tested two at a time for each material for a control group and each dose level. The results are shown in Fig. 4. The average stresses are as follows.

Material	Shear stress (MPa) with 345-MPa compression		
	Control	Top capsule	Midplane capsule
Spaulrad	125	129 (+3%)	120 (–5%)
PG 5-1	135	134 (–1%)	133 (–2%)
PG 3-1	123	119 (–4%)	137 (+11%)

The one low value from the Spaulrad-S control group was not included in these averages because it was due to a lack of grit blasting on the backing plate that resulted in a slip failure mode.

Fatigue Testing

The two bismaleimide systems (Spaulding and PG 5-1) were tested with 30,000 cyclic shear loads at 90% of the static strength with constant compression without any failures. As reported in ref. 1, the epoxy system failed at 300 and 900 cycles at 90% load (108 MPa). At 65% of the static strength (80 MPa), 30,000 cycles were completed without failure. The surviving samples from the control and irradiated groups were then tested to failure to see if fatigue damage had lowered the shear strength. The results are given in Fig. 5 and summarized as follows.

Material	Cyclic level (MPa)	Average post-fatigue shear strength (MPa) with 345-MPa compression		
		Control	Top capsule	Midplane capsule
Spaulrad	14–112	125 (–0%)	133 (+6%)	136 (+9%)
PG 5-1	14–117	130 (–3%)	130 (–3%)	129 (–4%)
PG 3-1	14–80	111(–10%)	113 (–8%)	133 (+8%)

The percentage changes given are compared to the unirradiated static control average.

Weight and Dimensions

The width and thickness of each flexure specimen were measured before and after irradiation at five equally spaced locations. The weight and length were also measured. In addition, the weight of all 18 shear/compression samples of each material group was measured.

The most significant finding was a general trend for the samples to shrink, particularly in thickness. The thickness of the PG3-1 increased for the top capsule; however, this was probably a measurement error due to warping of the samples. The average changes after irradiation are as follows.

	Change (%)				
				Weight	
Material/capsule	Thickness	Width	Length	Flex.	Stack
Spaulrad, top	−1.54	−0.37	−0.24	−0.8	−0.4
Spaulrad, midplane	−2.57	−0.74	−0.39	−0.2	−0.9
PG5-1, top	−0.67	−0.36	−0.05	+0.0	+0.2
PG5-1, midplane	−1.67	−0.65	−0.32	+1.4	+0.3
PG 3-1, top	+5.26	−0.78	−0.02	−2.2	−1.3
PG 3-1, midplane	−2.35	−0.94	−0.42	−1.2	−2.2

The weight changes are averages for the flexure samples (Flex.) and the total change for the stack of 18 shear compression samples (Stack).

The weight measurements do not show a consistent pattern; differences may be due to moisture content before irradiation. A definite pattern of shrinkage is shown. The 3-D weave material does show less shrinkage in thickness, probably because of the glass reinforcement in this direction.

CONCLUSIONS AND PLANS

There is little correlation between the reduction in flexure strength due to irradiation and the material strength in interlaminar shear, when thin samples are tested with applied compression. The interlaminar shear strength remained high for all three materials, even after exposure to 3×10^{10} rad with 40% of the dose from fast neutrons. The 3-D weave materials from Shikishima did show better strength and radiation resistance in flexure but little difference in interlaminar shear with high compression. The epoxy-based 3-D weave material demonstrated significantly more sensitivity to fatigue damage than either of the bismaleimide materials.

The large shrinkage observed should be investigated further. If a bonded system does not allow contraction, high internal stress could be generated, resulting in a loss of adhesive strength.

The current design for the CIT coils requires the turns to be bonded. Possible fabrication techniques and materials were investigated by the Applied Technology Division of Oak Ridge National Laboratory,[9] and vacuum impregnation was selected as the most promising method. Samples fabricated from $12.6 \times 12.6 \times 3.6$ mm^3 copper squares, bonded with a 1-mm bond with five layers of S-glass, are being irradiated at the ATR at room temperature. They will be tested in shear without applied compression. Flexure testing will be done on samples of the resin and tensile testing on glass filaments.

A series of cryogenic irradiations and cryogenic tests on bonded samples is planned for FY 1991, although the location and details of the testing have not yet been finalized.

ACKNOWLEDGMENT

The results presented represent the contributions of many people. While space does not permit a complete list, special credit should go to Darrel Sparks, Mike Jacox, and J. Rogers at INEL for performing the testing, dose calculations, and flux wire analysis. In addition, the vendors were very helpful in supplying the materials, particularly T. Hirokawa at Shikishima Canvas Co.

