22
5-23-77
25 cy to NTIS

SAND 77-0347
Unlimited Release

3151

BEHAVIOR OF KEVLAR 49 FABRIC/EPOXY LAMINATES SUBJECTED TO PIN BEARING LOADS

MASTER

R. E. Allred

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115 and Livermore, California 94550 for the United States Energy Research and Development Administration under Contract AT (29-1)-789

April, 1977

Sandia Laboratories

SF 2900 Q(7-73)

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Issued by Sandia Laboratories, operated for the United States Energy Research & Development Administration by Sandia Corporation.

NOTICE

Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22151
Price: Printed Copy $4.50; Microfiche $2.25

SAND 77-0347

Unlimited Release

April, 1977

BEHAVIOR OF KEVLAR 49 FABRIC/EPOXY LAMINATES SUBJECTED TO PIN BEARING LOADS

Ronald E. Allred
Composite Materials Development
Division 5844

ABSTRACT

The low compressive strength of Kevlar reinforced composites causes concern about the ability of these materials to withstand bearing loads in bolted joints. This paper presents the results of an experimental investigation of the pin bearing load-deflection response of [0/90/±45], [0/90] and [±45] Kevlar 49 fabric/epoxy laminates. Laminate thicknesses from 0.075 in. to 0.300 in. were examined for pin diameters ranging from 0.125 in. to 0.500 in. Results of this study revealed three significant points: (1) a synergistic effect takes place in the [0/90/±45] ply stacking sequence which results in higher yield and ultimate strengths than the [0/90] and [±45] laminates; (2) bearing strength varies inversely with pin diameter, probably due to the statistical strength behavior of these materials; and (3) nominal bearing yield strengths are very low (10-20 ksi). It is concluded that joint designs should incorporate local reinforcement in bolted or pinned areas.

I. INTRODUCTION

The design of structures which incorporate high performance composite materials is often limited by the properties of the structural joints. Pinned or bolted joints in composite materials are subject to composite bearing or shear-out failures as well as tensile failure of the composite or bolt.[1-4] In the case of Kevlar 49-reinforced composite materials, the probability of failure in bearing is enhanced by the low compressive strength of the Kevlar 49 filaments.[5,6] It is desirable to obtain not only the ultimate bearing strength of these materials but also the entire load (stress)-deflection curve. The material yield strength from such a curve provides a better design allowable than the bearing ultimate strength often reported. This is especially significant for structures subjected to repeated loadings.

This paper presents the results of an experimental study to determine the bearing load-deflection behavior of Kevlar 49 fabric/epoxy laminates. A fixture was designed which allowed deflections of the laminates to be measured with a strain gage extensometer. Both quasi-isotropic [0/90/±45] and aligned [0/90] fabric laminates were examined.

II. EXPERIMENT

Laminates used in this study were fabricated from Dupont style 181 Kevlar 49 fabric (50 x 50 yarns/in. 380 denier, 8 harness satin weave) preimpregnated with U.S. Polymeric E-781 epoxy resin. The E-781 system is believed to be a diglycidyl ether of bisphenol A type epoxide cured with a BF_3-monoethyl amine complex. The laminate cure cycle was carried out by matched die molding in a hot press. The prepreg plies were heated at a rate of 1°F/min. under contact pressure to 300°F, compressed to stops, heated to 325°F and held 1 hour, cooled under pressure to 120°F and then removed from the press. The laminates were subsequently post cured in air 4 hours at 350°F and slow cooled.

Laminates of two different ply stacking sequences were fabricated, viz. quasi-isotropic and aligned. The quasi-isotropic laminates were constructed of alternating 0-45° plies balanced about the mid plane. The other stacking sequence consisted of all warp-aligned plies which resulted in a [0/90] layup. Four quasi-isotropic laminate thicknesses were fabricated: (1) 0.075 in., (2) 0.150 in., (3) 0.225 in. and (4) 0.300 in. A single laminate 0.150 in. in thickness of the [0/90] construction was prepared. Samples of 1.50 in. width were cut with the specimen axis in the 0° direction of the quasi-isotropic laminates and in the 0° and 45° directions of the aligned laminate. Holes of diameter 0.125 in., 0.250 in., 0.375 in. and 0.500 in. were drilled in the quasi-isotropic samples with diamond tooling. The aligned samples were prepared only with 0.250 in. diameter holes. A distance of 0.75 in. was maintained between the end of the specimen and the hole.

Specimen width and end distance were chosen such that they did not influence the stress-state around the pinned hole.(7) Five specimens were prepared for each thickness-hole size-direction combination. Hole diameters were machined to a tolerance of plus 0.002 in. of the diameter of the pin to be used in testing. The specimens were compressed between two sacrificial Al plates during drilling to prevent distortion of the surface plies.

Prior to testing, Al doublar tabs were bonded to the specimen end to be clamped in the wedge action grips. A threaded rod was bonded to the opposite end for attachment of the extensometer fixture. The rest of the test fixture included a clevis through which the specimen was pinned with a hardened steel dowel, and a sleeve which fit over and bolted to the clevis. A specimen and clevis are shown in Figure 1. The assembled test fixture is shown mounted in the testing machine in Figure 2.

The fixture is so designed that deflections under the pin are the deflections being predominately measured. Deformations attributable to stress acting in the material away from the hole are assumed negligible. Load was applied at a cross-head rate of 0.02 in./min. All of the samples examined were characterized by classical bearing failures with the top layers on each surface delaminating, splitting and being pushed outward. No shearout or net section tensile failures were observed until considerable bearing deformations had occurred. The appearance of a typical failure surface is shown in Figure 3.

