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MATERIALS DIVISION RESEARCH AND TECHNOLOGY ACCOMPLISHMENTS FOR FY 88 AND PLANS FOR FY 89

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MATERIALS DIVISION
RESEARCH AND TECHNOLOGY ACCOMPLISHMENTS FOR FY 88 AND PLANS FOR FY 89

SUMMARY

The research program of the Materials Division is presented as FY 88 accomplishments and FY 89 plans. The accomplishments for each Branch are highlighted and plans are outlined. Publications of the Division are included by Branch. This material will be useful in program coordination with other government organizations, universities, and industry in areas of mutual interest.

ORGANIZATION

The Langley Research Center is organized by directorates as shown in figure 1. Each directorate is organized into divisions and offices. The Materials Division of the Structures Directorate consists of four branches as shown in figure 2. This figure also shows the technical areas addressed by each Branch. The Division consists of 69 NASA civil servants and 6 members of the Army Aerostructures Directorate, USAARTA, Army Aviation Systems Command located at the Langley Research Center. In addition, about 40 non-personal support contractors work at the Center to add major support to the in-house research program.

FUNCTIONAL STATEMENT

The Materials Division initiates, organizes, and conducts experimental and analytical research on structural materials and their application to aircraft and spacecraft structural systems (figure 3). More specifically the Division:

- Conducts fundamental and applied research studies to develop novel polymeric, metallic, and ceramic materials for advanced structural applications.
- Establishes materials processing and fabrication technology for structural components.
- Demonstrates the application and benefits of advanced materials to specific flight vehicle structures.
- Defines, evaluates, and conducts research on thermal protection materials requirements for high-speed aircraft and space transportation systems.
- Studies the fatigue and fracture behavior of materials to establish practical methods for insuring the structural integrity of aircraft and space structures.
- Characterizes the behavior of structural materials in extreme service environments using test facilities and laboratories for simulation of the flight environment.
- Originates and develops requirements for new facilities and research techniques.
- Operates the mechanics of materials, structural materials, polymer, metallurgical, and environmental effects laboratories.

The long range research thrusts of the Materials Division are shown in figure 4.

FACILITIES

The Materials Division has five major facilities to support its research program.

The Structures and Materials Laboratory houses various environmental effects labs and the metallurgical and metals processing labs. In the environmental effects labs, research is conducted to characterize and enhance the performance of structural materials operating in extreme service environments. Test techniques, instrumentation, and measurement techniques are developed to simulate environmental conditions required to evaluate high-temperature structural materials. The interaction of the space environment on properties of advanced composites, polymer films, and coatings for space systems is studied. Radiation and monoatomic oxygen damage in polymeric materials is studied and chemical formulations for enhanced long-term durability in space are identified.

Fundamental and applied research on advanced metallic and metal-matrix materials is conducted in the metallurgical and metals processing labs. Innovative processing methods for new alloy synthesis and development and fabrication of metallic structural components for future aircraft and space vehicles, including high-temperature applications, are explored. Metallic components are analyzed and tested to demonstrate improvements in advanced metallic alloys and their fabrication processes.

The Mechanics of Materials Laboratory is used to conduct research on the structural integrity of metals and composites for aircraft structures. Tests are conducted to measure the effect of loads on materials under simulated flight conditions. Materials and methods of strength and life prediction for airframes are assessed to develop ways to improve the structural reliability of aircraft.

Fundamental and applied research using advanced polymer synthesis, composites and adhesives processing science, and advanced characterization methodology to develop improved materials concepts for efficient aerospace structures are conducted in the Composites Processing Laboratory. Novel polymeric materials are synthesized for applications such as matrices for fiber-reinforced composites, adhesives for bonding lightweight composite and metal structures, and high-performance films for spacecraft. Innovative processing methods for fabricating composite components for aircraft and spacecraft structures are developed.

Radiation testing of spacecraft materials is conducted in the Space Environmental Effects Laboratory. Spacecraft materials tested include polymeric and metal matrix composites, polymeric films, thermal control coatings, adhesives, solar cells, and laser mirrors.

In addition, the Carbon-Carbon Research Laboratory was completed in July 1988. The Materials Division has expanded its research capability in carbon-carbon materials and this lab houses the processing equipment needed for fabricating carbon-carbon materials and for applying oxidation-protective coatings.

FY 88 ACCOMPLISHMENTS

Polymeric Materials Branch

The Polymeric Materials Branch (figure 5) conducts fundamental and applied research studies combining the disciplines of advanced polymer synthesis, composites and adhesives processing science, and advanced characterization methodology to develop improved materials concepts for efficient aerospace structures. These research and development activities are aimed at achieving maximum structural exploitation of advanced composites and adhesives through development of balanced mechanical/physical properties with good processability. The five year plan for this research is shown in figure 6.

The FY 88 accomplishments of the Polymeric Materials Branch are listed below and are highlighted in figures 7 through 12.

Composite Matrices

- LaRC-RP40: A New Tough High Temperature Matrix Resin
- New Toughened Thermosetting Structural Resins
- Semi-Crystalline Polyimide Sulfone
- LaRC-RP41: A New Tough High Temperature Matrix Resin
- Concept and Demonstration of a New Synthetic Route to a Family of Non-Classical Addition-Type Thermoplastic (ATT) Polyimides

Composite Processing and Adhesive Bonding

- In-Situ Optic Sensor for FTIR Monitoring of Composite Cure Cycles

Mechanics of Materials Branch

The Mechanics of Materials Branch (figure 13) performs research on the integrity of materials for load-bearing structures of metals and composites. This research includes fatigue, fracture mechanics, and structural reliability. Equations and analytical methods are formulated to predict fatigue life and residual strength of damaged and undamaged materials. Design, construction, operation, and inspection methods applied to airframes are assessed to develop ways to improve the overall structural reliability of aircraft and spacecraft. The five year plan of the Branch is shown in figure 14.

The FY 88 accomplishments of the Mechanics of Materials Branch are listed below and are highlighted in figures 15 through 22.

Metals and Metal Matrix Composites

- Static Strength of SCS_6/Ti-15-3
- Significance of the Small-Crack Effect for Fatigue Design

Composites

- Effects of Moisture, Temperature, and Fatigue on the Strength of Center-Cracked Graphite/Epoxy Panels With Buffer Strips
- Effect of Delamination Rate on Interlaminar Fracture Toughness
- Impact Damage in a Thick Gr/Ep Laminate Caused by Spherical Impacters
- Development of a Damage-Threshold/Fail-Safety Analysis for Composite Materials and Structures
- Mode I Delamination Fatigue Threshold for Graphite/PEEK
- Failure Modes for Laminates Under Bearing-Bypass Loading

Applied Materials Branch

The Applied Materials Branch (figure 23) conducts research to characterize and enhance the performance of structural materials operating in extreme service environments. The Branch identifies mechanisms of environmental degradation and failure in structural materials, provides quantitative understanding of degradation mechanisms and evolves models to predict the rate or extent of degradation for various advanced structural materials. Theoretical and experimental studies which relate to the environmental performance of high-temperature materials for thermal protection systems and hot structures of advanced space transportation systems and hypersonic vehicles are conducted. The interaction of the space environment on properties of advanced composites, polymer films, and coatings of interest for space systems is studied. The five year research plan for the Branch is shown in figure 24.

The FY 88 accomplishments of the Applied Materials Branch are listed below and are highlighted in figures 25 through 30.

Space Materials

- Analysis of Advanced Composite Materials for Precision Segmented Reflectors
- Thermal Cycling Induced Damage in Composite Tubes

Carbon-Carbon Composites

- Oxidation-Resistant Carbon-Carbon Composites Evaluation in Simulated Advanced Aerospace Vehicle Environments

Composite Materials for Rotorcraft and Aircraft Structures

- Damage-Tolerant Composite Material Concepts
- Composite Material In-Situ Viscosity Monitor
- 15-Year Flight Service Summary of B-737 Graphite/Epoxy Spoilers

Metallic Materials Branch

The Metallic Materials Branch (figure 31) conducts fundamental and applied research studies on advanced metallic and metal-matrix materials. The Branch performs research on advanced high-strength structural alloys and composites to achieve improved mechanical properties through understanding and control of microstructural features. A basic understanding of joining and forming processes for fabricating structural components from advanced metallic materials is developed and innovative processing methods for new alloy synthesis and development and fabrication of metallic structural components for future aircraft and space vehicles are explored. The five year research plan for the Branch is shown in figure 32.

The FY 88 accomplishments for the Metallic Materials Branch are listed below and are highlighted in figures 33 through 37.

Advanced Light Alloy and MMC Development

- Reinforced, Weldable Aluminum-Lithium Alloys Demonstrated
- Stress Corrosion Resistance of PM 7091 Determined With the Breaking Load Test Method

Innovative Metals Processing

- Characterization of Superplastically Formed Aluminum for Structural Applications
- LaRC Facility Produces Aluminum Alloy Sheet From Powder

High Temperature Thin Gage Metals and MMC for Airframes

- Characterization of Structural Metallics With High Strength and Toughness for Cryogenic Applications

PUBLICATIONS AND PRESENTATIONS

The FY 88 accomplishments of the Materials Division are highlighted by a number of publications and presentations. These are listed by organization and are identified by the categories of formal NASA reports, quick-release technical memorandums, contractor reports, journal articles and other publications, meeting presentations, technical talks, special documents, tech briefs, and patents.

DIVISION OFFICE

Formal Reports

1. Graybeal, J. D.; and Emerson, B. R.: NASA LDTM-1058, June 1988.

Meeting Presentations

2. Cebe, P.; Chung, S. Y.; Liang, R. H.; and St. Clair, A. K.: Optical and Mechanical Properties of Aromatic Polyimides. Presented at the American Chemical Society Meeting and Third Chemical Congress of the North American Continent, June 5-11, 1988, Toronto, Canada. In Polymer Preprints, Volume 29, No. 1, 1988, p. 130.

3. Dorogy, W. E., Jr.; and St. Clair, A. K.: Wet Spinning of Polyamic Acid Fibers. Presented at the National Meeting of the American Chemical Society, September 25-30, 1988, Los Angeles, California.

4. St. Clair, A. K.; and Stoakley, D. M.: Presented at the 1988 Air Force Systems Command Symposium, March 28-31, 1988, Atlanta, Georgia.

5. St. Clair, A. K.; St. Clair, T. L.; and Winfree, W. P.: Low Dielectric Polyimides for Electronic Applications. Presented at the National Meeting of the American Chemical Society, September 25-30, 1988, Los Angeles, California. Abstract published in Polymeric Materials Science and Engineering, Volume 59, 1988, p. 28.

6. Tenney, D. R.: Structural Materials for Space Applications. Presented at the NASA/SDIO Space Environmental Effects on Materials Workshop, June 28-30, 1988, Hampton, Virginia. NASA CP pending.

7. Tenney, D. R.; and Bowles, D. E.: Role of Composite Materials in Future Space Systems. Presented at the 34th Annual Meeting of the American Astronautical Society on Space - A New Community of Opportunity, November 2-5, 1987, Houston, Texas. Proceedings pending.

8. Tenney, D. R.; and Bowles, D. E.: Space Radiation Effects on Dimensional Stability of Composites. Presented at the Centre d'Etudes et de Recherches de Toulouse (CERT), Centre National d'Etudes Spatiales (CNES), ESA Fourth International Symposium Spacecraft Materials in Space Environment, September 6-9, 1988, Toulouse, France. Proceedings pending.

9. Tenney, D. R.; Lisagor, W. B.; and Dixon, S. C.: Materials and Structures for Hypersonic Vehicles. Presented at the 16th Congress of the International Council of the Aeronautical Sciences (ICAS), August 28-September 2, 1988, Jeruselem, Israel. ICAS Paper No. 2.3.1. In ICAS Proceedings, Volume 1, 1988, p. 398-415.

Technical Talks

10. St. Clair, A. K.: Soluble and Colorless Polyimides. Presented at the State University of New York Short Course on High-Temperature Polymers: Synthesis, Properties, and Applications, May 9-11, 1988, New Paltz, New York.

11. Tenney, D. R.: Radiation Durability of Polymeric Spacecraft Materials. Presented at the International Space University (ISU) at MIT, July 12, 1988, Boston, Massachusetts.

Polymeric Materials Branch

Formal Reports

12. Stoakley, D. M.; and St. Clair, A. K.: NASA LDTM-1056, July 1988.

13. Stoakley, D. M.; and St. Clair, A. K.: NASA LDTM-1057, July 1988.

Quick-Release Technical Memorandums

14. Hinkley, J. A.; Johnston, N. J.; and O'Brien, T. K.: Interlaminar Fracture Toughness of Thermoplastic Composites. NASA TM-100532, AVSCOM TM 88-B-002, February 1988, 32 p.

15. Nelson, J. B.: Effect of Geometry on Thermal Aging Behavior of Celion/LARC-160 Composites. NASA TM-100496, December 1987, 21 p.

16. Nelson, J. B.: Effect of Long-Term Thermal Aging on Coated Celion/LARC-160 Composites. NASA TM-100495, October 1987, 22 p.

17. Progar, D. J.: Evaluation of a Thermoplastic Polyimide (422) for Bonding GR/PI Composite. NASA TM-100584, April 1988, 26 p.

18. Progar, D. J.; and Dezern, J. F.: Initial Adhesive Screening of Novel Polyamide-imides and Their Copolymers. NASA TM-100641, August 1988, 19 p.

19. Progar, D. J.; and St. Clair, T. L.: Flexible Backbone Aromatic Polyimide Adhesives. NASA TM-100631, July 1988, 29 p.

20. St. Clair, T. L.; Johnston, N. J.; and Baucom, R. M.: High Performance Composites Research at NASA - Langley. NASA TM-100518, January 1988, 20 p.

Contractor Reports

21. Delano, C. B.: Development of an Impact-and-Solvent-Resistant Thermoplastic Composite Matrix - Phase IV. (NAS1-16808 Acurex Corporation.) NASA CR-178413, September 1987 (Released 1988), 124 p.

22. Hou, T-H; and Bai, J-M: Chemoviscosity Modeling for Thermosetting Resin Systems - III. (NAS1-18000 PRC Systems Services.) NASA CR-181718, August 1988, 41 p.

Journal Articles and Other Publications

23. Bell, V. L.; and Wakelyn, N. T.: Graft Copolymers From Poly(2,6-Dimethylphenylene Oxide) and Pivalolactone. Journal of Polymer Science, Part A: Polymer Chemistry, Volume 26, 1988, p. 827-834.

24. Burks, H. D.; and St. Clair, T. L.: High Temperature Polyimide Blends. SAMPE Quarterly, Volume 19, No. 1, October 1987, p. 1-6.

25. DeVilbiss, T. A.; Progar, D. J.; and Wightman, J. P.: SEM/XPS Analysis of Fractured Adhesively Bonded Graphite Fibre Surface Resin-Rich/Graphite Fibre Composites. Composites, Volume 19, No. 1, January 1988, p..67-71.

26. Dezern, J. F.: Synthesis and Characterization of BTDA-Based Polyamide-Imides. Journal of Polymer Science, Part A: Polymer Chemistry, Volume 26, 1988, p. 2157-2169.

27. Hergenrother, P. M.: Polyquinoxalines. Encyclopedia of Polymer Science and Engineering, Volume 13, Second Edition, 1988, p. 55-87.

28. Hergenrother, P. M.; and Havens, S. J.: Adhesive Properties of LARC-CPI, A New Semi-Crystalline Polyimide. SAMPE Journal, Volume 24, No. 4, 1988, p. 13-18.

29. Hergenrother, P. M.; Jensen, B. J.; and Havens, S. J.: Poly(arylene ethers). Polymer, Volume 29, 1988, p. 358-369.

30. Hinkley, J. A.; and Hoogstraten, C. A.: Tearing of Thin Polyimide Films. Journal of Materials Science, Volume 22, No. 12, December 1987, p. 4422-4425.

31. Hou, T-H.; Bai, J-M.; and St. Clair, T. L.: Polymerization and Crystallization Behavior of a LARC-TPI Powder. Journal of Applied Polymer Science, Volume 36, No. 2, July 1988, p. 279-293.

32. Hou, T-H.; Wakelyn, N. T.; and St. Clair, T. L.: Investigation of Crystalline Changes in LARC-TPI Powders. Journal of Applied Polymer Science, Volume 36, No. 2, December 1988, p. 1731-1739.

33. Pater, R. H.; and Morgan, C. D.: Interpenetrating Polymer Network Approach to Tougher and More Microcracking Resistant High Temperature Polymers 1. LaRC-RP40. SAMPE Journal, Volume 24, No. 5, September/October 1988, p. 25-32.

34. Progar, D. J.; and Pike, R. A.: Adhesive Evaluation of Water-Soluble LARC-TPI. International Journal of Adhesion and Adhesives, Volume 8, No. 1, January 1988, p. 25-32.

Meeting Presentations

35. Bass, R. G.; Waldbauer, R. O., Jr.; and Hergenrother, P. M.: Polyphenylquinoxalines Containing Carbonyl and Ether Connecting Groups. Presented at the American Chemical Society Meeting and Third Chemical Congress of the North American Continent, June 5-11, 1988, Toronto, Canada. In Polymer Preprints, Volume 29, No. 1, 1988, p. 292.

36. Connell, J. W.; Bass, R. G.; and Hergenrother, P. M.: Blends of an Ethynyl Terminated Imidothioether With Ethynyl Terminated Arylene Ether Oligomers. Presented at the 33rd International SAMPE Symposium and Exhibition, March 7-10, 1988, Anaheim, California. In SAMPE Preprint, Volume 33, p. 251-261.

37. Connell, J. W.; and Hergenrother, P. M.: Synthesis of Polyphenylquinoxalines Via Aromatic Nucleophilic Displacement. Presented at the American Chemical Society Meeting and Third Chemical Congress of the North American Continent, June 5-11, 1988, Toronto, Canada. In Polymer Preprints, Volume 29, No. 1, 1988, p. 172.