REFERENCES

1. T. J. McManamy et. al., "Insulation interlaminar shear strength testing with compression and irradiation," in Proc. IEEE 13th Symposium on Fusion Engineering (IEEE, New York, 1990), Vol. 1, pp. 342–347.

2. H. Blake, Stress Analysis of the Princeton Plasma Physics Laboratory 1/2-in. × 1/2-in. Shear/Compression Test Fixture, Oak Ridge National Laboratory Report ORNL/ATD-23, 1989.

3. S. Nishijima et al., "Development of radiation resistant composite materials for fusion magnets," presented at the ICMC Conference, Los Angeles, July 1989.

4. R. Schmunk, L Miller, and H. Becker, "Tests on irradiated magnet insulator materials," J. Nucl. Mater. 122 & 123 (1984) 1381–1385.

5. R. Coltman, Jr., and C. Klabunde, "Mechanical strength of low temperature-irradiated polyimides: A five- to tenfold improvement in dose-resistance over epoxies," J. Nucl. Mater. 103 & 104 (1981) 717–722.

6. R. Poehlchen, "The mechanical strength of irradiated electric insulation of superconducting magnets," presented at the ICMC Conference, Los Angeles, July 1989.

7. M.Jacox, Neutron and Gamma Dose Calculation for CIT Materials in the ATR I1 Position, Idaho National Engineering Laboratory Report NRRT-N-90-003, 1990.

8. J. Rodgers and R. Anderl, Neutron Monitoring Measurements for the CIT Matrials Irradiation in the ATR I1 Position," EG&G Report EGG-cS-8821,1989.

9. V. Cambell et al., An Interim Report on the Materials and Selection Criteria Analysis for the Compact Ignition Tokamak Toroidal Field Coil Turn-to Turn Insulation System, Oak Ridge National Laboratory Report ORNL/ATD-28, 1990.

FIGURE CAPTIONS

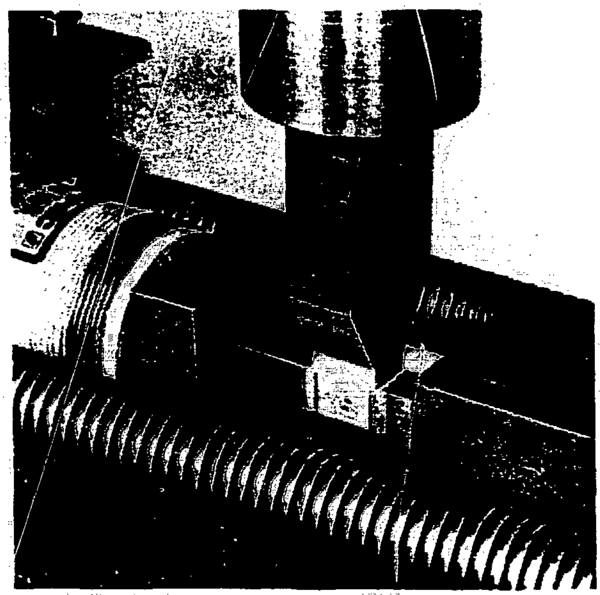
Fig. 1. Biaxial test device for 12.7- by 12.7-mm samples.