III. RESULTS AND DISCUSSION

The composite bearing load-deflection (P-δ) response was similar for all the conditions examined. This behavior may be broken down into five distinct regions as represented schematically in Figure 4. As the pin seats into the hole, the initial portion of the curve, labeled I in Figure 4, is nonlinear. The extent of region I is determined by the tolerances of the loading pin and the machined hole. Once contact is established along the pin-laminate interface, the P-δ curve enters a linear elastic region, II, characterized by a slope P/δ. In region III, the laminate has begun to yield and picks up some additional load with increasing deflection until the ultimate load, P_u, is reached. Yield is defined in this study as the first deviation from linearity in region II.

After the ultimate load is reached, the material under the pin begins to crush-up; this is accompanied by large deflections and no additional load buildup (region IV). The compression of the composite in region IV is not accompanied by filament breakage but rather by debonding and splitting parallel to the filaments. Eventually, the filaments are compacted to the point where they begin to carry increased loads and the curve enters region V. The deflection at this point is generally 0.150-0.200 in. The typical appearance at this point is shown in

Figure 3. Once the laminate P-δ curve has entered region V, further application of load eventually results in either pin failure or net section tensile failure of the laminate across the hole.

It should be noted that, before a curve of the type seen in Figure 4 can be obtained, the clevis must be wide enough to permit lateral deformation of the composite. A constrained bearing load-deflection curve will exhibit region III behavior until failure of the pin, or until tensile failure or cracking of the laminate takes place. Such a situation is probably characteristic of a bolt-washer joint with a degree of torque on the bolt. Stockdale and Matthews[8] have demonstrated that ultimate bearing loads are increased 40 to 100 percent in glass-reinforced laminates by such application of clamping pressure.

The ultimate bearing stress, defined as the ultimate load divided by the projected area, i.e., P_u/td, (d = pin diameter, t = laminate thickness) vs laminate thickness for the quasi-isotropic stacking sequence laminates is given in Figure 5. The data indicate that a plane stress-plane strain transition takes place at a laminate thickness of about 0.200 in. In laminates less than 0.200 in. thickness, the outer plies are unable to constrain the inner plies and all the layers peel back under the pin force. The ultimate strength for the plane stress case is determined by the force necessary to deform the plies in such a manner. Once the inner plies are constrained at laminate thicknesses greater than 0.200 in., the ultimate strength is determined by the force necessary to crush the laminate and the strength becomes independent of thickness. Such behavior is not seen in Figure 5 for the 0.125 in. diameter pin because of pin failures in the thicker laminates. If the pins had not failed, one would also expect to see a similar transition with the 0.125 in. diameter pins. Micrographs of the 0.150 in. and 0.300 in. laminates after being loaded to their ultimate bearing strengths are shown in Figure 6. The effect of constraint on failure mode is seen by the increased evidence of filament buckling by the center plies of the 0.300 in. laminate (Figure 6b). The pin bearing yield strength vs thickness behavior for the same material is given in Figure 7. As would be expected, pin bearing yield strength, which is related to the yield properties of the constituent materials, is independent of thickness. The large amount of scatter seen in Figure 7 for the 0.125 in. pin is due to the difficulty in reading the P-δ curves for those samples and the sensitivity of yield stress to load for such a small area. The relative position of the curves in Figures 5 and 7 in terms of pin diameter indicate that an increasing stress concentration effect is occurring with increasing pin diameter. A similar effect has been noted by Waddoups, Eisenmann and Kaminski[9] for the tensile strength of laminated composites containing a circular hole. The appearance of the failed surfaces in this study and the work of Althof and Mueller,[7] make it unlikely that the stress concentration seen is due to edge effects. Rather, in the manner presented by Whitney,[10] the concentration effect may be due to the larger volume of material exposed to a high stress with the larger pins and the concurrent higher probability of having a large flaw in the highly stressed region.

The warp-aligned laminate, [0/90], exhibited P-δ curves similar to the curve shown in Figure 4 for the quasi-isotropic laminates. In the warp direction, 0°, an average yield stress of 10.1 ksi and ultimate stress of 25.2 ksi were determined. For the 45° specimens, these values were 14.1 and 25.1 ksi respectively. These results compare to yield and ultimate values for the comparable quasi-isotropic laminate-hole size combination of 16.7 and 27.3 ksi. On the surface, one might expect that the yield strength of the quasi-isotropic plate be an average of the [0/90] and [± 45] laminates. That the quasi-isotropic material is stronger than its components suggests a synergistic mechanism which utilizes the positive features of both the [± 45] and [0/90] laminates. A clue to such a mechanism, which reflects relative fiber loading efficiencies, is seen in the slopes of the stress-deflection curves of the three laminates.