38. Dezern, J. F.: Novel Polyamide-Imides. Presented at the 19th International SAMPE Technical Conference on The Nation's Future Material Needs, October 13-15, 1987, Arlington, Virginia. In Preprint Book, Volume 19, p. 386-397.

39. Hergenrother, P. M.: High Performance Organic Adhesives. Presented at the Association of European Adhesives Manufacturers World Adhesive Congress Conference, June 8-10, 1988, Munich, West Germany. Proceedings pending.

40. Hergenrother, P. M.: High Performance Polymers. Presented at the 172nd Meeting of the Electrochemical Society, October 18-23, 1987, Honolulu, Hawaii. Extended abstract printed in proceedings.

41. Hergenrother, P. M.; and Havens, S. J.: Adhesive Properties of a New Semi-Crystalline Polyimide. Presented at the American Defense Preparedness Association Joint Government-Industry Symposium on Structural Adhesive Bonding, November 3-5, 1987, Dover, New Jersey. In Proceedings, p. 23-34.

42. Hergenrother, P. M.; and Havens, S. J.: Adhesive Properties of LARC-CPI, a New Semi-Crystalline Polyimide. Presented at the 33rd International SAMPE Symposium and Exhibition, March 7-10, 1988, Anaheim, California. In SAMPE Preprint, Volume 33, p. 451-463.

43. Hergenrother, P. M.; and Johnston, N. J.: Organic Polymeric Composites for Aerospace Applications. Presented at the National Meeting of the American Chemical Society, September 25-30, 1988, Los Angeles, California. In Polymeric Materials Science and Engineering Proceedings, Volume 59, p. 697-701.

44. Hinkley, J. A.: A Review of High Performance Thermoplastics Research at NASA-Langley. Presented at the Clemson University and Textile Hall Corporation Fiber Producer Conference 1988, April 26-28, 1988, Greenville, South Carolina. Abstract in Proceedings, p. 5A-3.

45. Hou, T-H.; and St. Clair, T. L.: Characterization of a Semicrystalline Polyimidesulfone Powder. Presented at the Society of Plastics Engineers and SAE 1988 International Congress & Exposition, February 29 - March 4, 1988, Detroit, Michigan. SAE Paper No. 880112. In SAE SP-748, Polymer Composites for Automotive Applications, p. 31-41.

46. Pater, R. H.: A New Synthetic Route to a Family of Non-Classical Addition-Type Thermoplastics 1. Concept and Demonstrations. Presented at the Society for the Advancement of Materials and Process Engineering 20th International SAMPE Technical Conference, September 27-29, 1988, Minneapolis, Minnesota. In SAMPE Preprint, Volume 20, p. 174-186.

47. Pater, R. H.: A Review of Dynamic Mechanical Characterization of High Temperature PMR Polyimides and Composites. Presented at the Society of Plastics Engineers and SAE 1988 International Congress & Exposition, February 29 - March 4, 1988, Detroit, Michigan. SAE Paper No. 880152. In SAE SP-748, Polymer Composites for Automotive Applications, p. 43-51.

48. Pater, R. H.: Novel Biscitraconimides Containing Hexafluoropropylidene Linkage. Presented at the National Meeting of the American Chemical Society, September 25-30, 1988, Los Angeles, California.

49. Pater, R. H.; and Morgan, C. D.: Interpenetrating Polymer Network Approach to Tougher and More Microcracking Resistant High Temperature Polymers 1. - LaRC-RP40. Presented at the 1988 Society of Plastics Engineers Annual Technical Conference (ANTEC), April 18-21, 1988, Atlanta, Georgia. In Proceedings, p. 1639-1644.

50. Pratt, J. R.; Blackwell, D. A.; St. Clair, T. L.; and Allphin, N. L.: 4,4'-Isophthaloyldiphthalic Anhydride Polyimides. Presented at the American Chemical Society Meeting and Third Chemical Congress of the North American Continent, June 5-11, 1988, Toronto, Canada. In Polymer Preprints, Volume 29, No. 1, 1988, p. 128-129.

51. Progar, D. J.; and St. Clair, T. L.: Flexible Backbone Aromatic Polyimide Adhesives. Presented at the U. S. Army Materials Technology Laboratory Thirty-Fifth Sagamore Army Materials Research Conference, June 26-30, 1988, Manchester, New Hampshire. Proceedings pending.

52. St. Clair, T. L.; Johnston, N. J.; and Baucom, R. M.: High Performance Composites Research at NASA-Langley. Presented at the Society of Plastics Engineers and SAE 1988 International Congress & Exposition, February 29 - March 4, 1988, Detroit, Michigan. SAE Paper No. 880110. In SAE SP-748, Polymer Composites for Automotive Applications, p. 1-19.

53. St. Clair, T. L.; and Progar, D. J.: Adhesive Evaluation of New Polyimides. Presented at the American Defense Preparedness Association Joint Government-Industry Symposium on Structural Adhesive Bonding, November 3-5, 1987, Dover, New Jersey. In Proceedings, p. 37-53.

54. Stoakley, D. M.; and St. Clair, A. K.: The Effect of Diamic Acid Additives on the Dielectric Constant of Polyimides. Presented at the National Meeting of the American Chemical Society, September 25-30, 1988, Los Angeles, California.

55. Young, P. R.; and Chang, A. C.: FTIR Characterization of Thermally Cycled PMR-15 Composites. Presented at the 33rd International SAMPE Symposium and Exhibition, March 7-10, 1988, Anaheim, California. In SAMPE Preprint, Volume 33, p. 538-550.

56. Young, P. R.; Druy, M. A.; Stevenson, W. A.; and Compton, D. A. C.: In Situ Composite Cure Monitoring Using Infrared Transmitting Optical Fibers. Presented at the Society for the Advancement of Materials and Process Engineering 20th International SAMPE Technical Conference, September 27-29, 1988, Minneapolis, Minnesota. In SAMPE Preprint, Volume 20, p. 336-347.

Technical Talks

57. Boston, H. G.; Stoakley, D. M.; and St. Clair, A. K.: Structure-Property Study of Polyimide Films Using Autovibron With Improved Clamping Technique. Presented at the American Chemical Society 39th Southeast Regional Meeting, November 3-6, 1987, Orlando, Florida.

58. Hergenrother, P. M.: New High Performance Thermoplastic Composite Matrices. Presented at the 1988 Gordon Research Conference on Composite Materials, January 11-15, 1988, Ventura, California.

59. Hergenrother, P. M.: New Polyimides Containing Carbonyl and Ether Connecting Groups. Presented at the Pennsylvania State Polymer Symposium on Synthesis of Polymers, October 5-6, 1987, University Park, Pennsylvania.

60. Hergenrother, P. M.: Recent Advances in High Performance Organic Adhesives. Presented at the 1988 Gordon Research Conference on the Science of Adhesion, August 14-19, 1988, New Hampton, New Hampshire.

61. Hergenrother, P. M.: Synthetic Approaches to Thermoplastic Composite Matrices. Presented at the American Chemical Society Workshop on Chemistry and Properties of High Performance Composites, March 28-31, 1988, Jackson, Wyoming.

62. Hinkley, J. A.: Effect of Fiber/Matrix Adhesion on Interlaminar Toughness of Thermoplastic Matrix Composites. Presented at the University of Connecticut Symposium/Workshop on the Control of Polymer Interface Properties, May 19-20, 1988, Storrs, Connecticut.

63. Hinkley, J. A.; Johnston, N. J.; and O'Brien, T. K.: Interlaminar Fracture Toughness of Thermoplastic Composites. Presented at the ASTM Symposium on Advances in Thermoplastic Matrix Composite Materials, October 18-20, 1987, Bal Harbour, Florida.

64. Howes, J. C.; Loos, A. C.; and Hinkley, J. A.: The Effect of Processing on Interfacial Strength Development in Thermoplastic Resins and Composites. Presented at the ASTM Symposium on Advances in Thermoplastic Matrix Composite Materials, October 18-20, 1987, Bal Harbour, Florida.

65. Jensen, B. J.: High Performance Thermosets. Presented at the Virginia Commonwealth University, Chemistry Department, May 5, 1988, Richmond, Virginia.

66. Johnston, N. J.: High Performance Composites: Resin Property/Composite Property Relationships. Presented at the University of Florida Advanced Materials Conference, November 9-13, 1987, Palm Coast, Florida.

67. Johnston, N. J.: High Performance Composites: Resin Property/Composite Property Relationships. Presented at the American Chemical Society Workshop on Chemistry and Properties of High Performance Composites, March 28-31, 1988, Jackson, Wyoming.

68. Johnston, N. J.: Introduction to High Performance Composites. Presented at the State University of New York Short Course on Principles of High Performance Composites, October 26-28, 1987, West Point, New York.

69. Johnston, N. J.: Introduction to High Performance Composites. Presented at the American Chemical Society Workshop on Chemistry and Properties of High Performance Composites, March 28-31, 1988, Jackson, Wyoming.

70. Johnston, N. J.: Resin Property/Composite Property Relationships. Presented at the State University of New York Short Course on Principles of High Performance Composites, October 26-28, 1987, West Point, New York.

71. Johnston, N. J.: Thermoplastic Composites. Presented at the Navy Council on Materials and Structures Tutorial on Thermoplastic Composites, December 2-3, 1987, Washington, DC.

72. Johnston, N. J.: Thermoset and Thermoplastic Matrices: Room for Both? Presented at the Gordon Research Conference on Thermosetting Polymers, June 20-24, 1988, New London, New Hampshire.

73. Pater, R. H.: Interpenetrating Polymer Network Approach to Tough High Temperature Polymers and Composites. Presented at the American Chemical Society Workshop on Chemistry and Properties of High Performance Composites, March 28-31, 1988, Jackson, Wyoming.

74. Pater, R. H.: LaRC-RP40: A New Tough High Temperature Matrix Resin. Presented at the Air Force, Army, Navy, High Temple Workshop VIII, January 25-28, 1988, Riviera Beach, Florida.

75. Progar, D. J.: High Temperature Polyimide Composite Bonding. Presented at the 1988 Gordon Research Conference on the Science of Adhesion, August 14-19, 1988, New Hampton, New Hampshire.

76. St. Clair, T. L.: Advanced Polymers for Aerospace Application. Presented at the ACS, Society of Analytical Chemists of Pittsburgh, et al., Seminar on Emerging Materials: The Shape of New Technologies, March 29, 1988, Pittsburgh, Pennsylvania.

77. St. Clair, T. L.: High Performance Thermoplastics. Presented at the State University of New York Short Course on High-Temperature Polymers: Synthesis, Properties, and Applications, May 9-11, 1988, New Paltz, New York.

78. St. Clair, T. L.: High Temperature Aerospace Adhesives. Presented at the State University of New York Short Course on Adhesion Science, October 20, 1987, West Point, New York.

79. St. Clair, T. L.: Novel Developments in Polymers for Aerospace Applications. Presented .at the 1987 Fall Meeting of the Association for Chemical Technology Transfer, November 19, 1987, Crystal City, Virginia.

80. St. Clair, T. L.: Thermoplastic Polyimides. Presented at the Polysar Limited Polymer Seminar Series, July 14, 1988, Sarnia, Canada.

81. St. Clair, T. L.: Thermoplastic Polyimides. Presented at the State University of New York Short Course on High-Temperature Polymers: Synthesis, Properties, and Applications, May 9-11, 1988, New Paltz, New York.

82. St. Clair, T. L.: Thermoplastic Resins in High Performance Composites. Presented at the State University of New York Short Course on Principles of High Performance Composites, October 26-28, 1987, West Point, New York.

Tech Briefs

83. St. Clair, T. L.; and Kumar, D.: Method for Producing Isomeric Trisaryloxycyclotriphosphazene Polymer Precursors and Intermediates. NASA Tech Brief LAR-13819.

Patents

84. Bell, V. L.: Polyether-Polyester Graft Copolymer, U.S. Patent 4,711,932. Issued December 8, 1987.

85. St. Clair, T. L.; Maudgal, S.; and Pratt, R. J.: Poly(Carbonate-Imide) Polymer. U.S. Patent 4,713,439. Issued December 15, 1987.

86. Hergenrother, P. M.; Bass, R. G.; Sinsky, M. K.; and Connell, J. W.: Polyenamines From Aromatic Diacetylenic Diketones and Diamines. U.S. Patent 4,774,359. Issued September 27, 1988.

Mechanics of Materials Branch

Formal Reports

87. Whitcomb, J. D.: Three-Dimensional Analysis of a Postbuckled Embedded Delamination. NASA TP-2823, July 1988, 25 p.

Quick-Release Technical Memorandums

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89. Bigelow, C. A.: Effects of Moisture, Elevated Temperature, and Fatigue Loading on the Behavior of Graphite/Epoxy Buffer Strip Panels With Center Cracks. NASA TM-100558, February 1988, 26 p.

90. Crews, J. H., Jr.; and Reeder, J. R.: A Mixed-Mode Bending Apparatus for Delamination Testing. NASA TM-100662, August 1988, 39 p.

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FY 89 PLANS

Polymeric Materials Branch

Major research thrusts for FY 89 in the Polymeric Materials Branch are in the areas of resin-matrix composite studies, high performance polymers and space durable polymers. Plans for this research are outlined in figure 38. The research will be conducted under the following three RTR's.

RTR 505-63-01-01 Resin Matrix Composite Development

Objective:

Develop technology leading to high performance composites with high damage tolerance and durability for advanced structural applications.

Approach:

Conduct large scale synthesis of new thermoplastics, semi-crystalline polymers, toughened thermosets and polymer blends and evaluate promising new candidates as composite matrices. Study and optimize prepreg formation and composite fabrication of new matrices. Conduct work to develop better prepregging and composite fabrication processes. Test composites under variety of conditions.

Milestones:

- Demonstrate feasibility of fabricating complex composite panels from LARC-TPI and $PISO_2$ using high temperature expandable rubber tooling - May 1989.
- Develop new process to prepare graphite/thermoplastic resin prepreg by hot melt impregnation of uniweave graphite cloth - June 1989.
- Obtain composite properties using in-house prepared prepreg from a blend of acetylene terminated materials - July 1989.
- Correlate damage tolerance of small composite panels with that obtained on standard panels - August 1989.
- Determine damage tolerance of composites from three in-house developed high temperature polymers - September 1989.
- Scaleup synthesis of one promising new polymer and evaluate in composites - September 1989.
- Develop powder impregnation technique to make prepreg - September 1989.

RTR 506-43-11-01 High Performance Polymers

Objective:

Develop readily processable polymers for use as adhesives, composite matrices and films in hostile high temperature environments.

Approach:

Synthesize and characterize new polyimides, polyphenylquinoxalines, polyarylene ethers, acetylene containing materials and polymer blends. Evaluate as high temperature adhesives, composite matrices and films.

Milestones:

- Evaluate composite properties of a semi-crystalline polyimide (LARC-CPI) - February 1989.
- Prepare and characterize new, more processable polyimides containing carbonyl and ether connecting groups with methyl substituents - March 1989.
- Synthesize and characterize novel imidazole and benzimidazole containing polyarylene ethers - April 1989.
- Evaluate new polyphenylquinoxalines prepared by aromatic nucleophilic displacement route as adhesives, composites and films - June 1989.
- Obtain preliminary adhesive, composite and film properties on new semi-crystalline imide copolymers - July 1989.
- Optimize blends of acetylene terminated arylene ether oligimers and other acetylene terminated materials to obtain best balance of processability and composite properties - August 1989.
- Comprehensively evaluate the adhesive performance of a new high temperature polyimide - August 1989.
- Develop a new tough matrix based upon the reaction of acetylene terminated resins and bismaleimides - September 1989.
- Optimize characterization methodology to correlate polymer molecular weight and distribution with processability and mechanical properties - September 1989.

RTR 506-43-21-05 Space Durable Polymers

Objective:

Develop space durable adhesives, coatings and films.

Approach:

Synthesize and characterize new polymers containing chemical units that impart radiation stability and low color. Adhesive, film and coating samples of the most promising material will be exposed to simulated space environment and their stability monitored through spectroscopic techniques and retention of mechanical properties.

Milestones:

- Initiate new grant to develop synthesis of unique monomers for use in the preparation of space durable polymers - December 1988.
- Correlate the effect of chemical structure and crosslink density of thermosets on coefficient of thermal expansion - February 1989.
- Determine the effect of various degrees and types of crystallinity in a polymer on coefficient of thermal expansion and radiation stability - September 1989.
- Expose promising polymers to simulated space environment and monitor stability by spectroscopic means and mechanical property retention - September 1989.

Mechanics of Materials Branch

Research in the Mechanics of Materials Branch will focus on mechanics of damage in laminates and 3-D forms, micromechanics, characterization of the thermomechanical behavior of metal-matrix composites, damage tolerance of light alloys, and computational fracture mechanics. Trends for this research are outlined in figure 39. The research will be carried out under the following two RTR's.

RTR 505-63-01-05 Mechanics of Materials Research in Laminated Composites and Metals

Objectives:

Develop the methodology to predict the initiation and growth of critical levels of damage in laminated composites under general mechanical loading conditions. Develop the experimental data base and methodologies to predict the initiation and growth of cracks in metals under constant amplitude and spectrum loading for expected operational conditions. Develop experimental and numerical solutions to fatigue and fracture problems in support of current NASA missions. Predict the fatigue and fracture behavior of composites from the fiber, resin, and interface constituent behavior by the application of micromechanics models.

Develop a fundamental understanding of the initiation and growth of microstructural damage in candidate 3-D material forms including stitching, braiding, weaving, and filament winding.