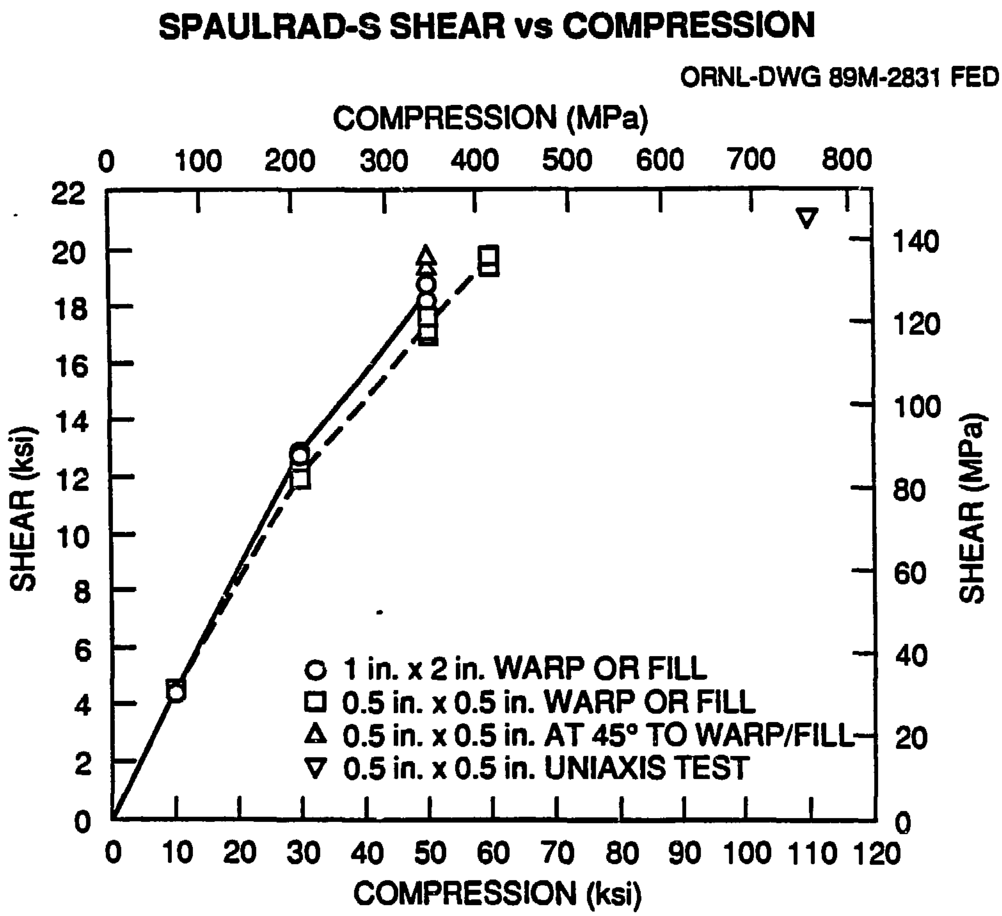
Fig. 2. Spaulrad-S interlaminar shear strength vs compression.

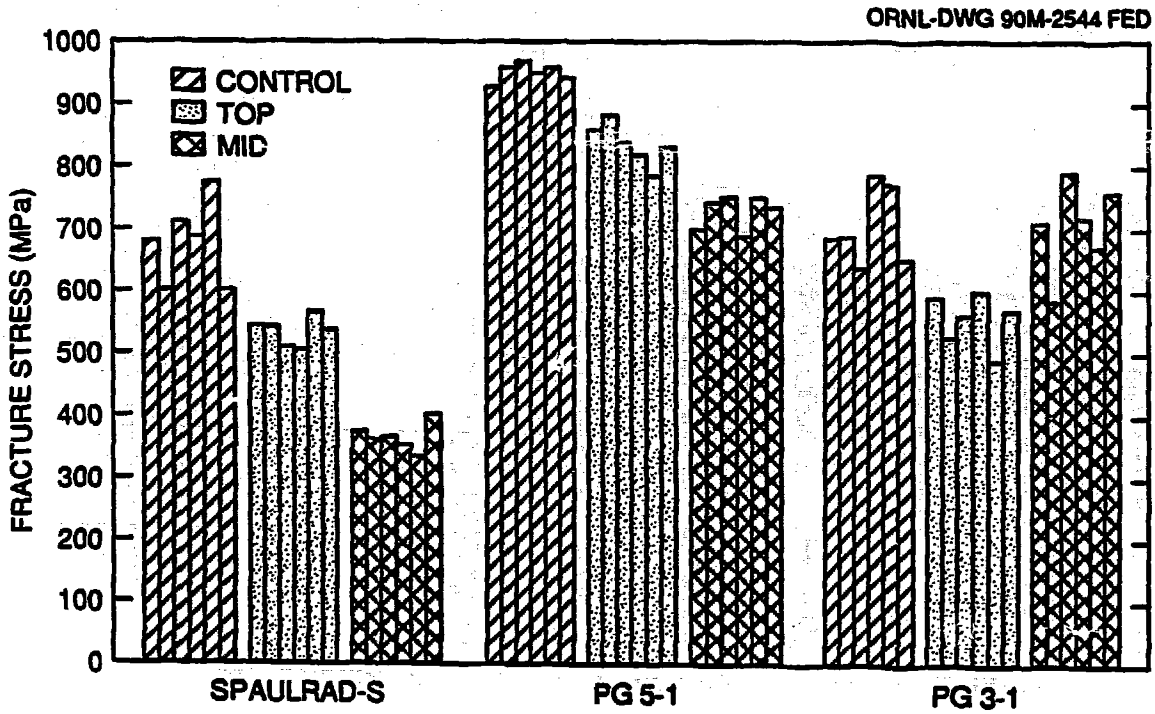
Fig. 3. Fracture stress of samples of each material from control group, top capsule (4×10^9 rad), and midplane capsule (3×10^{10} rad).