The [±45] layup is the most stiff at 7.4 x 10^6 lb/in., followed by the quasi-isotropic at 6.0 x 10^6 lb/in. and the [0/90] at 3.8 x 10^6 lb/in. The roughly double slope of the [± 45] compared to the [0/90] indicates that, in toto, the filaments in the [±45] are loaded nearly as efficiently as only the axial filaments in the [0/90]. In the [0/90] layup, the axial filaments pick up the majority of the load in compression and buckle at a low value of bearing stress. Once initiated, the buckling mode predominates to large deflections as seen in Figure 8. The filaments in the [±45] laminate do not see direct compressive loads. Yield in such a geometry is controlled by the resin, which resists the filaments from being spread apart in a sissors-like fashion. As such, a micrograph of the bearing failure surface of a [±45] laminate is for the most part nondescript as seen in Figure 9. When the two different ply sequences are combined to form a quasi-isotropic laminate, the filaments at 45° share the load with the 0° filaments, thereby reducing the stress on the 0° filaments and, consequently, suppressing the buckling mode. The reduced amount of buckling in the quasi-isotropic laminate compared to the 0° direction of the [0/90] layup may be seen by comparing Figures 6a and 8. While the 0° filaments are prevented from buckling, the 90° filaments suppress the resin yield mode seen in the [±45] laminate by sustaining transverse loads. The result is that the material yield strength is raised in the quasi-isotropic laminate by delaying the normal yield modes of the [0/90] and [±45] laminates.

Even with the 60 percent increase in yield strength exhibited by the quasi-isotropic stacking sequence, the bearing yield and ultimate strengths of Kevlar fabric laminates are much lower than seen in other high performance composites such as boron and graphite.(1-4) Because of the low bearing strength, design with bolted or pinned joints in highly loaded Kevlar-reinforced composite structures should incorporate local joint reinforcements such as bushings. A lightweight alternative to bushings which consists of local ply reinforcement with boron film has been demonstrated by Padawer.(11) These methods should circumvent the bearing problem while retaining the desirable properties of Kevlar-reinforced laminates.

IV. CONCLUSIONS

The results of this experimental study on the bearing response of Kevlar 181 fabric/epoxy laminates lead to the following conclusions:

(1) Bearing yield in these materials occurs substantially below the ultimate bearing strength.

(2) The yield strength in bearing is very sensitive to ply stacking sequence, with the quasi-isotropic configuration [0/90/±45] exhibiting the highest strength of those tested.

(3) Ultimate bearing strength is not sensitive to stacking sequence, but does exhibit a plane stress-plane strain transition at a laminate thickness of approximately 0.200 in.

(4) Both ultimate and yield strengths in bearing exhibit an increasing stress concentration effect with increasing pin diameter. It is believed that this phenomenon is due to the statistical strength behavior of composite materials.

(5) Bearing strengths of these materials are substantially below those reported for other high performance composites. For this reason, it is recommended that local reinforcement be incorporated into the joint area when designing with Kevlar-reinforced composite materials.

V. ACKNOWLEDGEMENT

The author would like to thank D. W. Miller for design and construction of the bearing deflection fixture, and J. E. Perea for conducting the bearing tests. The author would also like to thank A. Lindrose, J. G. Curro and F. P. Gerstle for their valuable discussions and careful review of this paper.

VI. REFERENCES

1. R. N. Dallas, "Methods of Joining Advanced Fibrous Composites," Composite Materials: Testing and Design, ASTM STP 460, American Society for Testing and Materials (1969), pp. 381-392.
2. J. P. Waszczak and T. A. Cruse, "Failure Mode and Strength Predictions of Anisotropic Bolt Bearing Specimens," J. Comp. Mat'ls. 5 (1971), pp. 421-425.
3. R. Y. Kim and J. M. Whitney, "Effect of Temperature and Moisture on Pin Bearing Strength of Composite Laminates," J. Comp. Mat'ls. 10 (1976), pp. 149-155.
4. R. C. Van Siclen, "Evaluation of Bolted Joints in Graphite/Epoxy," Proc. of Army Symp. on Solid Mech., 1974: The Role of Mechanics in Design-Structural Joints, AMMRC MS 74-8 (September 1974), pp. 120-138.
5. J. H. Greenwood and P. G. Rose, "Compressive Behavior of Kevlar 49 Fibers and Composites," J. Mat'ls. Sci. 9 (1974), pp. 1809-1814.
6. S. V. Kulkarni, J. S. Rice and B. W. Rosen, "An Investigation of the Compressive Strength of Kevlar 49/Epoxy Composites," Composites (September 1975), pp. 217-225.
7. W. Althof and J. Mueller, "Investigations of Cemented and Detachable Joints of Fiber Reinforced Plastics," NASA Technical Translation, NASA TT F-14,041 (1971).
8. J. H. Stockdale and F. L. Matthews, "The Effect of Clamping Pressure on Bolt Bearing Loads in Glass Fibre-Reinforced Plastics," Composites (January 1976), pp. 34-38.
9. M. E. Waddoups, J. R. Eisenmann and B. E. Kaminski, "Macroscopic Fracture Mechanics of Advanced Composite Materials," J. Comp. Mat'ls 5 (1971), pp. 446-454.
10. J. M. Whitney, "The Effect of Stress Concentrations on the Fracture Behavior of Fiber Reinforced Composite Materials," Proc. 12th Annual Meeting of the Society of Engineering Science, U. of Texas, Austin, Texas (1975), pp. 173-179.

11. G. E. Padawer, "The Strength of Bolted Connections in Graphite/Epoxy Composites Reinforced by Colaminated Boron Film," Composite Materials: Testing and Design (second conf.), ASTM STP 497, American Society for Testing and Materials (1972), pp. 396-414.