Approach:

- The evolution of damage under general loading conditions will be experimentally observed and documented. These experimental results will be interpreted through appropriate analyses based on mechanics principles. The correlation of the experimental and analytical results will give rise to the development of analytical methods and failure criteria necessary to predict the strength and life of composite structures. Failure methodology will be verified by predicting the behavior of tapered laminates subjected to combined loads typical of those experienced in composite rotor hub flexure.

- Experimentally evaluate the fatigue and fracture performance of promising new alloys relative to established alloys and evaluate the adequacy of current methods to predict the life of new alloys under expected spectrum loading and temperature conditions. Broaden the applicability of current life-prediction methods by developing methods to describe mixed-mode crack-growth behavior and by developing a three-dimensional model of closure incorporating both plasticity- and roughness-induced closure behavior. Develop an experimental data base on the growth of small cracks to explore the potential of crack-growth life analyses to replace traditional "initiation" analyses. Establish correlations between observed performance and metallurgical features which might be used to guide development of alloys with improved performance.

- Generate stress-intensity factor solutions for common crack configurations using existing numerical methods (Boundary-Force, Finite-Element-Alternating methods) for NASA FLAGRO and for aerospace industry. Evaluate crack-closure model options planned for NASA FLAGRO and compare with current options planned to be used by the European Space Agency. Conduct fracture tests on various surface-and corner-crack configurations to simulate expected crack configurations in Shuttle solid-rocket motor case (D6AC steel) clevis-tang joint region under expected operating conditions and compare with current NDI capabilities. Develop elastic and elastic-plastic solutions for surface cracks in welded 2219 aluminum Shuttle external tank structure to verify newly-developed elastic-plastic methodology for predicting stable crack growth during proof and operating conditions.

- Conduct tests to identify microdamage onset and growth and to determine inelastic constitutive relationships that account for multiaxial stress states and microdamage. Then, use the constitutive relationships in composite stress analyses to compute stresses, strains, and fracture mechanics parameters corresponding to observed composite failures. Establish constituent failure criteria by comparing the observed microfailures with computed stress analysis results. Finally, develop models to relate composite failures to the corresponding fiber, matrix, and interface constituent failures.

- Conduct critical experiments to identify damage mechanisms and damage growth in advanced 3-D material forms under tension and compression fatigue loadings. Also, experimentally investigate the post impact damage tolerance of candidate material forms. By comparing the experimental results to those for baseline materials and together with analytical results from mechanics models of the local fiber behavior, identify the most promising new materials forms on the basis of stiffness, damage tolerance, and fatigue life.

Milestones:

- Elastic-plastic finite-element analyses of surface cracks in welded aluminum structure - Shuttle external tank - January 1989.
- Determine how stitching affects the fatigue life of graphite/epoxy - January 1989.
- Fracture toughness and critical flaw sizes for D6AC solid-rocket motor cases - February 1989.
- Determine modes of damage in braided graphite/epoxy produced by foreign object impacts - February 1989.
- AGARD Report on Supplemental Test Program for Short-Crack Behavior - May 1989.
- NASA/Chinese Aeronautical Establishment Report on Fatigue and Fracture Cooperative Program - June 1989.
- Develop and verify analysis for predicting the onset of 2-D damage in laminates caused by impact-like contact stresses.
- Complete analysis of ply microdamage that accompanies mode I and mode II delamination - September 1989.

RTR 506-43-71-03 Mechanics of Damage in Metal Matrix Composites

Objectives:

Develop the methodology necessary to predict the fatigue, fracture, and mechanical behavior of MMC's required to insure structural integrity at elevated temperatures in support of supersonic and hypersonic vehicles.

Approach:

The mechanical behavior of MMC's and the development of damage mechanisms under thermal and mechanical loadings will be experimentally observed and documented. Material models and mechanics analyses will be developed to explain the observed material behavior. These analyses will include the effects of plasticity, viscoelasticity, and thermal stresses. The correlation of the experimental and analytical results will give rise to the development of analytical methods and failure criteria necessary to predict the strength and life of laminated composite structures.

Milestones:

- Complete a preliminary test program to identify the failure mechanisms under thermal mechanical fatigue loading of Ti based MMC - June 1989.

- Complete the next generation PAFAC program to include thermal and elastic-plastic behavior - September 1989.

Applied Materials Branch

Research emphasis in the Applied Materials Branch for FY 89 will be in the areas of space materials, carbon-carbon composites, and composite materials for aircraft and rotorcraft structures. Plans for this research are outlined in figure 40 and will be carried out under the following five RTR's.

RTR 505-63-01-06 Composites for Rotorcraft/Aircraft Structures

Objectives:

To develop the technology for the application of advanced composite materials and innovative design concepts in rotorcraft and aircraft structures in order to improve performance, efficiency, damage tolerance, environmental durability, and energy absorption capability compared to metal structures.

Approach:

In-house, contractual, and grant studies will be conducted to develop innovative material forms and processing science concepts for lightweight composite structure applications. Composite materials that incorporate toughened resins and high strength/strain fibers will be evaluated for improved damage tolerance. New net-shaped material forms that are fabricated with automated textile processes such as 2-D and 3-D weaving, braiding, stitching, and knitting will also be evaluated. Improvements in through-the-thickness properties and damage tolerance will be evaluated. Process models for resin transfer molding of textile materials will be developed. Composite structural elements that are fabricated with cost-effective filament winding and resin transfer molding processes will be evaluated. Long-term durability of composites in-service and repaired composite components will be established. Analytical methods to predict the energy absorption capability of composite beam elements will be developed.

Milestones:

- Complete evaluation of stitching parameters in through-the-thickness reinforcement with resin transfer molding - December 1988.
- Conduct residual strength tests on repaired graphite/epoxy components after 5 years of outdoor exposure at NASA Langley - December 1988.
- Complete 10 years of flight service of Sikorsky S-76 composite components - March 1989.
- Complete 15-year and final residual strength tests on B-737 graphite/epoxy spoilers - June 1989.
- Demonstrate dielectric monitor of autoclave impregnation and cure in CMDS tool and autoclave - June 1989.
- Perform ballistic impact evaluation of stitched composite panels - September 1989.
- Complete development of analysis capability to predict the crushing response of composite tube and beam webs - September 1989.
- Evaluate the mechanical properties of through-the-thickness braided graphite/epoxy composites - September 1989.
- Verify RTM process model with experiments and use sensor data to optimize RTM process conditions - September 1989.

RTR 506-43-21-04 - Composite Materials for Spacecraft Applications

Objectives:

Develop new composite materials and protective/thermal control coatings for enhanced environmental and thermal-mechanical durability in long-life space structures.

Approach:

Advanced polymeric-, metallic-, and ceramic-matrix, fiber-reinforced composites will be developed and evaluated for long-term use in spacecraft structures. Evaluation will include thermal cycling, and atomic oxygen, electron, proton, and UV exposure. Advanced laser interferometry will be used to determine dimensional stability. Thin metallic and oxide protective coatings will be evaluated on flat and tubular surfaces. The optical, chemical, and mechanical property degradation will be characterized and analytically modeled. Shuttle experiments will be used to verify models and laboratory simulations.

Milestones:

- Complete mechanical characterization of composite tubes after 15K thermal cycles - September 1989.
- Complete development of micromechanics analysis of thermally induced damage in resin-matrix composites - September 1989.
- Measure thermal expansion of Gr/Ep tubes after 10 to 20K thermal cycles - September 1989.
- Determine effects of Gr fiber modulus on microdamage/thermal expansion during thermal cycling - September 1989.
- Examine the effects of electron radiation on 930/P75 composites cured at various temperatures - September 1989.
- Develop combined thermal cycling and electron radiation exposure capability - September 1989.

RTR 506-43-71-02 Carbon-Carbon Composites

Objectives:

To develop high strength, minimum gauge, oxidation-protected carbon-carbon materials for hot structure and TPS applications in advanced space transportation vehicles and hypersonic aircraft.

Approach:

Advanced processing methods, alternate matrix precursor materials, fiber surface modifications, and alternate reinforcement concepts will be developed to improve substrate mechanical properties. Matrix and fiber oxidation inhibitors, sealants, and advanced coatings will be developed to improve oxidation resistance. Environmental testing will be performed in simulated mission dynamic environments and in multiparameter (temperature, pressure, load) facilities.

Milestones:

- Angle-interlock reinforcement concepts evaluated for thin gauge carbon-carbon composites - June 1989.
- Potential assessed for surface treatment of high-modulus fibers to increase interlaminar strengths - June 1989.
- Potential assessed for small-diameter tow to increase interlaminar strengths/reduce per-ply thickness of 2-D laminates - September 1989.

RTR 585-02-21-01 Advanced Materials for PSR

Objectives:

Develop advanced composite materials and coatings that are durable and have stable thermal and mechanical properties in the space service environment of precision segmented reflector spacecraft.

Approach:

New, novel low expansion polymer resins will be developed and used to fabricate composites. Alternate composite fabrication methods that result in lower residual stresses will be investigated. As a long range goal, low temperature fabrication methods will be developed for advanced, highly stable graphite/glass laminates. Material constitutive equations and analytical models will be developed to correlate/predict environmental effects on thermal and mechanical properties of the advanced composites. These models will aid in directing the materials development activities. The surface distortion of composite laminates/panels will be measured and modeled.

Milestones:

- Fabricate composites with low-expansion resin - September 1989.

RTR 763-01-41-17 Oxidation-Resistant C-C Composites for NASP

Objectives:

To develop oxidatively protected carbon-carbon material concepts to meet airframe requirements in support of Aero-Space Plane.

Approach:

Evaluate in simulated NASP mission environments various promising oxidation-protection systems which were developed for propulsion applications. Build on these results, tailoring a new oxidation-protection system (in-depth oxidation protection, sealants, coatings) to meet specific NASP mission requirements.

Milestones:

- Complete multiparameter environmental simulation evaluations of state-of-the art candidate test materials - December 1988.

- Initiate development of improved oxidation-protection system - December 1988.

- Complete dynamic environment (arc jet) testing of state-of-the-art candidate test materials - March 1989.

- Field-applied sealant feasibility demonstrated - June 1989.

Metallic Materials Branch

Research in the Metallic Materials Branch for FY 89 will focus on advanced light alloy and metal-matrix composites development, innovative metals processing, and high temperature, thin gage metals and metal-matrix composites for airframe applications. Plans for this research are outlined in figure 41 and will be carried out under the following five RTR's.

RTR 505-63-01-02 Advanced Structural Metallics for Service to 1000°F

Objectives:

To develop a fundamental understanding of the metallurgical structure/mechanical property interactions resulting from powder processing, consolidation, and subsequent thermomechanical processing of intermediate and high temperature aluminum alloys prepared by advanced ingot and powder metallurgy techniques.

Approach:

Prepare new aluminum alloy compositions of laboratory quantities by advanced I/M and P/M techniques. Develop and evaluate promising in-situ composite materials systems with light alloy metallic matrices and correlate microstructural/mechanical property relationships. Identify metallurgical characteristics controlling specific properties through laboratory analysis and development of optimized processing techniques to obtain tailored properties.

Milestones:

- Produce PM aluminum alloy powders for high temperature applications using the LaRC gas atomization facility - October 1988.

- Complete initial characterization of Al-Cu-Li-In-Zr alloy designed to achieve high strength through heat treatment without the need for intermediate mechanical processing - December 1988.

- Complete results of developed PM Al-Cu-Mg-Zr alloy in unreinforced and particulate reinforced product form - January 1989.

- Develop environmental degradation laboratory capabilities to support electrochemical, slow strain rate, and controlled temperature-humidity testing of advanced metallic systems - March 1989.

- Determine role of hydrogen embrittlement, anodic dissolution and surface films on corrosion fatigue of Al-Li-Cu alloy 2090 in aqueous environments - March 1989.

- Determine mechanisms controlling corrosion fatigue and stress corrosion cracking of advanced PM and IM aluminum alloys - June 1989.

- Develop supporting information for preparation of new standards for stress corrosion evaluation using both the breaking load test method and precracked specimen techniques and for revision of existing C-ring standard test methodology - June 1989.

- Determine metallurgical characteristics and material properties of powder with Mn, Ca, and Si additions for high temperature applications - July 1989.

- Define the mechanisms of dispersion strengthening and fracture in in-situ reinforced Al-Cu-Mg alloys - July 1989.

RTR 505-63-01-03 Innovative Metals Processing

Objectives:

Develop improved aluminum alloys and innovative processing methods for fabricating lightweight aerospace structural components. Develop advanced forming and joining techniques for lightweight Al-Li and high temperature aluminum alloys and evacuated titanium honeycomb-core sandwich concepts.

Approach:

Combined in-house, contractual, and university efforts to define the potential of advanced aluminum alloys for aerospace structural applications. Demonstrate weldability, enhanced post-SPF properties and evaluate the cryogenic behavior of superplastic Al-Li alloys of modified compositions. Assess the potential of high temperature aluminum alloys and develop improved brazing and joining processes for fabricating evacuated titanium honeycomb-core sandwich structure. Characterize material properties and design, fabricate, and test structural elements.

Milestones:

- Complete initial characterization of the mechanical properties of Weldalite® with and without discontinuous reinforcement - December 1988.

- Determine the superplastic formability of high temperature Al-Fe-V-Si alloys at various dispersoid volume fractions - January 1989.

- Complete materials characterization and joining studies on high temperature Al-Fe-V-Si alloy before and after superplastic forming - February 1989.
- Cryogenic property characterization of SPF Al-Li-Cu-Zr-In alloy - July 1989.

- Fabricate advanced aluminum alloy curved cap, beaded web panels - August 1989.

- Demonstrate vacuum integrity of 15-3 Ti honeycomb core sandwich - September 1989.

RTR 505-80-31-02 Advanced Metal Matrix Composites for NASP

Objectives:

Develop specific, high temperature metal matrix composites and associated fabrication technology for aero-space plane applications.

Approach:

Establish surface treatments and/or coating systems for selected fibers for optimum fiber/matrix stability. Fabricate and test minimum gage composite panels to establish performance limits. Develop techniques for structural component fabrication. Define scale-up requirements for large panel manufacture.

Milestones:

- Cross-ply composite laminates fabricated - December 1988.
- Service limits defined - June 1989.

RTR 506-43-71-01 High Temperature Thin Gage Metallics

Objectives:

Develop new high temperature metallics, processing and joining techniques, and coatings for environmental protection for use at temperatures from 500°F to 2000°F including in-situ and continuously reinforced advanced metal-matrix composites and light alloy metallics.

Approach:

Combined in-house and contract research studies to develop and characterize advanced metallic systems produced by deposition techniques, rapid solidification rate technology and conventional high temperature processing. Establish suitable joining processes for very thin gage, lightly loaded structure. Demonstrate technology readiness through design, fabrication, testing and evaluation of structural sub-components.

Milestones:

- Determine high temperature properties of foil gage, ingot metallurgy titanium aluminide materials - December 1988.
- Demonstrate low catalysis, high emittance coating concepts for titanium aluminide composites - December 1988.
- Complete preliminary evaluation of the potential for designing nonequilibrium phases to improve high temperature properties and stability of RSR intermetallics - January 1989.

- Evaluate very thin gage metallic substrates produced by deposition techniques - June 1989.

RTR 763-01-41-11 Advanced Processing of Ti_xAL Composites for NASP

Objectives:

Develop advanced joining processes for fabricating Ti_xAl metal-matrix composite, RSR titanium honeycomb core sandwich structure and develop an analytical model for predicting composite properties.

Approach:

Conduct in-house studies using available titanium based ingot metallurgy (IM) model materials to develop joining processes suitable for fabricating Ti_xAl composite sandwich structure. Screen candidate processes including brazing and enhanced diffusion bonding (EDB) based on both metallurgical studies and mechanical property tests. Evaluate alternate EDB material compositions to improve elevated temperature properties of IM Ti_3Al-Ti_3Al joints. Develop an analytical model for predicting fatigue behavior and verify experimentally. Fabricate, test and evaluate small sandwich specimens and structural sub-elements using Ti_3Al composites as they become available.

Milestones:

- Develop alternate EDB compositions for improved elevated temperature properties of EDB joints - September 1988.

- Fabricate IM Ti_3Al - Ti-15-3 sandwich panels for elevated temperature testing - October 1988.

- Include time and temperature effects in micromechanics model of continuous fiber reinforced MMC - January 1989.

- Conduct edge compression tests of Enhanced Diffusion Bonded Ti_3Al - H/C panels at room and elevated temperature - January 1989.

- Demonstrate the use of the melt overflow process for casting RSR titanium foil by producing four inch wide strip - March 1989.

- Room/elevated temperature properties of EDB honeycomb core coupons using Ti_3Al/SCS_6 MMC face sheet - June 1989.

- Modify existing failure analysis models to include thermal residual stresses in MMC - June 1989.

Concluding Remarks

This document presents the FY 88 accomplishments, presentations and publications, and the FY 89 research plans of the Materials Division.