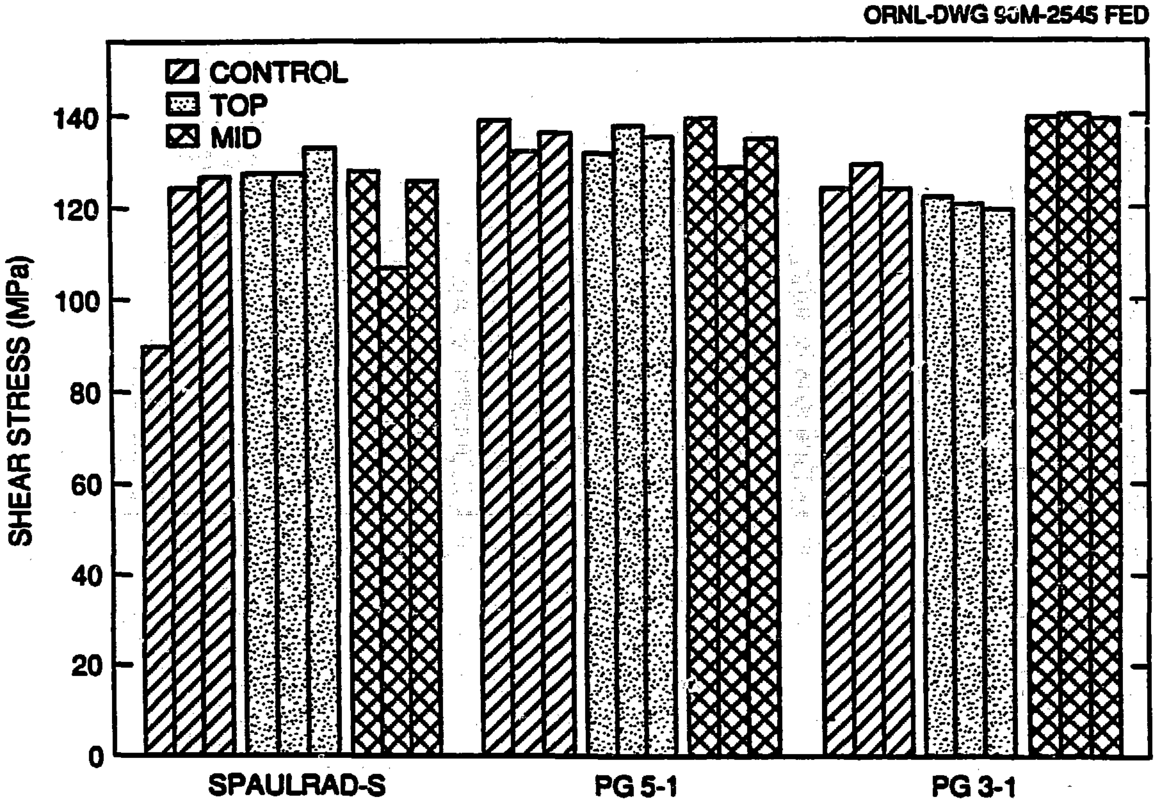
Fig. 4. Shear strength with 345-MPa compression of samples of each material from control group, top capsule (4×10^9 rad), and midplane capsule (3×10^{10} rad).

Fig. 5. Shear strength with 345-MPa compression after 30,000 cycles of samples of each material from control group, top capsule (4×10^9 rad), and midplane capsule (3×10^{10} rad).




SPAULRAD-S SHEAR vs COMPRESSION
ORNL-DWG 89M-2831 FED
COMPRESSION (MPa)
0
100
200
300
400
500
600
700
800
SHEAR (ksi)
0
2
4
6
8
10
12
14
16
18
20
22
SHEAR (MPa)
0
20
40
60
80
100
120
140
1 in. x 2 in. WARP OR FILL
0.5 in. x 0.5 in. WARP OR FILL
0.5 in. x 0.5 in. AT 45° TO WARP/FILL
0.5 in. x 0.5 in. UNIAXIS TEST
0
10
20
30
40
50
60
70
80
90
100
110
120
COMPRESSION (ksi)


ORNL-DWG 90M-2544 FED
FRACTURE STRESS (MPa)
1000
900
800
700
600
500
400
300
200
100
0
CONTROL
TOP
MID
SPAULRAD-S
PG 5-1
PG 3-1


ORNL-DWG 93M-2545 FED
CONTROL
TOP
MID
SHEAR STRESS (MPa)
0
20
40
60
80
100
120
140
SPAULRAD-S
PG 5-1
PG 3-1

ORNL-DWG 90M-2546 FED