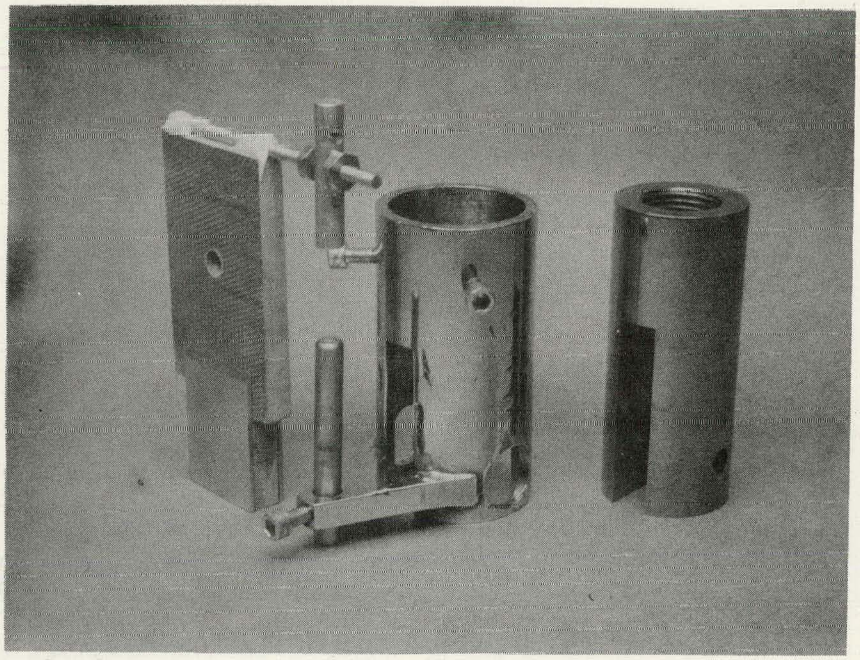


Figure 1. Fixturing for pin bearing test - (l-r) composite test specimen, sleeve extensometer mount, hardened steel clevis.

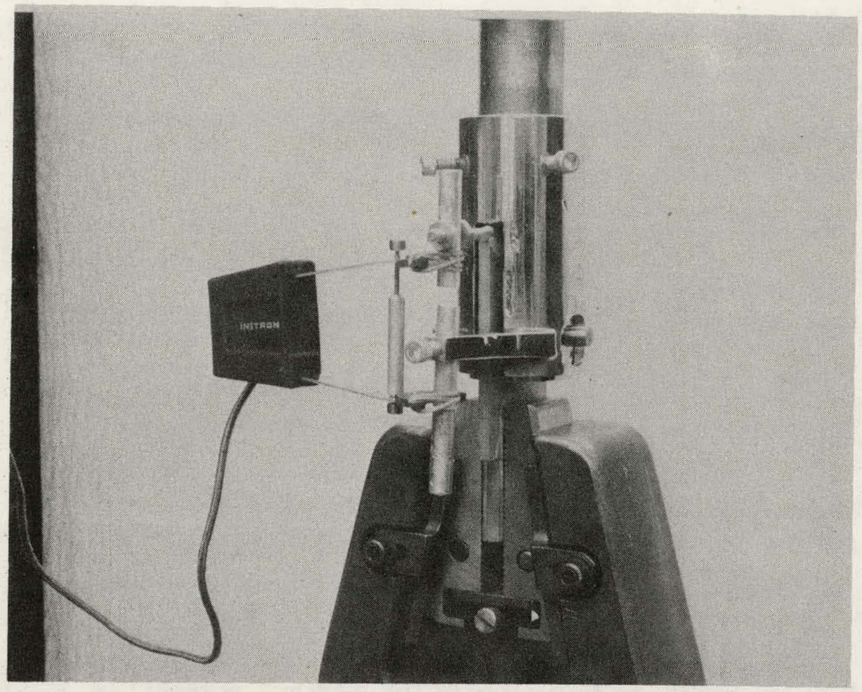


Figure 2. Assembled pin bearing test setup.

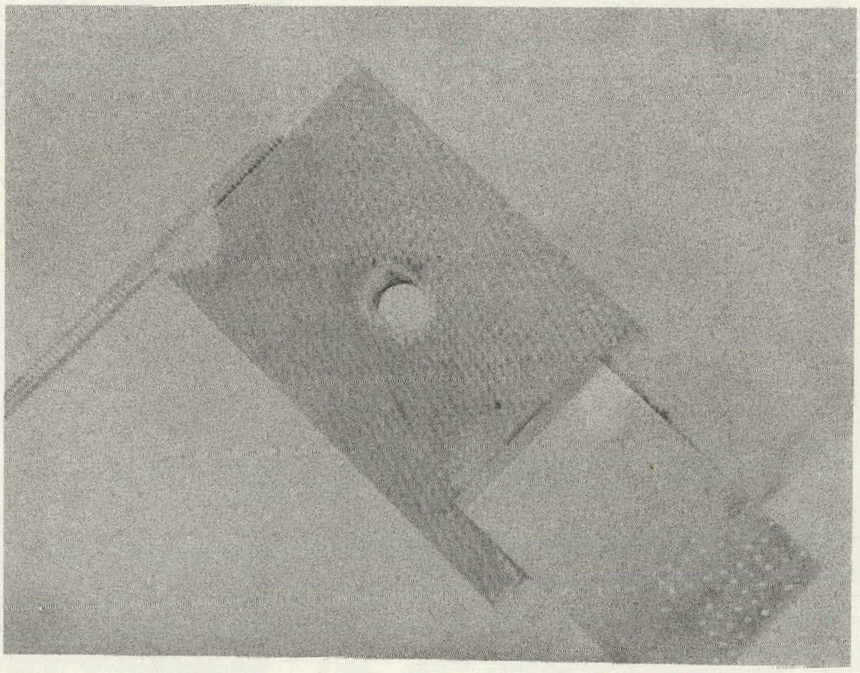


Figure 3. Surface appearance of bearing failure in quasi-isotropic Kevlar 181 fabric/epoxy laminate loaded with a 0.250 in. pin.