LANGLEY RESEARCH CENTER

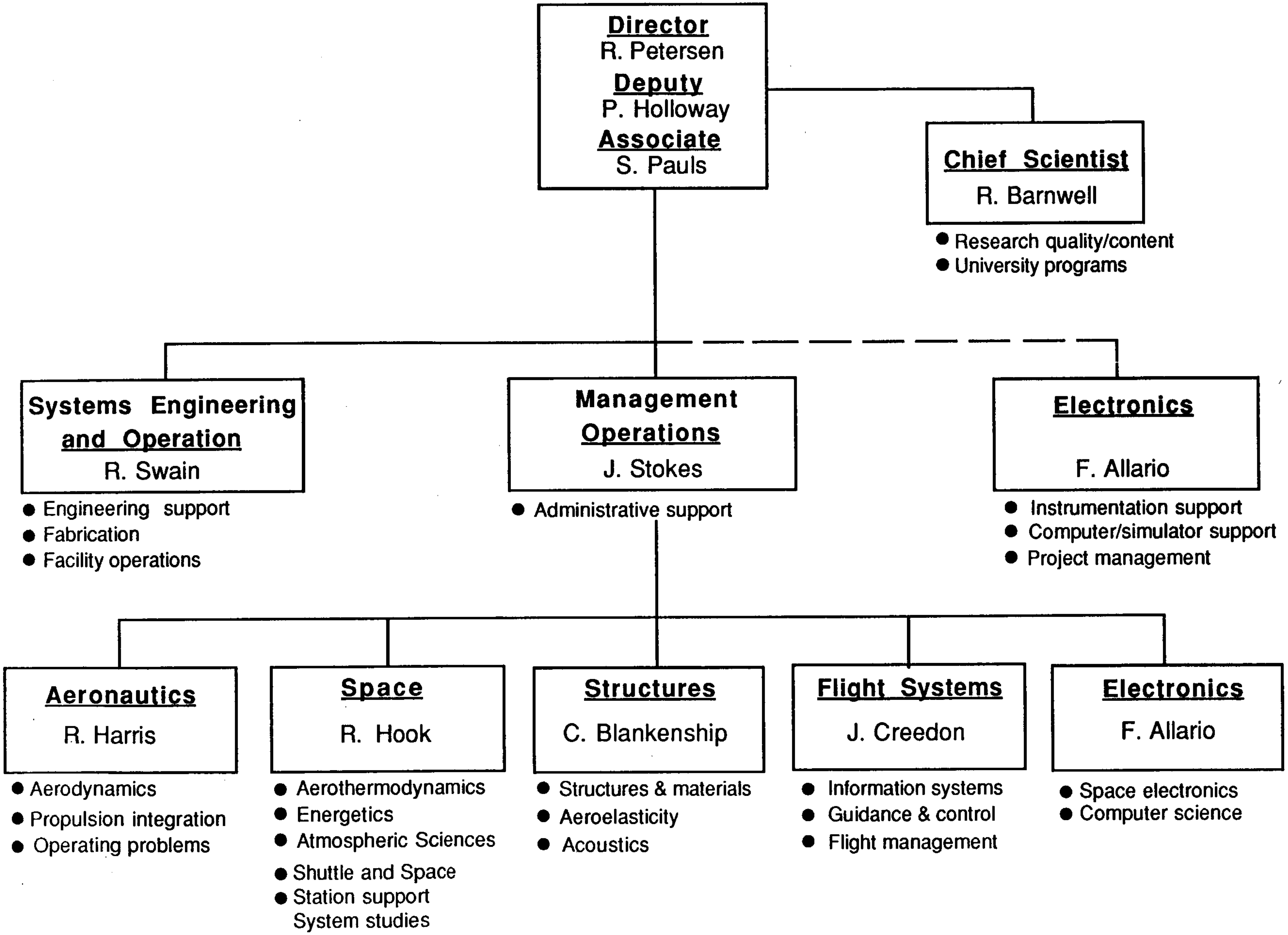
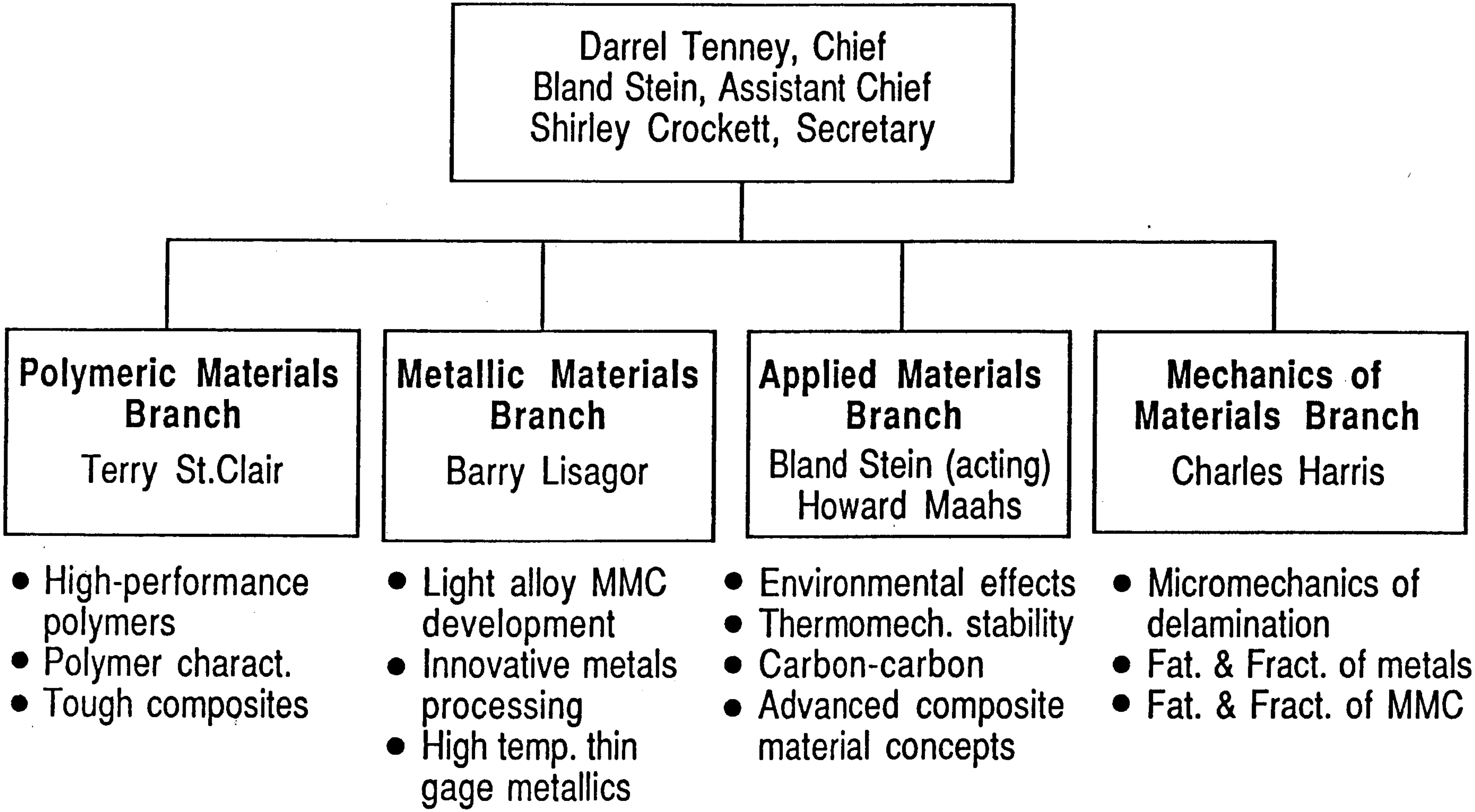


Figure 1.

MATERIALS DIVISION



Darrel Tenney, Chief
Bland Stein, Assistant Chief
Shirley Crockett, Secretary

Polymeric Materials Branch
Terry St.Clair

- High-performance polymers
- Polymer charact.
- Tough composites

Metallic Materials Branch
Barry Lisagor

- Light alloy MMC development
- Innovative metals processing
- High temp. thin gage metallics

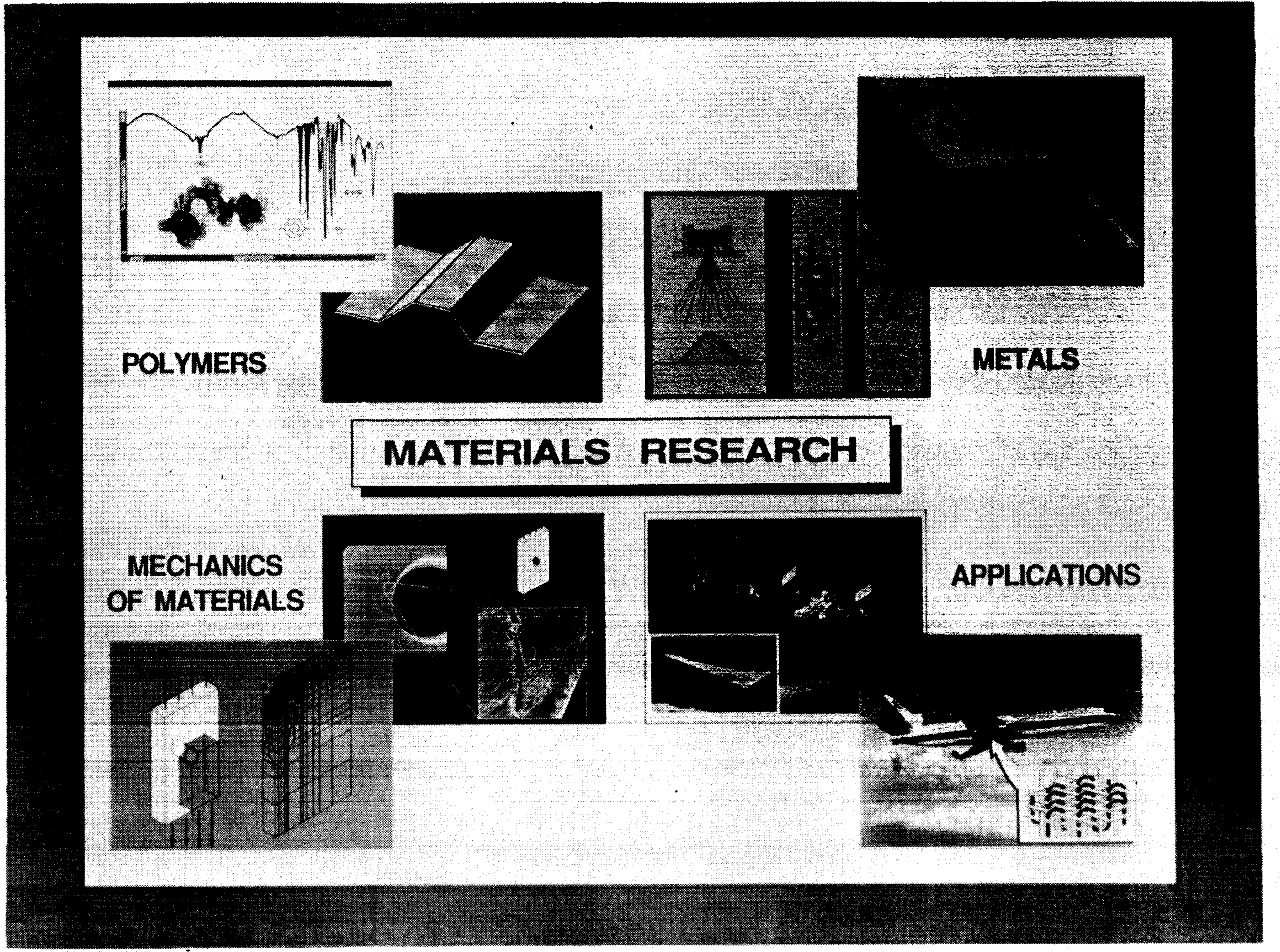
Applied Materials Branch
Bland Stein (acting)
Howard Maahs

- Environmental effects
- Thermomech. stability
- Carbon-carbon
- Advanced composite material concepts

Mechanics of Materials Branch
Charles Harris

- Micromechanics of delamination
- Fat. & Fract. of metals
- Fat. & Fract. of MMC

Figure 2.



POLYMERS

METALS

MATERIALS RESEARCH

MECHANICS
OF MATERIALS

APPLICATIONS

Figure 3.

MATERIALS DIVISION
LONG RANGE THRUSTS - AERONAUTICS

Lead Role

- Metallic materials for aircraft structures
- Carbon-carbon composites for hypersonic vehicles
- High temperature composites and Al alloys for high speed aircraft

Support Role

- Composite materials for primary aircraft structures

Figure 4(a).

MATERIALS DIVISION
LONG RANGE THRUSTS - SPACE

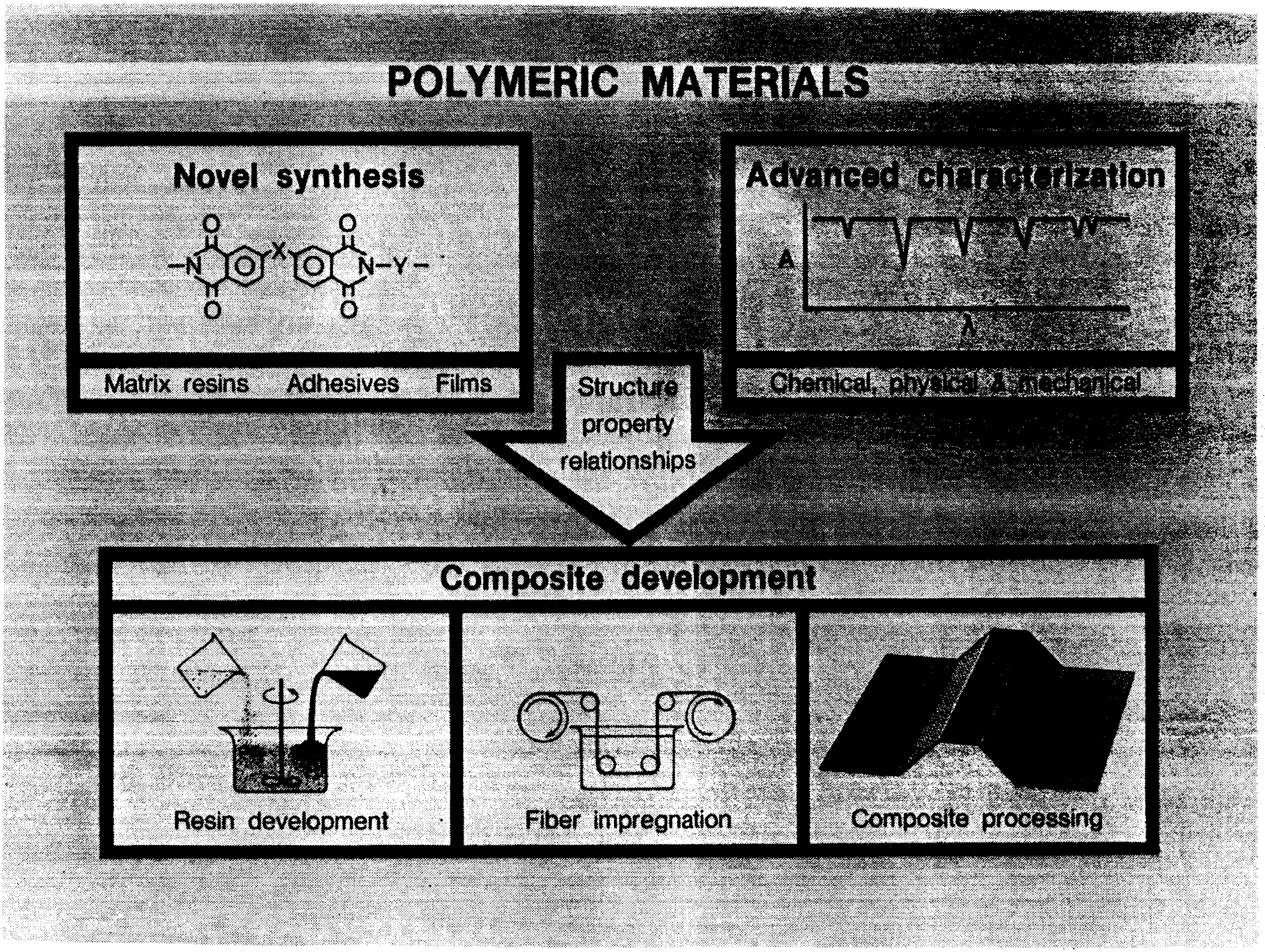
Lead Role

- Materials & structures technology for Advanced Launch Systems
- Materials durability in the space environment

Support Role

- Structures, materials and dynamics technology for Space Station

Figure 4(b).



POLYMERIC MATERIALS

Novel synthesis

Matrix resins Adhesives Films

Advanced characterization

Chemical, physical & mechanical

Structure property relationships

Composite development

Resin development

Fiber impregnation

Composite processing

Figure 5.

ORIGINAL PAGE
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POLYMERIC MATERIALS BRANCH
FIVE YEAR PLAN

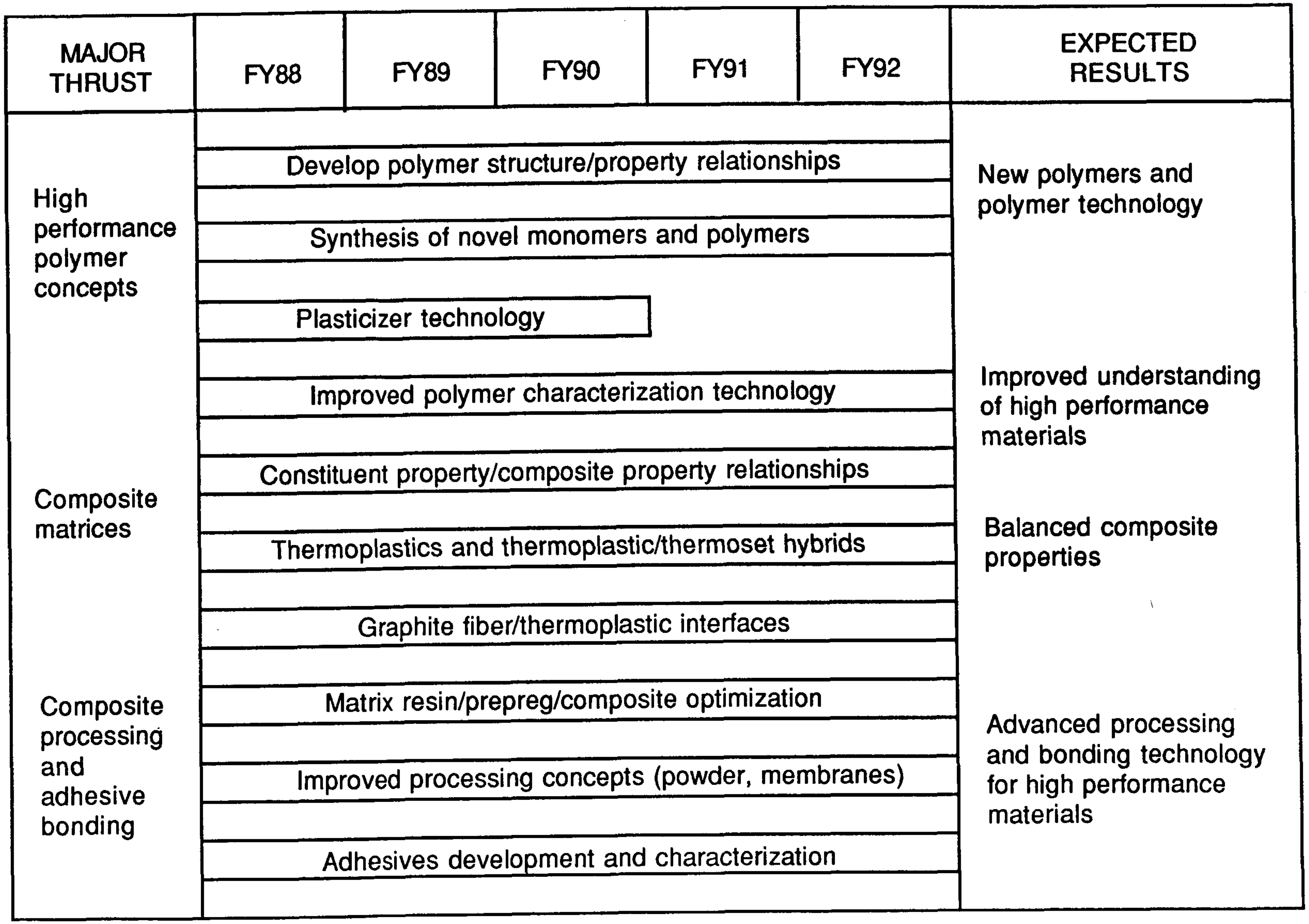


Figure 6.

LARC-RP40: A NEW TOUGH HIGH TEMPERATURE MATRIX RESIN

Ruth H. Pater
Polymeric Materials Branch
Ext. 44277 December 1987
RTOP 506-43-11

Research Objective: To develop a high temperature, composite matrix material with significantly improved toughness microcracking resistance characteristics over state-of-the-art resins.

Approach: (1) Synthesize a semi-interpenetrating polyimide network consisting of thermosetting PMR-15 and thermoplastic NR-150B2. (2) Characterize the neat resin and composite. (3) Compare the properties of the new material and PMR-15 prepared and tested under identical conditions.

Accomplishment: LARC-RP40 shows significantly improved properties over PMR-15 in three areas: (1) toughness (322 percent increase, G_{Ic} 368 vs. 87 J/m^2), (2) microcracking resistance (0 vs. 58 microcracks/inch after 1000 thermal cycles), and (3) glass transition temperature (369 vs. 339°C). These property improvements have been achieved without compromising the processability and elevated temperature mechanical performance characteristic of PMR-15. All raw materials necessary for the preparation of this new matrix resin are commercially available.

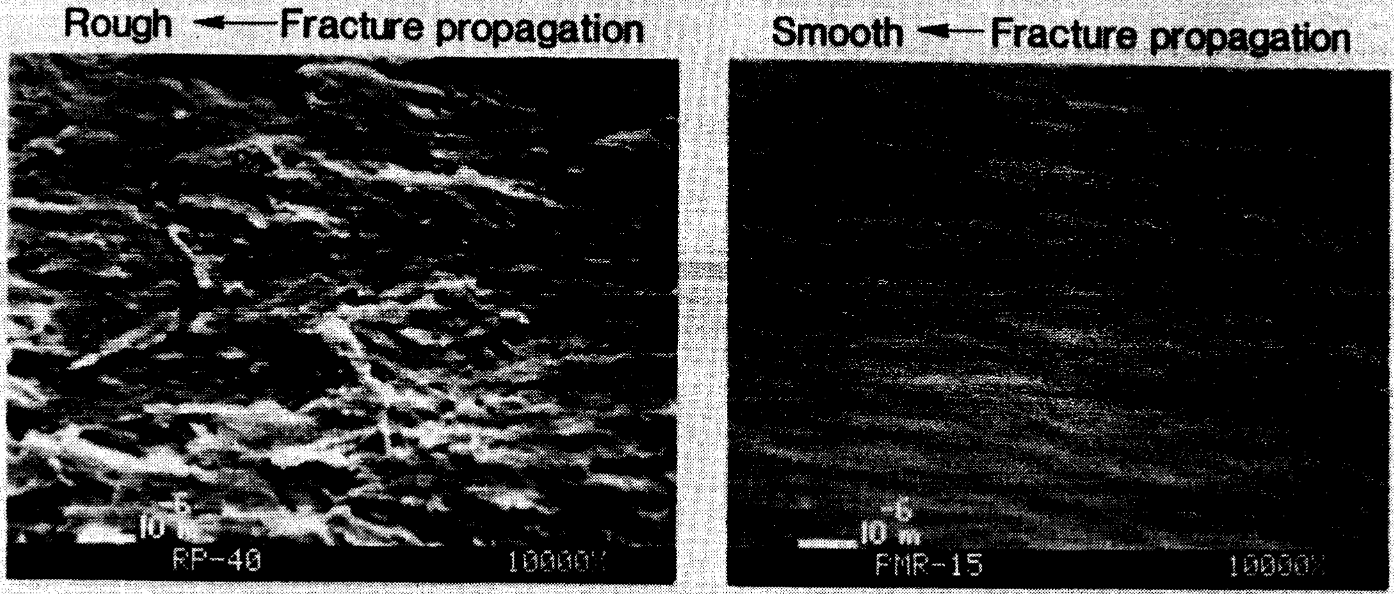
Significance: LARC-RP40 is a novel high temperature matrix resin which shows considerable promise for a variety of aerospace structural applications. The development of this semi-IPN system has also demonstrated the feasibility of attaining both improved toughness and increased glass transition temperature, a combination of properties that is difficult to achieve by conventional synthetic routes.

Future Plans: A fundamental understanding of the interrelationship between processing, morphology, and mechanical properties of LARC-RP40 neat resin will be pursued and a more detailed property evaluation of LARC-RP40 composites will be continued.

Figure 7(a).

LaRC-RP40: A NEW TOUGH HIGH TEMPERATURE MATRIX RESIN

Neat Resin Fracture Surfaces



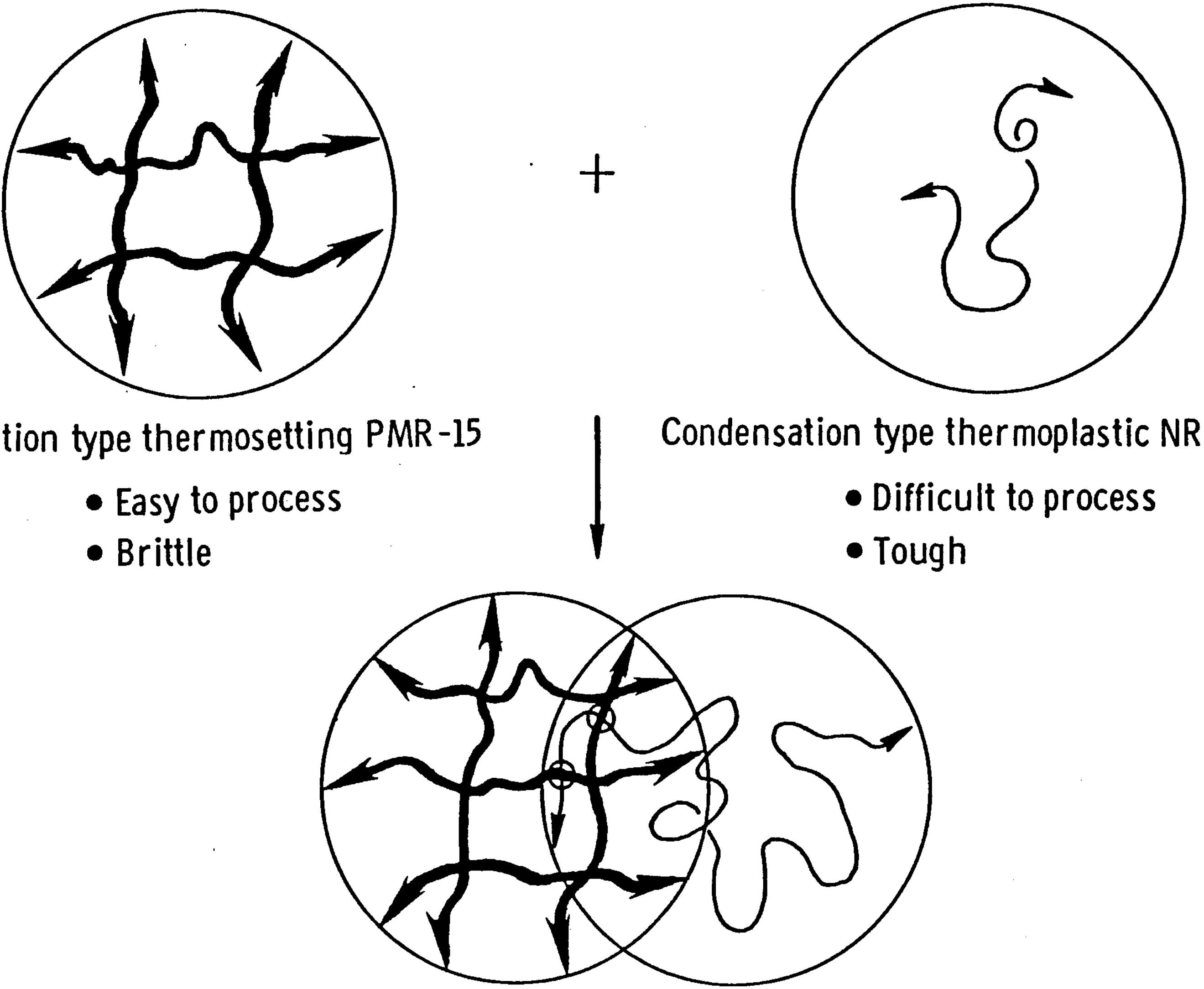
(a) LaRC-RP40

(b) PMR-15

G_{Ic}, J/m^2	368	87
Microcracks after 1000 thermal cycles, cracks/in.	0	58
316°C flexural strength, Ksi	174	159

Figure 7(b).

SYNTHESIS OF LaRC-RP40



Addition type thermosetting PMR-15

- Easy to process
- Brittle

Condensation type thermoplastic NR-150B2

- Difficult to process
- Tough

Semi-IPN LaRC-RP40

- Easy to process
- Tough

Figure 7(c).

NEW TOUGHENED THERMOSETTING STRUCTURAL RESINS

Paul M. Hergenrother, Stephen J. Havens and John W. Connell
Polymeric Materials Branch
Ext. 44270 February 1988
RTOP 506-43-11

Research Objective: To develop new, readily processable, solvent resistant structural resins that possess improved toughness and mechanical properties over state-of-the-art epoxies for use as composite matrices and adhesives on aerospace vehicles.

Approach: Prepare toughened polymers by blending an acetylene terminated aspartimide or imidothioether (thermoset) with an acetylene terminated arylene ether oligomer (toughener).

Accomplishments: Toughened thermosets have been prepared by blending various structurally different acetylene terminated aspartimides (ATAs and imidothioethers (ITEs) with acetylene terminated arylene ether oligomers (ATAE) of differing chemical structure and molecular weight. Varying the compositions provided control of properties such as processability, solvent resistance, toughness and modulus. A comparison of selected properties of ATA and ITE blends and a state-of-the-art 177°C curing epoxy are shown in the accompanying figure.

The fracture toughness of the blends was significantly higher than that of the epoxy which should translate into more damage tolerant composites. The adhesive strengths of the blends were also higher than that of the epoxy because of the extremely brittle nature of the epoxy. Preliminary composite properties of the blends (short beam shear strength, flexural strength and flexural modulus) were essentially comparable to those of the epoxy. This was encouraging considering the inferior quality of the initial prepreg and the unoptimized laminate cure conditions for these new polymers.

Significance: Several novel, toughened thermosets were prepared that exhibited good processability, solvent resistance and mechanical properties. After optimizing the composition and process conditions, better mechanical properties are anticipated. These materials afford a new class of structural resins potentially useful as adhesives, composite matrices and moldings.

Future Plans: The composition of the blends will be optimized to obtain material with the best combination of properties. This blend will be scaled-up and evaluated more comprehensively in composites.

Figure 8(a).

THERMOSET/TOUGHENER BLENDS POSSESS IMPROVED MECHANICAL PROPERTIES

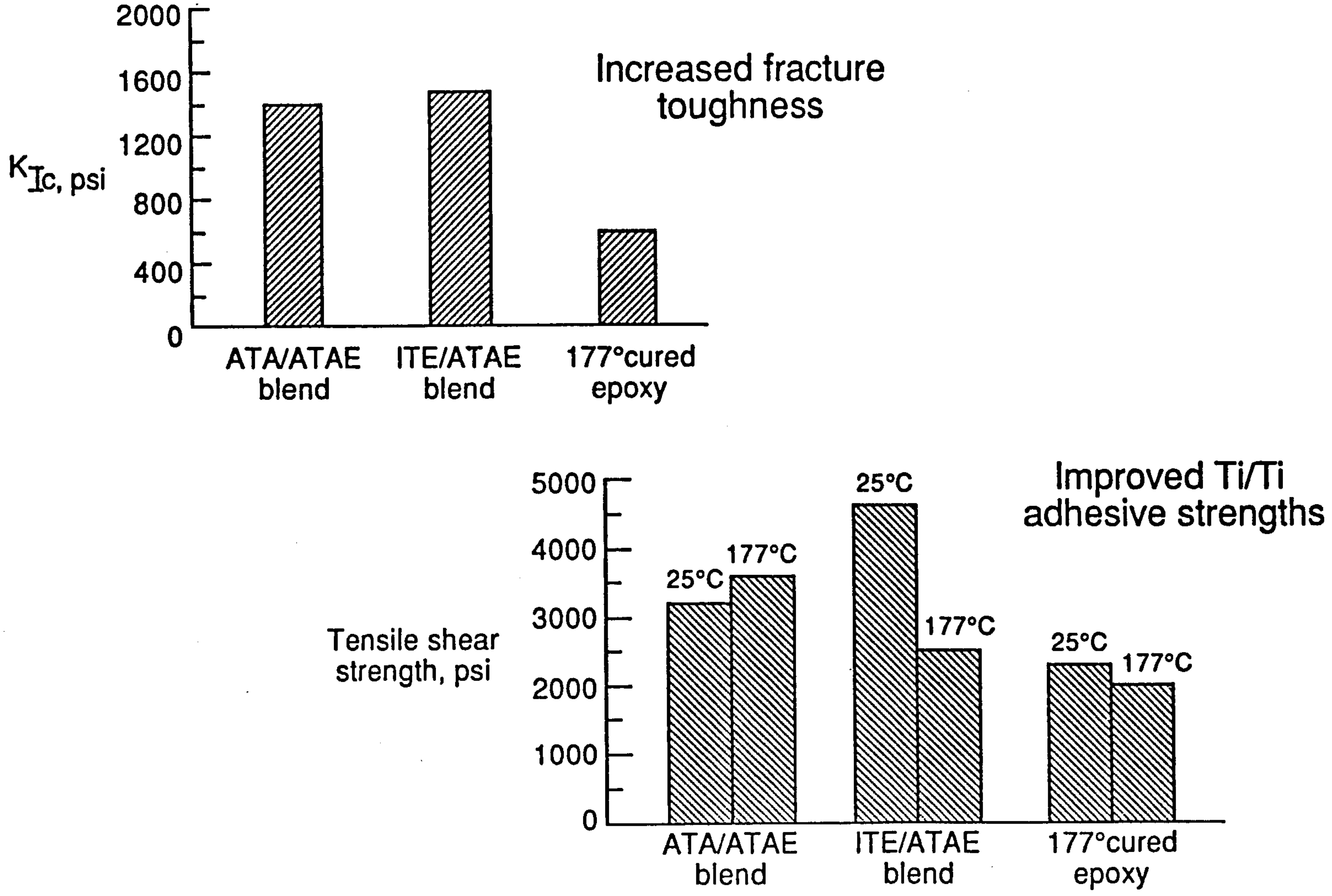


Figure 8(b).

SEMI-CRYSTALLINE POLYIMIDE SULFONE

Terry L. St. Clair
Polymeric Materials Branch
Ext. 44273 May 1988
RTOP 505-63-01

Research Objective: To develop a powder form of Polyimide Sulfone ($PISO_2$) for use as a dopant in advanced composite development.

Approach: Prepare and evaluate various forms of $PISO_2$ powder which can be used to improve flow properties in advanced matrix resins.