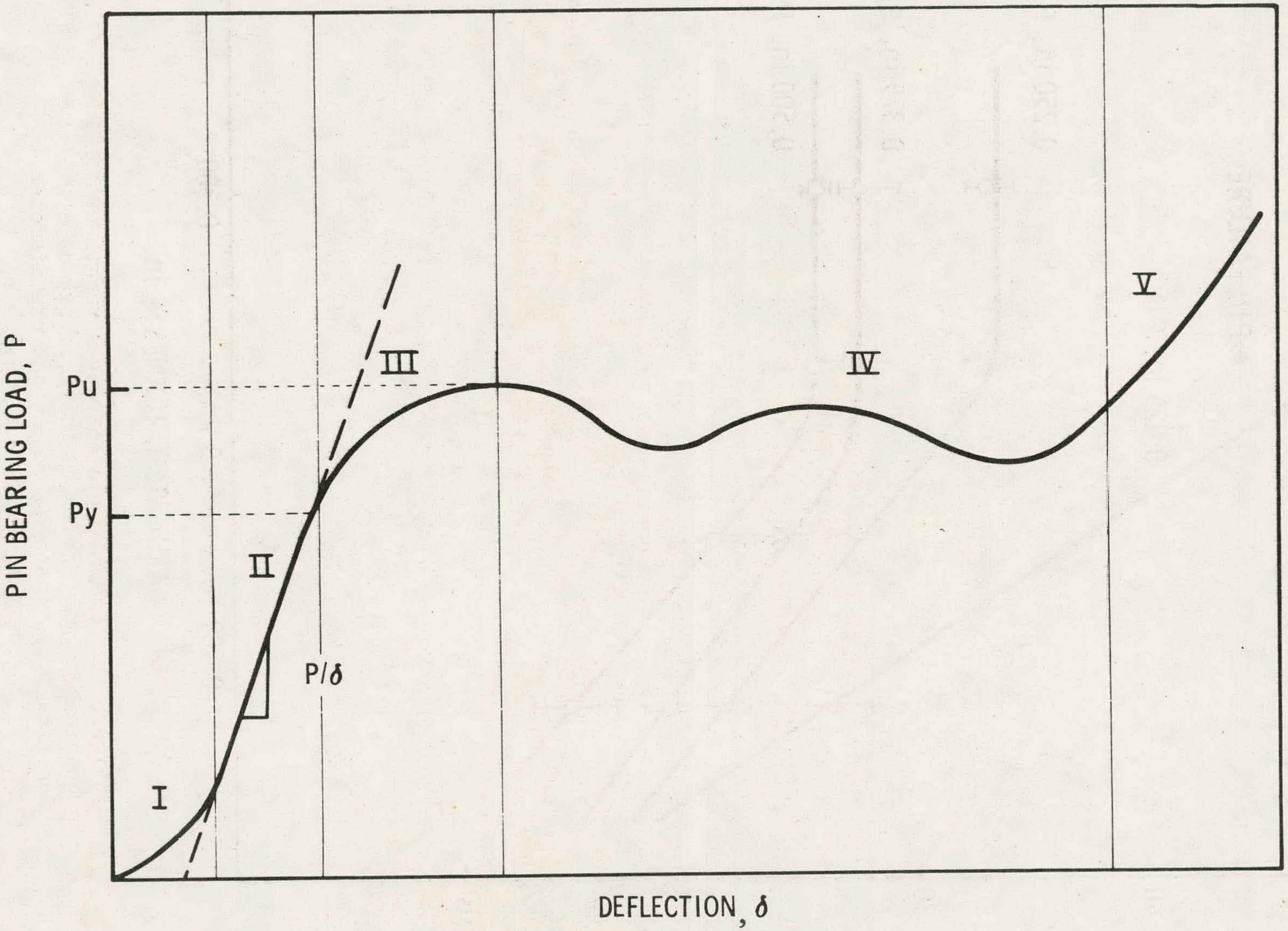


Figure 4. Schematic pin bearing load-deflection curve for Kevlar 49 fabric/epoxy laminate.