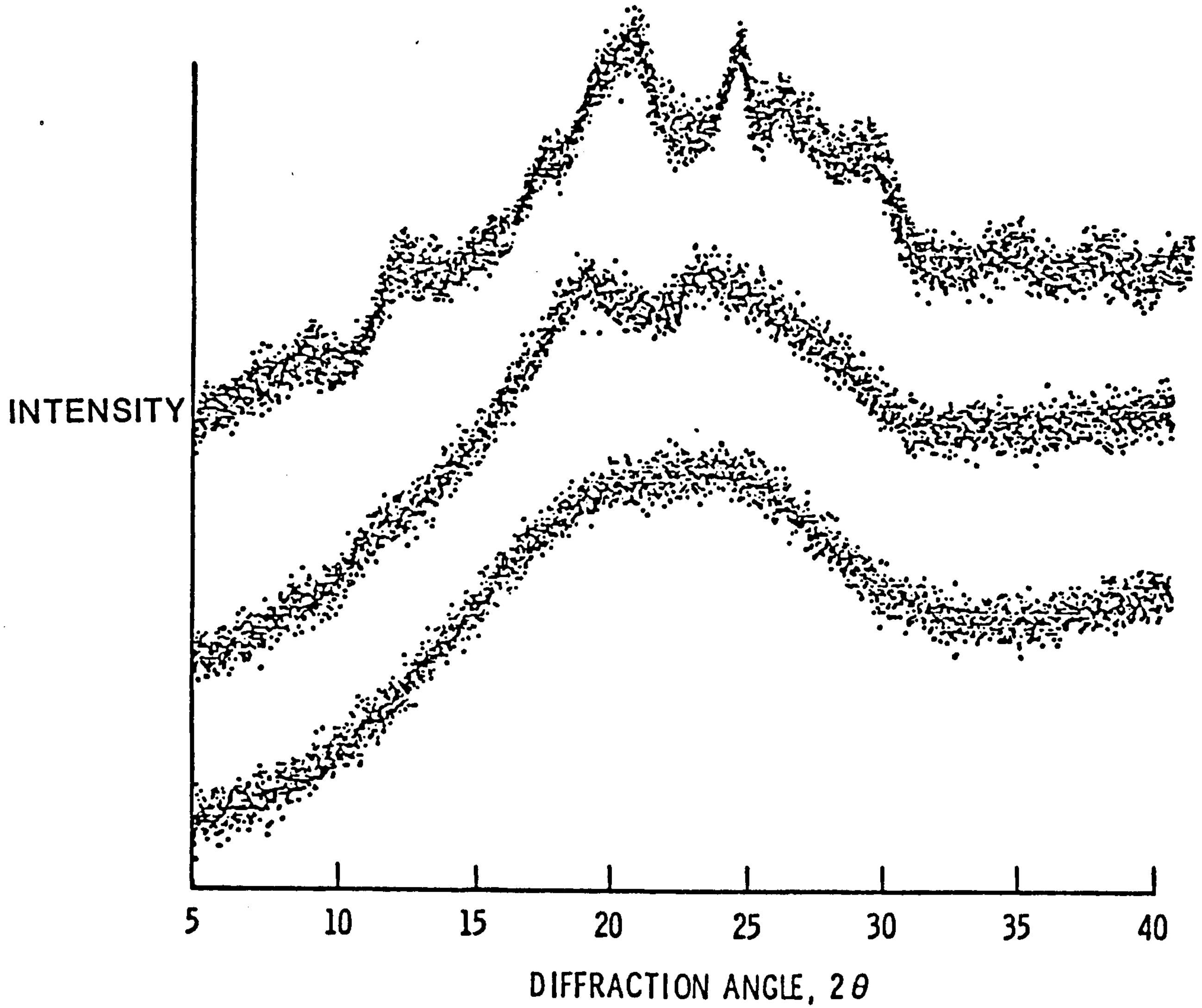
Accomplishments: Semi-crystalline LARC-TPI has been shown by LaRC researchers to impart enough flow to high temperature matrix resins to allow high quality fiber-reinforced composites to be fabricated. The most promising system that has been studied is the semi-crystalline LARC-TPI in amorphous $PISO_2$. The $PISO_2$ is believed to afford exceptionally high mechanical properties to the composite because of its high modulus - 700 Ksi.

Experimental work on the chemical cyclization of $PISO_2$ has led to three forms of powders which range from amorphous to significantly crystalline (See figure). The amorphous form exhibits very little melt flow, however the powders which exhibit crystallinity by x-ray diffraction have considerably improved flow properties. Initial rheological experiments indicate a level of flow similar to the semi-crystalline LARC-TPI.

Significance: The development of a $PISO_2$ powder with good flow properties will allow for the preparation of novel matrix resins which should impart improved mechanical performance in fiber-reinforced composites. Also, since $PISO_2$ is commercially available, large quantities of this powder should be available for use in the near future for blending with various high temperature polymers as well as for use alone in powder prepregging.

Future Plans: Complete rheological data will be generated on the new form of $PISO_2$ as well as on blends with semi-crystalline LARC-TPI. A scaleup of the powder will be used in preparing graphite-reinforced composites from several formulations.

Figure 9(a).



COMPARED DIFFRACTION PATTERNS

Figure 9(b).

LARC-RP41: A NEW TOUGH HIGH TEMPERATURE MATRIX RESIN

Ruth H. Pater
Polymeric Materials Branch
Ext. 44277 July 1988
RTOP 506-43-11

Research Objective: To improve the toughness and microcracking resistance of state-of-the-art thermosetting polyimides, like PMR-15, by incorporating linear thermoplastics as additives.

Approach:
- Synthesize a new semi-interpenetrating network polyimide consisting of 80% thermosetting PMR-15 and 20% thermoplastic LARC-TPI that can be processed using conventional autoclave technology.
- Characterize the neat resin and composite.
- Compare the properties of the new material and PMR-15 prepared and tested under identical conditions.

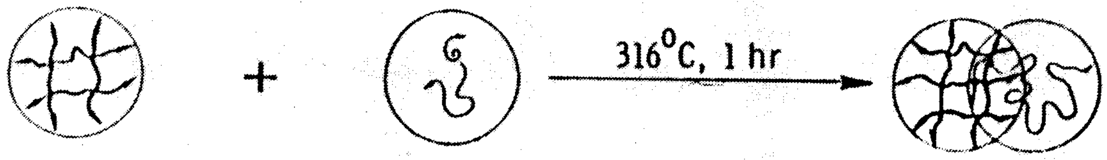
Accomplishments: LARC-RP41 shows significantly improved properties over PMR-15 in two areas: (1) toughness (460 percent increase, G_{Ic} 476 vs. 85 J/m^2) and (2) microcracking resistance (0 vs. 58 microcracks/inch). These property improvements have been achieved without compromising the easy processing and outstanding elevated temperature mechanical performance of PMR-15. These improvements are accompanied by a significant reduction in the apparent Tg of the system. The lowered Tg (259°C), however, is a reflection of the softening of the LARC-TPI component in LARC-RP41 rather than the polymer network as a whole. All raw materials necessary for the preparation of this new matrix resin are commercially available.

Significance: LARC-RP41 appears to offer significant improvements in toughness and microcracking resistance over state-of-the-art thermosetting polyimides while retaining their ease of processing. It shows potential for aircraft engine and aerospace structural applications where microcracking resistance and damage tolerance are important property requirements.

Future PLans: Studies will be conducted to optimize the processing and properties of the composite. Scale-up composite fabrication will also be performed. This polymer system, as well as a previously reported material, LARC-RP40, are two very promising candidates for high temperature structural applications. Northrop, a large user of PMR-15, has shown considerable interest and plans to have these materials scaled up by a prepregger.

Figure 10(a).

LaRC-RP41:
A NEW TOUGH HIGH TEMPERATURE MATRIX RESIN



PMR-15
(Thermoset)

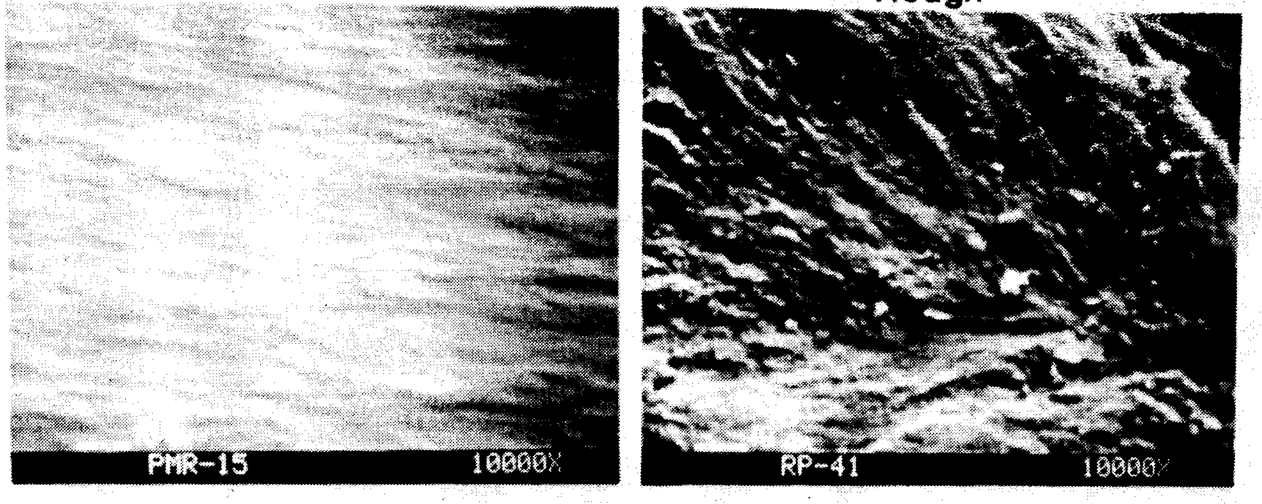
LaRC-TPI
(Thermoplastic)

LaRC-RP41
(Semi-IPN)

Neat resin fracture surfaces

Smooth

Rough



	PMR-15	LaRC-RP41
Cure temp, °C	316	316
Tg, °C	352	259
G_{Ic}, J/m^2	85	476
Microcracks after 1000 thermal cycles, cracks/in.	58	0

Figure 10(b).

CONCEPT AND DEMONSTRATION OF A NEW SYNTHETIC ROUTE TO A FAMILY OF NON-CLASSICAL ADDITION-TYPE THERMOPLASTIC (ATT) POLYIMIDES

Ruth H. Pater
Polymeric Materials Branch
Ext. 44277 September 1988
RTOP 506-43-1

Research Objective: This is a basic and applied research effort to develop a fundamental understanding and application of a new synthetic route to a family of non-classical addition-type thermoplastic (ATT) polyimides. The synthetic scheme is designed to provide polymers possessing a combination of easy processability, toughness, high temperature performance and good thermooxidative stability in one material. These ATT polymers are intended for use as high performance composite matrices and adhesives.

Approach: As depicted in the figure, the concept of the ATT synthesis involves the cycloaddition of an acetylene-terminated prepolymer with either a bismaleimide or biscitraconimide. Although other reaction mechanisms are possible, the synthetic reaction can proceed through an addition curing mechanism leading to a linear polymer structure. The cycloaddition adduct is to be further heat treated to affect aromatization. Because of their addition curing, linear structure and formation of stable aromatic rings, the ATT polymers can combine easy processability, toughness, high temperature performance and good thermooxidative stability in one material.

Accomplishment: In order to demonstrate the above concept, LaRC-RP80 has been synthesized from commercially available Thermid 600 and a new biscitraconimide prepared in-house. The neat resin physical and mechanical properties and adhesive properties of the new material have been evaluated. The table shows the preparation and properties of LaRC-RP80. This new material exhibits 10 times the toughness of the commercial BMI, Kerimid 601, while maintaining a respectable T_g. It has the highest thermooxidative stability among the existing BMI's reported to date and absorbs very little moisture while retaining good thermal/mechanical properties in wet environments. Furthermore, it can be processed quickly at a moderately high temperature without formation of voids in the finished product.

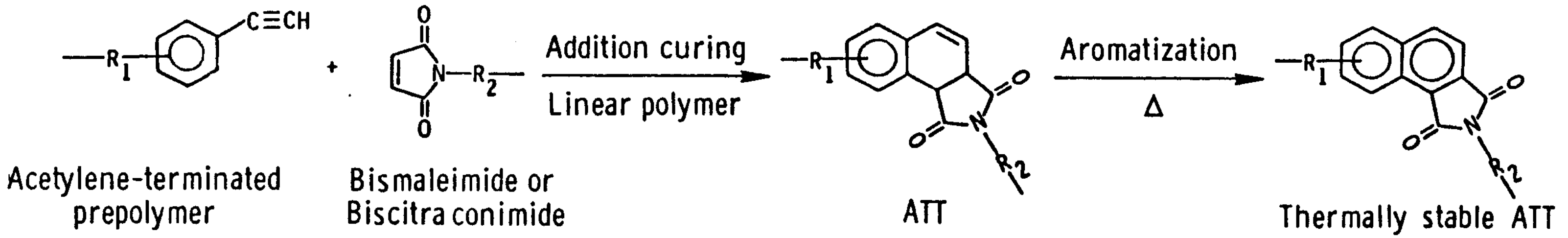
Significance: The ATT synthesis shows considerable promise for the development of a wide variety of new composite matrices and adhesives suitable for electronic, aircraft and aerospace applications. Its general applicability resides in the fact that a large number of acetylene-terminated, bismaleimide and biscitraconimide compounds are currently available and these compounds can be combined in various ways. The synthesis opens up an important technological area which has not been explored until this investigation.

Future Plans: A model compound study has been initiated to further clarify the reaction mechanism. In addition, a series of new high performance ATT polymers are being synthesized and their neat resin, composite and adhesive properties are being evaluated.

Figure 11(a).

A NEW SYNTHETIC ROUTE TO A FAMILY OF NON-CLASSICAL ADDITION-TYPE THERMOPLASTIC(ATT) POLYIMIDES

CONCEPT



PROPOSED SYNTHESIS OF ATT POLYIMIDES

DEMONSTRATION

PREPARATION AND PROPERTIES OF LaRC-RP80

Preparation: Thermid 600 + CA/MDA/6F $\xrightarrow[\text{1 hour}]{288^{\circ}C}$ LaRC-RP80

Properties:	Tg, ^{0}C	Toughness G_{Ic}, J/m^2	Temperature at 5% wt. loss by TGA in air, ^{0}C	Moisture uptake, %	Lap shear strength, psi
LaRC-RP80	268 dry 254 wet	324	514	2.6	2963 Wet at 232^{0}C
Commercial BMI Kerimid 601	290 dry	34	347	4.5	620 Dry at 250^{0}C

Figure 11(b).

IN SITU OPTIC SENSOR FOR FTIR MONITORING OF COMPOSITE CURE CYCLES

Philip R. Young
Polymeric Materials Branch
Ext. 44265 October 1987
RTOP 506-43-11

Research Objective: To demonstrate the feasibility of using an embedded optical fiber to sense and transmit infrared spectra which indicate the state of cure of a thermoset composite material.

Approach: Design an optical interface which will allow an infrared-transmitting optical fiber to couple an infrared source and interferometer with a detector. Demonstrate that interpretable Fourier transform infrared (FTIR) spectra can then be obtained on materials in contact with that fiber.

Accomplishment: Foster-Miller, Inc., a small business working on NASA Contract NAS1-15420 under the SBIR program, recently demonstrated that fiber optics can be used to sense infrared spectra. This is the first time this feat has been accomplished. The concept was conceived at Langley as an outgrowth of diffuse reflectance-FTIR research conducted in PMB. Working with Digilabs, Inc., a leader in FTIR spectrometer design and manufacture, a 2-meter optical fiber (0.1 mm O.D.) was used to carry the infrared beam outside an FTIR optical bench to remotely analyze a graphite/polyimide matrix resin prepreg during a simulated cure cycle.

A schematic of the sensor is shown in the first figure. A small portion of cladding is removed to contact the sample to be analyzed. Infrared radiation passes down the fiber where the sample absorbs selected wavelengths via an attenuated total reflection mechanism. Radiation exiting the fiber thus contains optical information about the sample.

The second figure illustrates how this sensor might be used to monitor the cure of advanced composite materials. Feedback to control processing and manufacture may be possible. The approach is unique because it directly monitors the chemical state of the matrix resin - a prime quality control concern. Other techniques (dielectrics, ultrasonics, etc.) do not provide a direct measure of resin chemistry.

Significance: The repeatable manufacture of advanced composite materials is a significant problem for airframe manufacturers and improvements in composite processing could result in substantial cost reductions for aircraft composite structures. This obstacle drives our interest in the technique. However, many potential applications exist for a sensor that is universal for all organic materials and most inorganic gases. These include monitoring the integrity of composites in the in-service environment, the remote sensing of hazardous materials, and the examination of industrial processes in reactors and furnaces.

Future Plans: The anticipated research on Phase II will be demonstrations that composite cure can be monitored in the manufacturing environment.

Figure 12(a).

FIBER OPTIC FTIR SENSOR

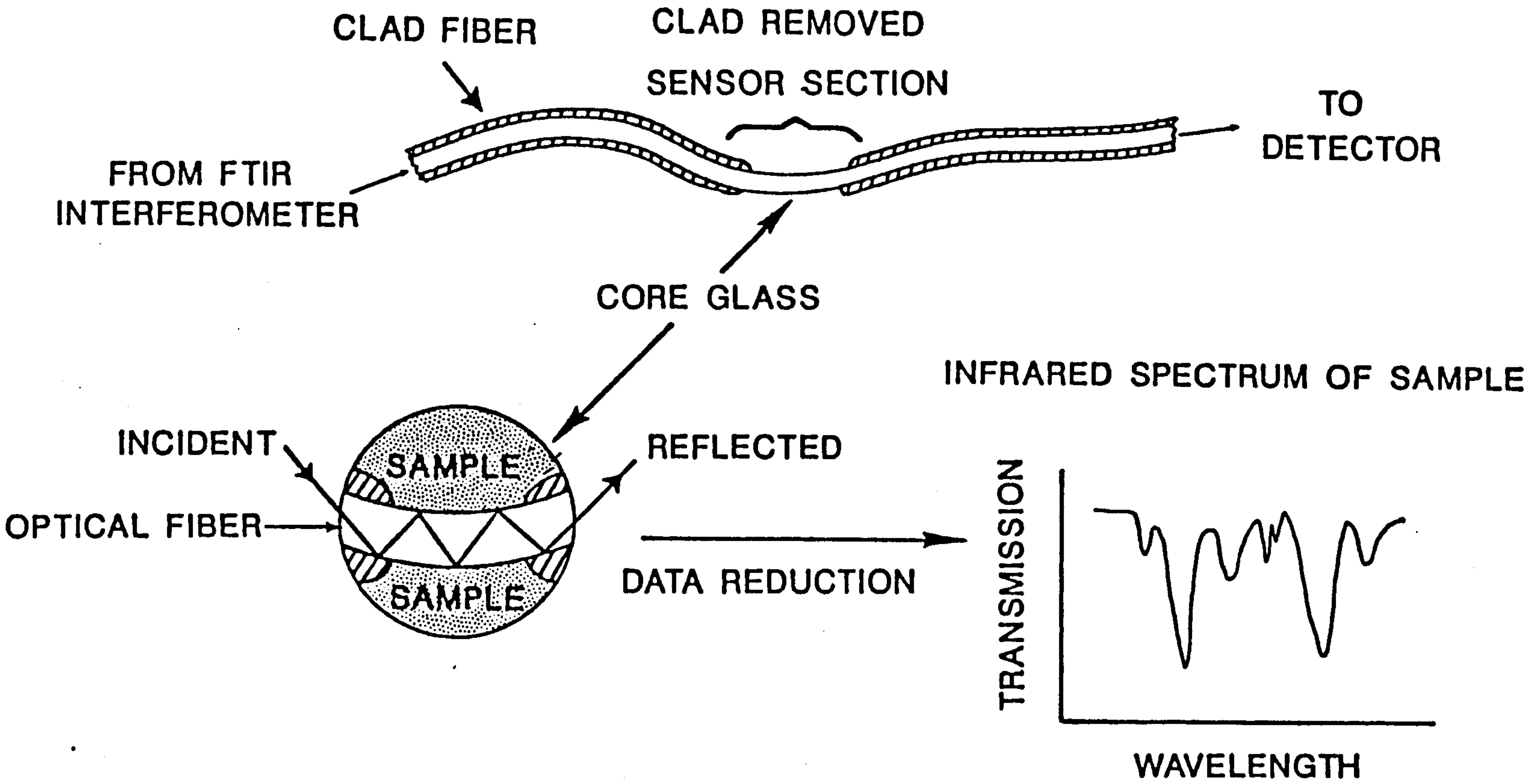


Figure 12(b).

FIBER OPTIC COMPOSITE CURE MONITORING

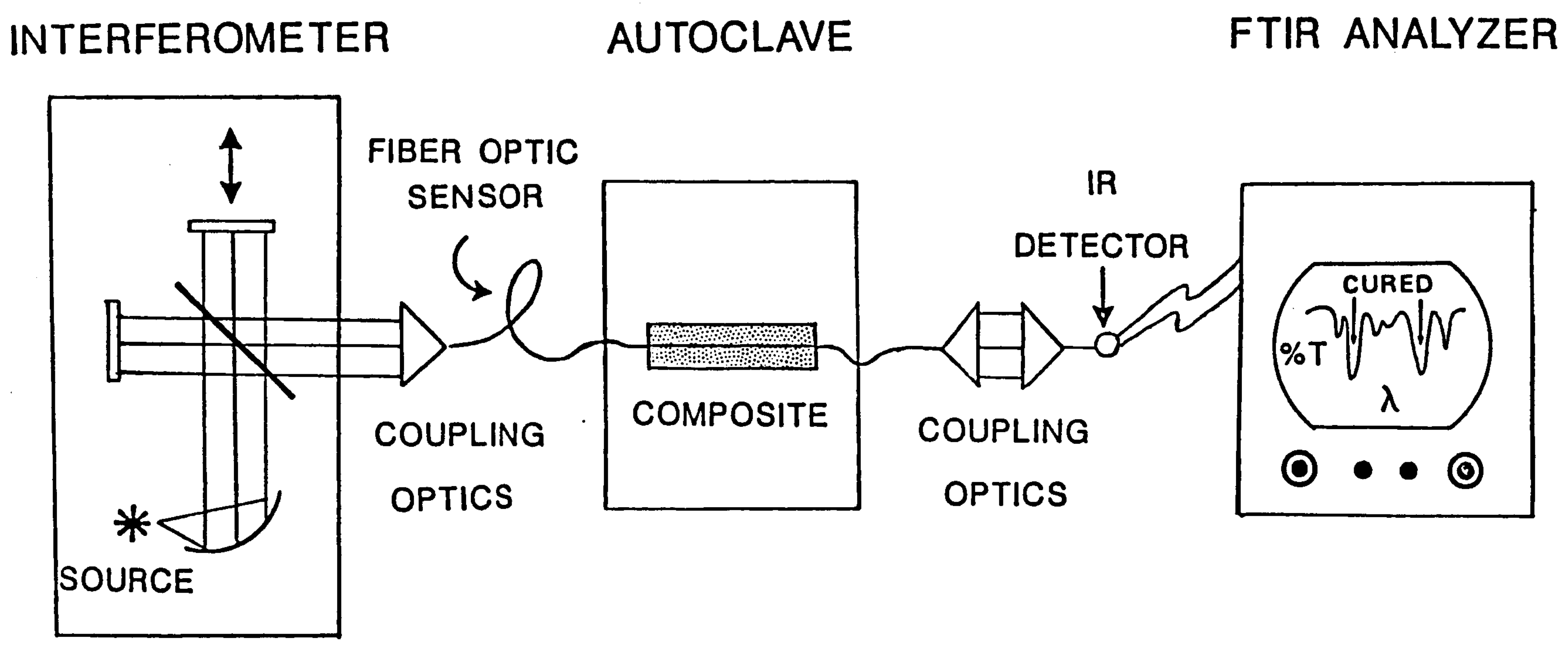
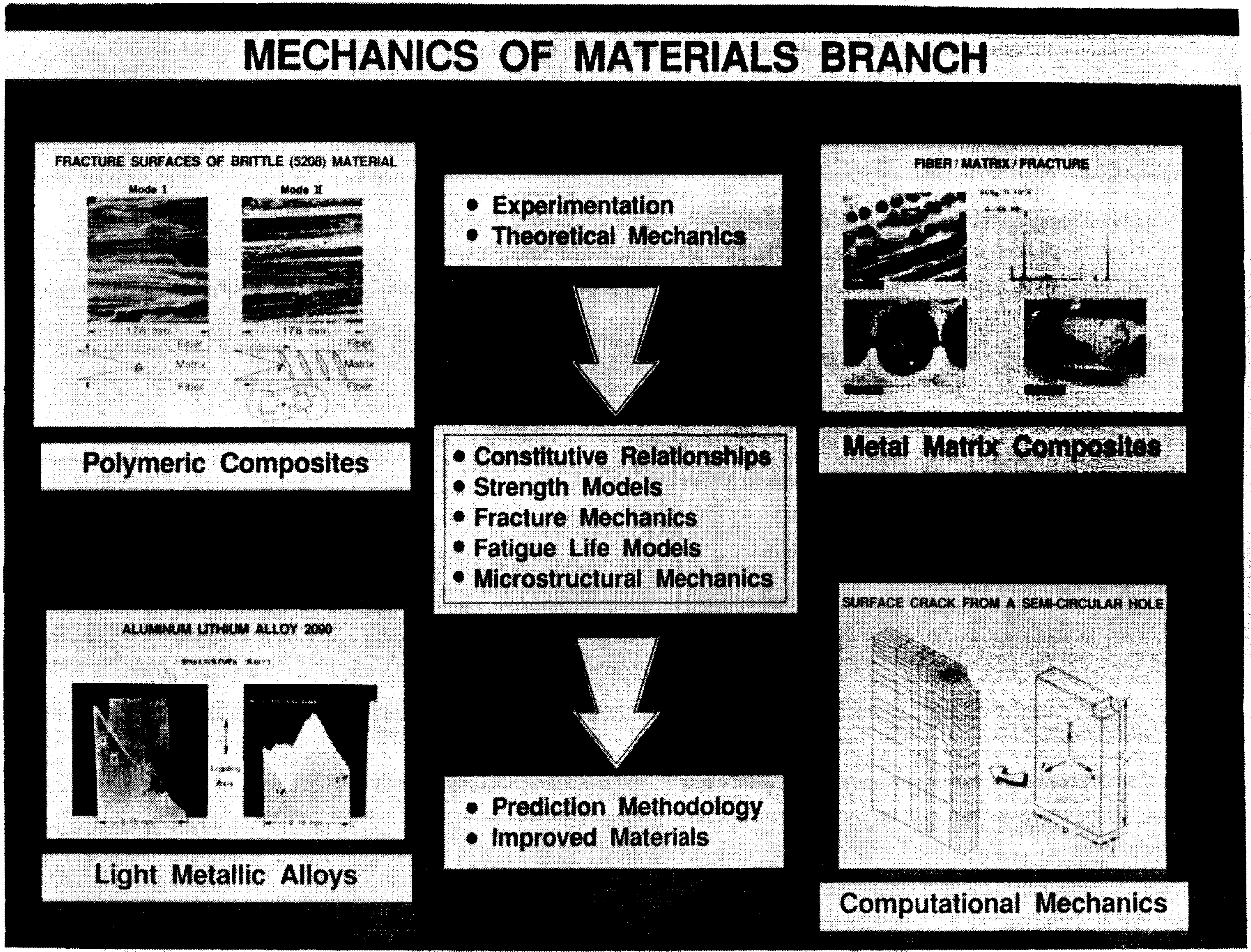


Figure 12(c).



MECHANICS OF MATERIALS BRANCH

FRACTURE SURFACES OF BRITTLE (5208) MATERIAL

Polymeric Composites

- Experimentation
- Theoretical Mechanics

- Constitutive Relationships
- Strength Models
- Fracture Mechanics
- Fatigue Life Models
- Microstructural Mechanics

- Prediction Methodology
- Improved Materials

FIBER / MATRIX / FRACTURE

Metal Matrix Composites

ALUMINUM LITHIUM ALLOY 2090

Light Metallic Alloys

SURFACE CRACK FROM A SEMI-CIRCULAR HOLE

Computational Mechanics

Figure 13.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

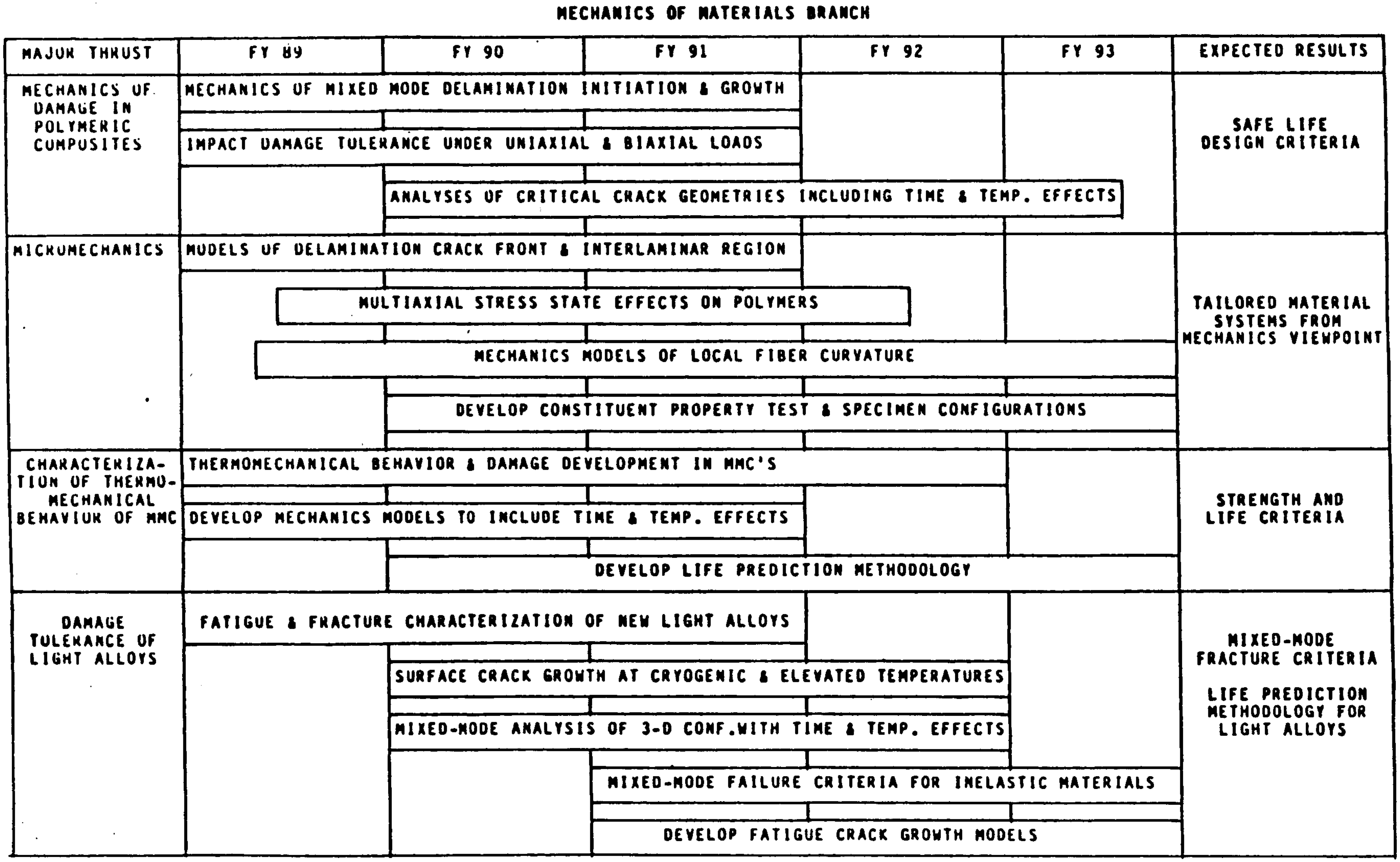

MECHANICS OF MATERIALS BRANCH
MAJOR THRUST
FY 89
FY 90
FY 91
FY 92
FY 93
EXPECTED RESULTS
MECHANICS OF DAMAGE IN POLYMERIC COMPOSITES
MECHANICS OF MIXED MODE DELAMINATION INITIATION & GROWTH
IMPACT DAMAGE TOLERANCE UNDER UNIAXIAL & BIAXIAL LOADS
ANALYSES OF CRITICAL CRACK GEOMETRIES INCLUDING TIME & TEMP. EFFECTS
SAFE LIFE DESIGN CRITERIA
MICROMECHANICS
MODELS OF DELAMINATION CRACK FRONT & INTERLAMINAR REGION
MULTIAXIAL STRESS STATE EFFECTS ON POLYMERS
MECHANICS MODELS OF LOCAL FIBER CURVATURE
DEVELOP CONSTITUENT PROPERTY TEST & SPECIMEN CONFIGURATIONS
TAILORED MATERIAL SYSTEMS FROM MECHANICS VIEWPOINT
CHARACTERIZATION OF THERMO-MECHANICAL BEHAVIOR OF MMC
THERMOMECHANICAL BEHAVIOR & DAMAGE DEVELOPMENT IN MMC'S
DEVELOP MECHANICS MODELS TO INCLUDE TIME & TEMP. EFFECTS
DEVELOP LIFE PREDICTION METHODOLOGY
STRENGTH AND LIFE CRITERIA
DAMAGE TOLERANCE OF LIGHT ALLOYS
FATIGUE & FRACTURE CHARACTERIZATION OF NEW LIGHT ALLOYS
SURFACE CRACK GROWTH AT CRYOGENIC & ELEVATED TEMPERATURES
MIXED-MODE ANALYSIS OF 3-D CONF. WITH TIME & TEMP. EFFECTS
MIXED-MODE FAILURE CRITERIA FOR INELASTIC MATERIALS
DEVELOP FATIGUE CRACK GROWTH MODELS
MIXED-MODE FRACTURE CRITERIA
LIFE PREDICTION METHODOLOGY FOR LIGHT ALLOYS

Figure 14.

STATIC STRENGTH OF SCS$_6$/TI-15-3

W. S. Johnson and S. J. Lubowinski
Mechanics of Materials Branch
Ext. 43463 April 1988
RTOP 505-63-01

Research Objective: To determine the failure mechanisms associated with titanium matrix composites and to develop analytical models to predict the material response.

Approach: The material system studied in this investigation consisted of a titanium (Ti-15-3) matrix reinforced by continuous silicon carbide (SCS$_6$) fibers. Room temperature quasi-static tension tests were performed to identify failure mechanisms and static strength of five different layups: $[0]_8$, $[90]_8$, $[0,90]_{2s}$, $[0/\pm 45/90]_s$. Earlier it was reported that fiber/matrix separations were found to occur at stress levels as low as 20 ksi in the off-axis plies. This was shown to be a result of very low fiber/matrix interface strength in the Ti-Si reaction zone and residual stresses in the matrix due to fabrication. An analytical model was used to predict an upper and lower bound on the strength of each layup. The upper bound predictions assumed that all fiber/matrix interfaces remained intact. The lower bound predictions were made with reduced transverse fiber modulus to simulate fiber/matrix separation. The AGLPLY program was used to estimate the static strength of the laminates tested. The as-fabricated [0] laminate was first analyzed to determine the approximate axial fiber stress at failure. The program predicted an axial stress of 465 ksi in the 0° fibers for the laminate failure stress of 220 ksi. Failure was predicted to occur in the other laminates containing 0° fibers when the 0° fiber stress reached 465 ksi. McDonnell Aircraft tested some of our material using a 0.15-inch wide specimen while the NASA specimen was 0.75 inches wide.