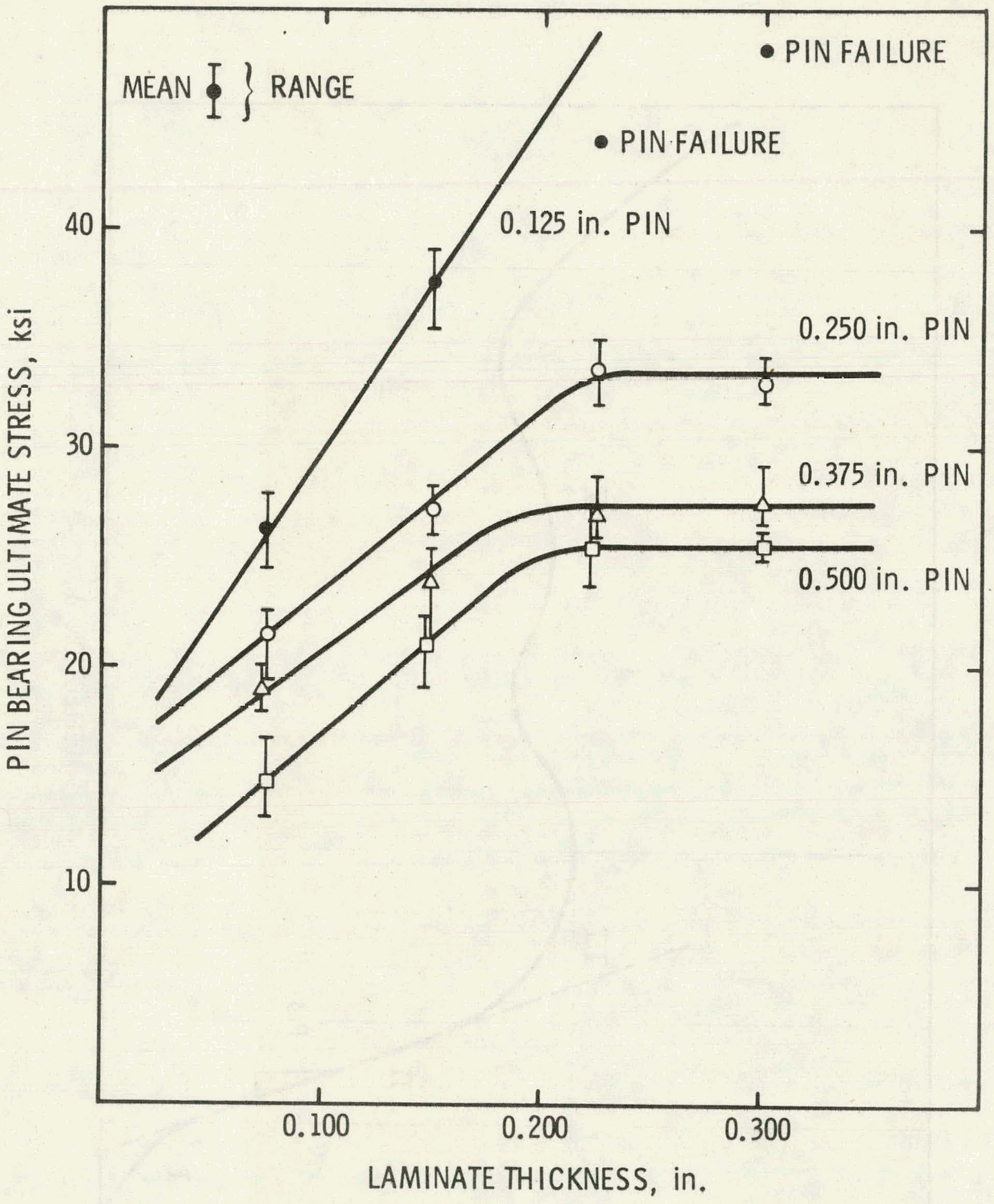
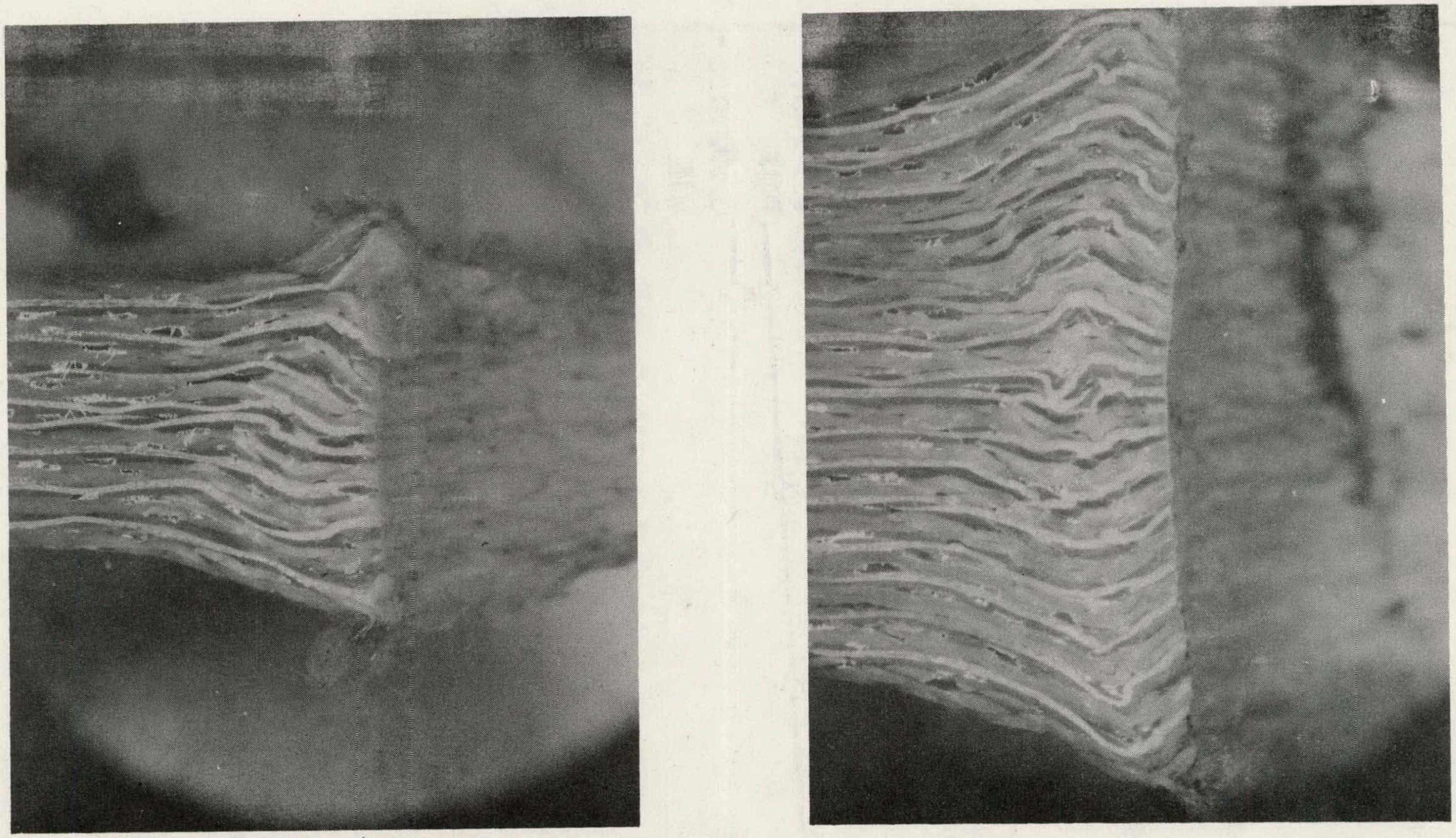


Figure 5. Ultimate pin bearing strength of quasi-isotropic Kevlar 49 fabric/epoxy as a function of laminate thickness and pin diameter (sample width = 1.5 in.).



(a) (b)

Figure 6. Micrographs of bearing failure surfaces in 0/90/±45 Kevlar 181 fabric/epoxy laminates. (a) 0.150 in., (b) 0.300 in. (10X). Constraint of the inner plies in the thicker laminate is evidenced by increased buckling of the inner plies in 6b.

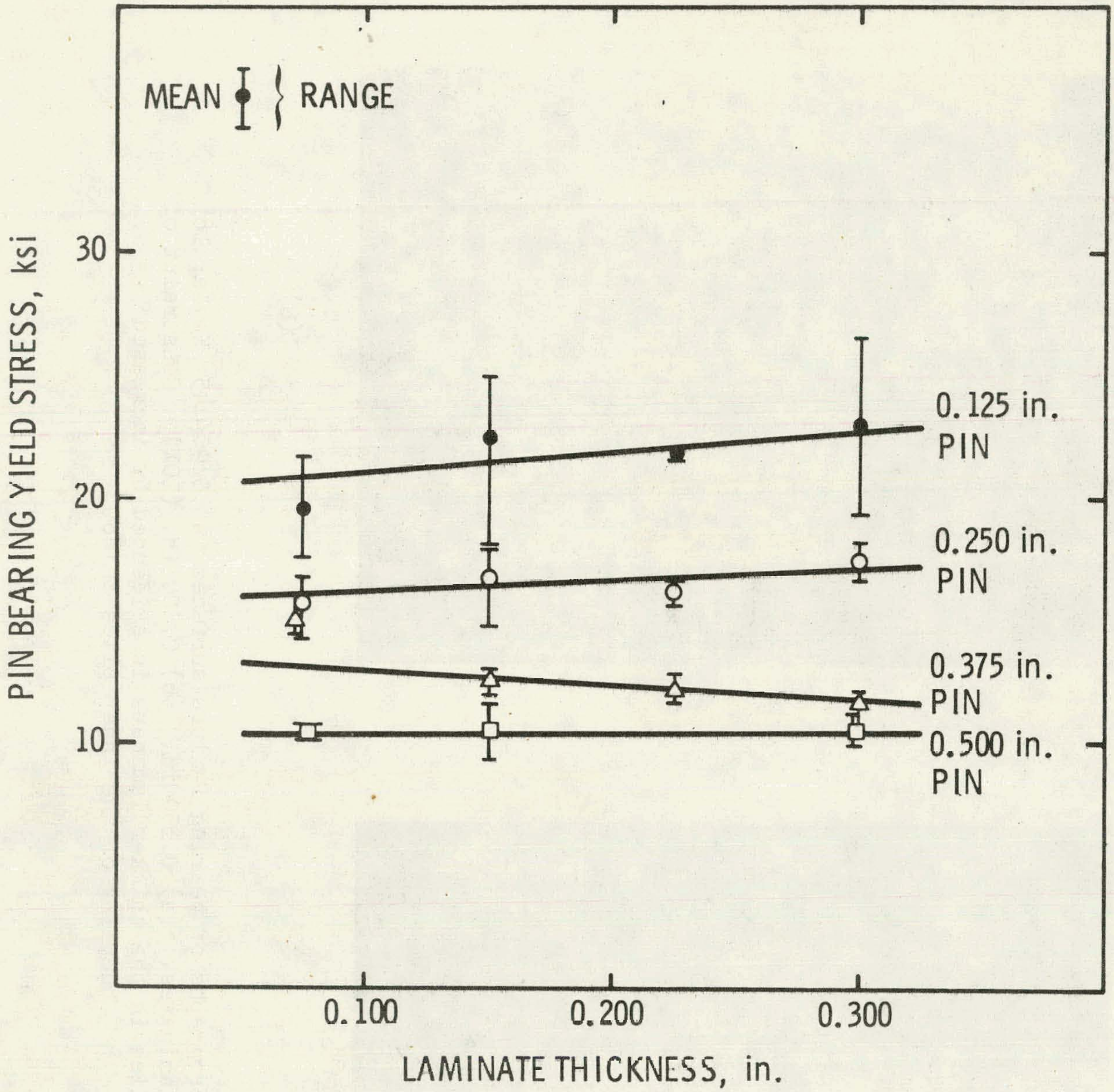


Figure 7. Pin bearing yield strength of quasi-isotropic Kevlar 49 fabric/epoxy as a function of laminate thickness and pin (sample width = 1.5 in.).

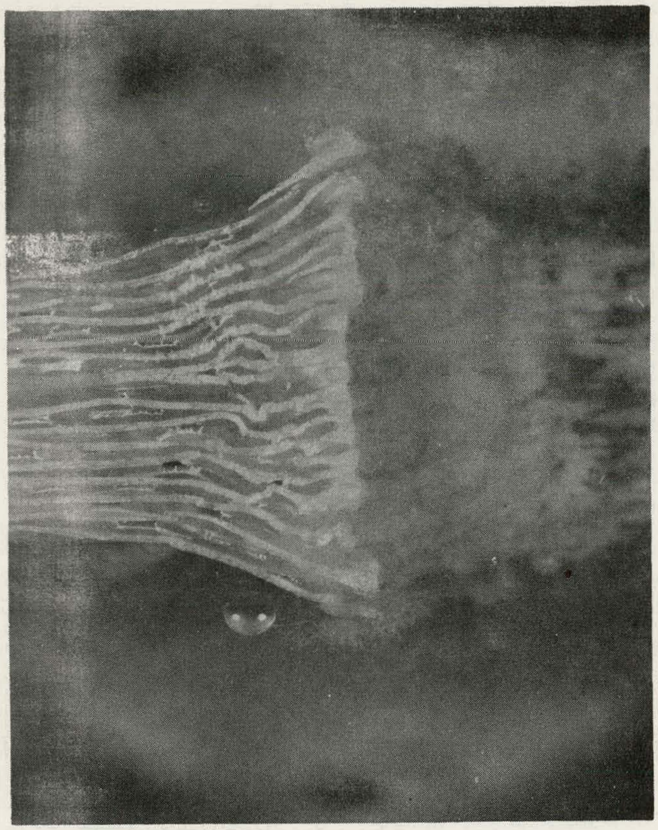


Figure 8. Micrograph of bearing failure surface in [0/90] Kevlar 181 fabric/epoxy laminate loaded at 0° showing buckling mode of 0° filaments. (10X)

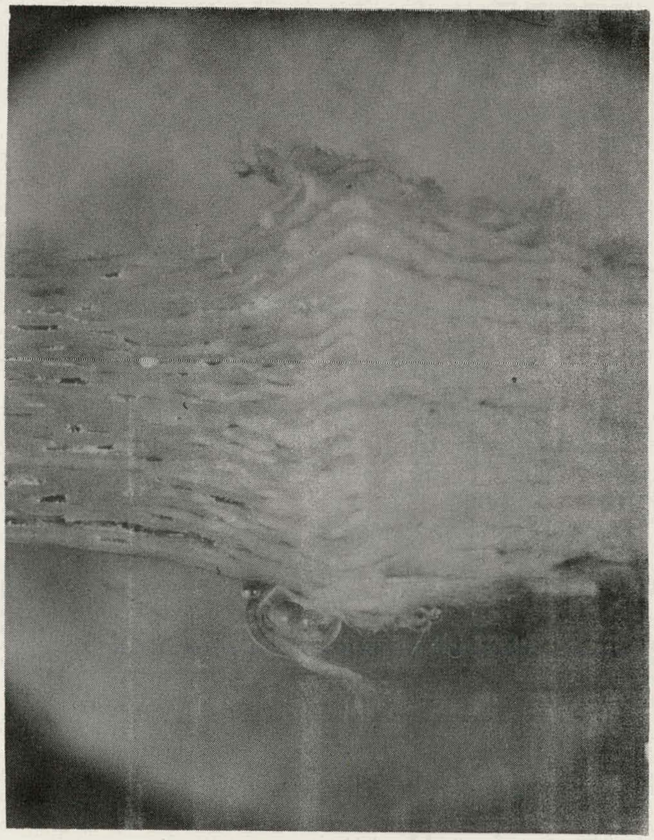


Figure 9. Bearing failure surface micrograph of [± 45] Kevlar 181 fabric/epoxy laminate. (10X)

Unlimited Release

Distribution:

C. H. Smith 814 BKC
  Attn: D. J. Fossey

V. E. Alley 861 BKC
  Attn: G. W. Edman
    R. J. Schwalbe

T. T. Chiao LLL (3)

R. L. Huddleston Y-12 (2)

1284 P. P. Stirbis

5000 A. Narath
  Attn: 5100 J. K. Galt
    5200 E. H. Beckner
    5400 A. W. Snyder
    5700 J. H. Scott

5800 R. S. Claassen
  Attn: 5810 R. G. Kepler
    5820 R. L. Schwoebel
    5830 M. J. Davis

5840 H. J. Saxton
  Attn: 5842 J. N. Sweet
    5845 R. J. Eagan
    5846 E. K. Beauchamp

5844 F. P. Gerstle, Jr. (2)

5844 T. R. Guess

5844 A. M. Lindrose

5844 R. E. Allred (25)

5844 E. D. Reedy, Jr.

5844 R. H. Ericksen

8122 Y. R. Kan

8150 D. E. Gregson
  Attn: 8158 A. S. Rivenes

8157 G. N. Beeler
  Attn: D. A. Clarin
    D. W. Putz

8310 D. M. Schuster
  Attn: W. R. Hoover

8266 Tech. Library (2)

3141 Tech. Library (5)

3151 W. L. Garner (3)
  For ERDA/TIC (Unlimited Release)

ERDA/TIC (25)
  (R. P. Campbell 3171-1)