Accomplishment: The predictions bounded the experimental data quite well as shown in the attached figure. Reducing the fiber transverse modulus did not effect the predicted axial strength of the unidirectional specimens. Edge replicas showed that the 90° fibers tended to separate earlier and in greater numbers than did the 45° fibers. It follows that the lower bound predictions correlate better with the $[0/90]_{2s}$ laminates. The laminates containing 45° plies tended to give strengths considerably higher than the lower bound. The difference between the measured strengths and the upper bound predictions for each laminate indicated the potential strength improvement that would be possible with a stronger fiber/matrix interface.

Significance: The results of this study have identified potential failure modes for this and other titanium-based composites. Further, we have shown that the results of such behavior can be estimated with current material models. This type of information is very valuable for guiding the development of future metal matrix composites.

Future Plans: Fatigue of these laminates is under way. High temperature testing is planned on these laminates, as well as on some titanium-aluminide matrix composites that are currently in procurement.

Figure 15(a).

STATIC STRENGTH OF AS-FABRICATED MATERIAL

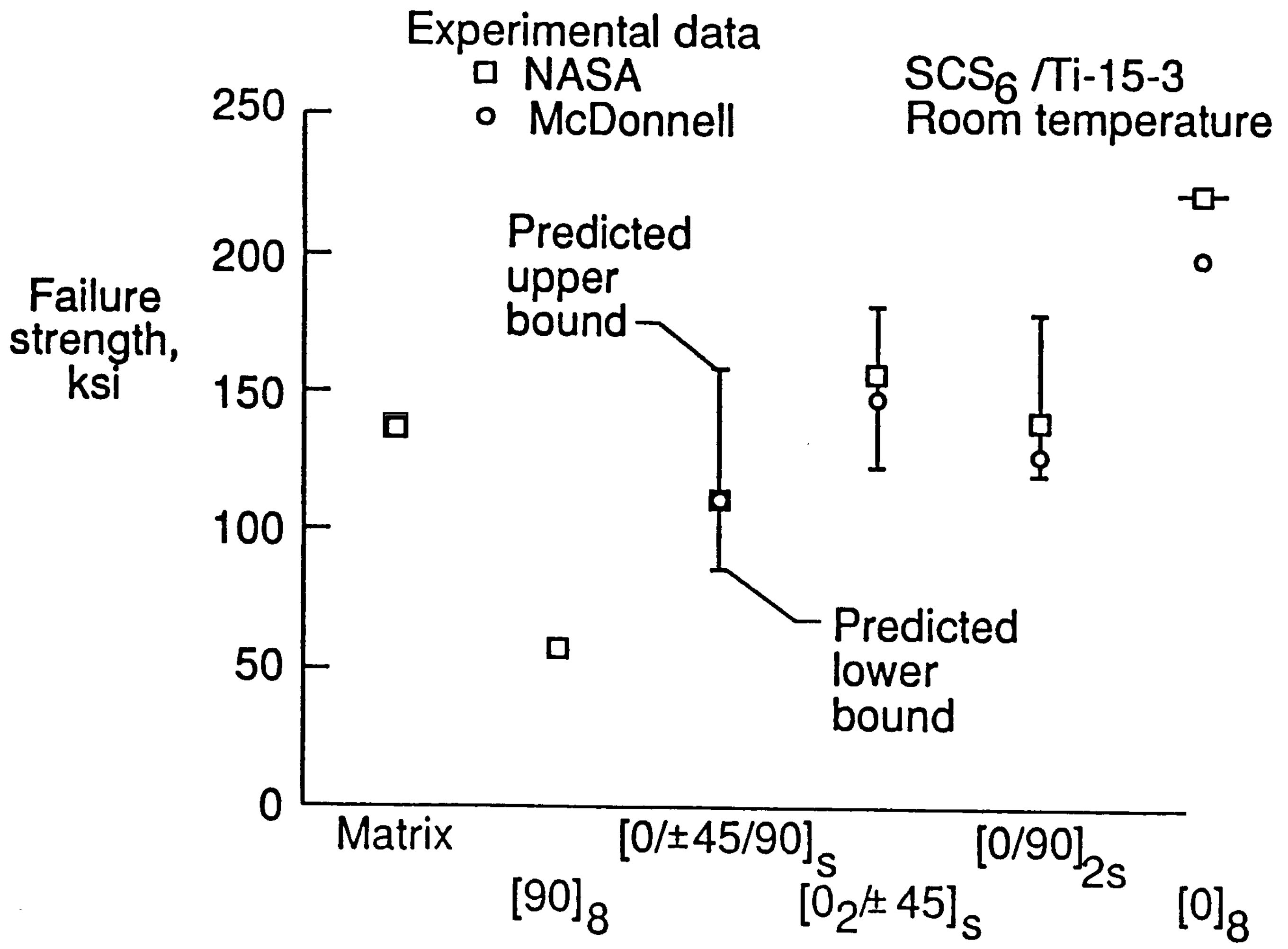


Figure 15(b).

SIGNIFICANCE OF THE SMALL-CRACK EFFECT FOR FATIGUE DESIGN

E. P. Phillips and J. C. Newman, Jr.
Fatigue and Fracture Branch
Ext. 43488 June 1988
RTOP 505-63-01

Research Objective: Assess the potential impact of the small-crack effect on design calculations of fatigue-crack-growth life.

Approach: Current standard tests to evaluate fatigue-crack-growth rates use specimens with crack sizes greater than 1 mm. For these large cracks (> 1 mm), the crack-growth-rate data at different stress levels and crack lengths are correlated very well by the stress-intensity-factor-range parameter, ΔK. Design calculations of crack-growth life are based on the assumption of a unique growth rate against ΔK relationship. However, in recent years it has been found that in some materials, small cracks (< 0.5 mm) grow faster than large cracks at the same ΔK level. To assess the significance of this small-crack effect on fatigue design calculations for an airframe aluminum alloy (2024-T3), crack-growth lives computed using only the large-crack data were compared to lives computed using a combined small-crack and large-crack data base.

Accomplishment: The figure shows the crack-growth lives computed for a fighter-aircraft loading spectrum as a function of the initial crack size assumed in the analysis. The solid line was computed using only the large-crack data and the dotted line was computed using the combined data base. Also shown in the figure are the lives from two tests of initially crack-free specimens. The test lives are plotted at the mid-point of the material-defect crack size range, that is, the size of the inclusion particles where the cracks initiated. The results show that for assumed initial crack sizes below about 0.3 mm, the lives computed using the small-crack data were lower than those computed using large-crack data. Life computed using the small-crack data agreed well with the test lives, whereas the large-crack data predicted infinite life.

Significance: This study indicates that crack-growth lives calculated using conventional, large-crack data are unconservative when small initial cracks are assumed in the analysis, such as in analyses to determine the economic fatigue life of an airframe. Current damage-tolerance design analyses (crack sizes >1 mm) are not affected by the small-crack effect.

Future Plans: The significance of the small-crack effect will be assessed for two other aluminum alloys and a high-strength steel. Small-crack data are currently being generated for those materials.

Figure 16(a).

CALCULATED CRACK GROWTH LIVES USING SMALL-CRACK AND LARGE-CRACK DATA BASES

2024-T3, FALSTAFF Spectrum, $S_{max} = 205$ MPa

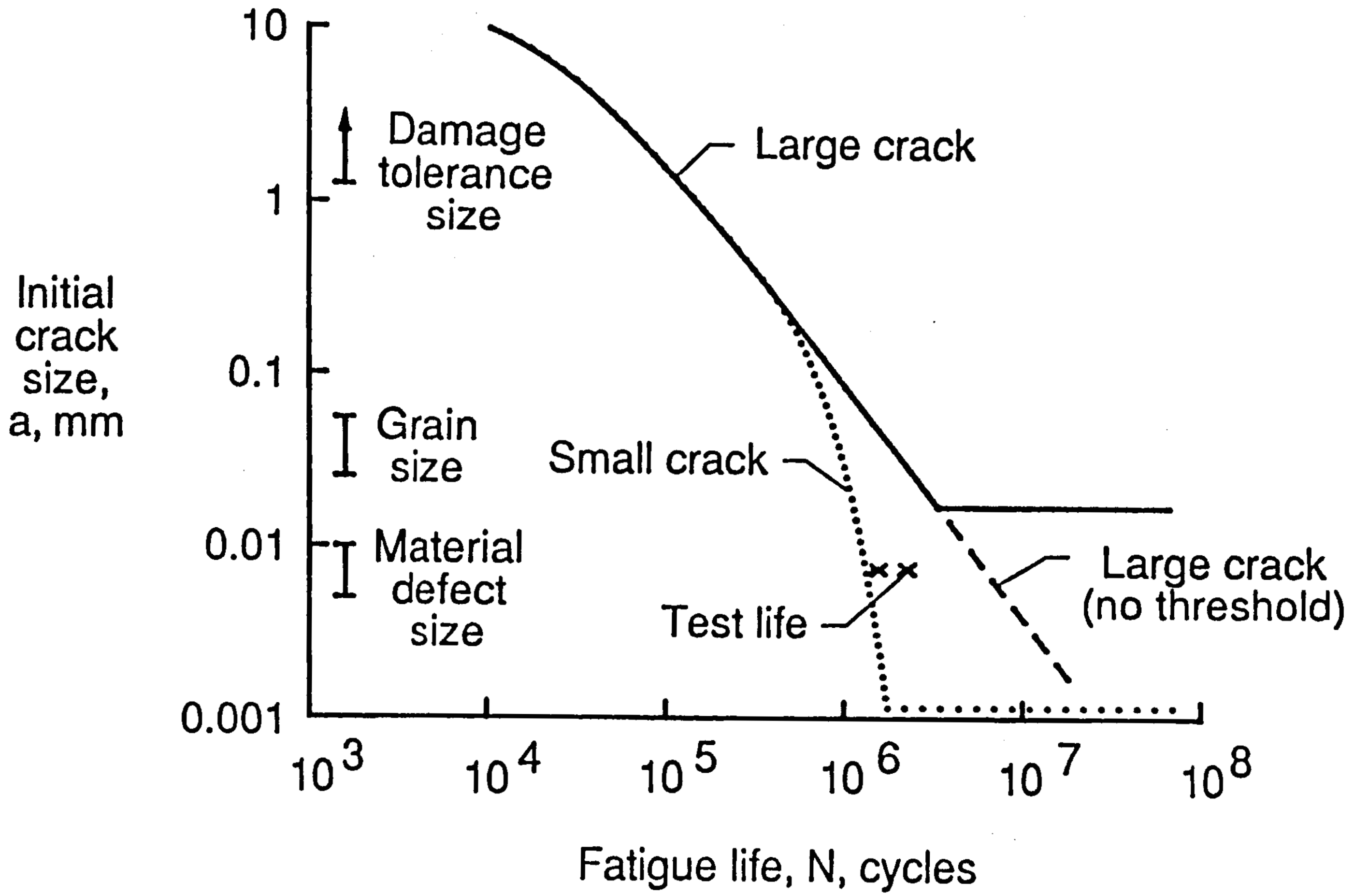


Figure 16(b).

EFFECTS OF MOISTURE, TEMPERATURE, AND FATIGUE ON THE STRENGTH OF CENTER CRACKED GRAPHITE/EPOXY PANELS WITH BUFFER STRIPS

Catherine A. Bigelow
Mechanics of Materials Branch
Ext. 43462 November 1987
RTOP 506-43-11

Research Objective: To determine the influence of moisture, elevated temperature and fatigue loading on the effectiveness of buffer strips in graphite/epoxy panels with a center crack.

Approach: Graphite/epoxy panels of T300/5208 were made with a $[45/0/-45/90]_S$ layup and either S-glass or Kevlar-49 buffer strips as shown in the figure. The panels had a center slit to represent damage. The panels were subjected to either moisture conditioning, elevated temperature, or fatigue loading, then statically loaded to failure to determine their residual strengths. The panels were fatigued with the spectrum loading, MINITWIST, a shortened version of a standardized loading program for the wing lower surface of a transport aircraft. Plain panels without buffer strips were also tested.

Accomplishment: The figure shows results for S-glass buffer strips. As expected, the buffer strips arrested crack growth and significantly increased the residual strengths over those of plain laminates without buffer strips. For those panels tested after fatigue loading, the buffer strips also arrested the crack growth and increased the residual strengths. However, as shown in the figure, for those panels with moisture conditioning, the effectiveness of the S-glass buffer strips was decreased for panels with and without fatigue loading. After moisture conditioning, the buffer strip arrested the crack growth, but the residual strength was increased only slightly over the strength of a plain laminate. The elevated temperature of 80°C did not have a significant effect on the residual strengths after fatigue cycling. However, as before, when moisture conditioning and fatigue cycling were combined, the effectiveness of the buffer strips was reduced significantly.

Similar results were found for buffer strip panels with Kevlar-49 buffer strip material. However, for the Kevlar-49 buffer strip panels, the moisture conditioning did not degrade the effectiveness of the buffer strips.

Significance: These results show that the improved fracture strength produced by the buffer strip configuration is not significantly degraded by fatigue, elevated temperature or moisture conditions, except for the moisture-conditioned S-glass buffer material.

Future Plans: None

Figure 17(a).

EFFECTS OF MOISTURE, TEMPERATURE, AND FATIGUE
ON THE STRENGTH OF CENTER CRACKED GRAPHITE/EPOXY PANELS WITH BUFFER STRIPS

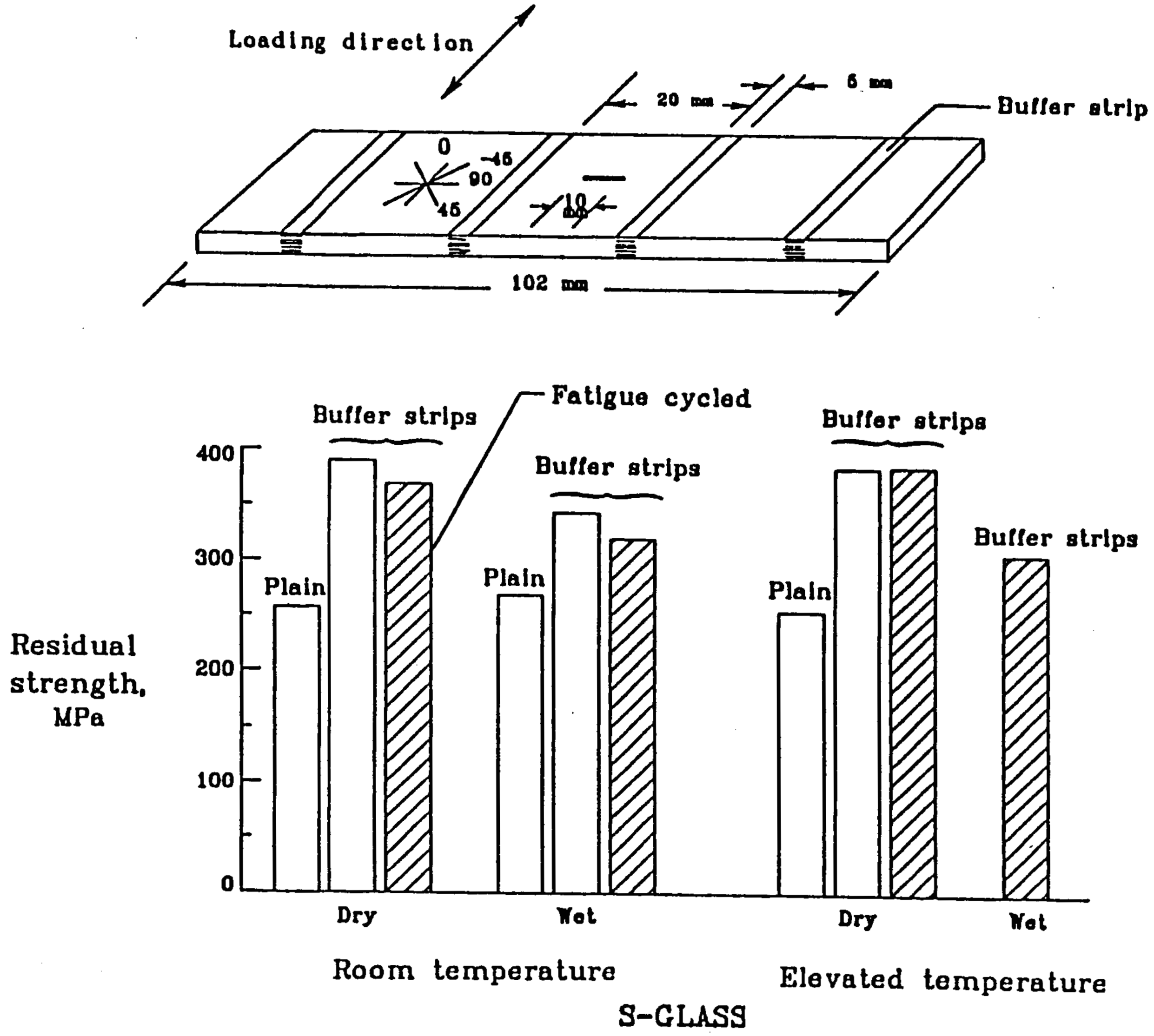


Figure 17(b).

EFFECT OF DELAMINATION RATE ON INTERLAMINAR FRACTURE TOUGHNESS

Rajiv A. Naik and John H. Crews, Jr.
Fatigue and Fracture Branch
Ext. 43477 November 1987
RTOP 505-63-01

Research Objective: To investigate rate effects on interlaminar fracture toughness (G_{Ic}) of a tough composite for opening mode delamination.

Approach: Double cantilever beam (DCB) specimens were used to measure G_{Ic} for a IM7G/X8551-7 graphite/epoxy composite. The DCB specimens consisted of a 24-ply, unidirectional laminate with a mid-plane Kapton insert at one end. As shown in the figure, the specimens were loaded through bonded aluminum hinges and were tested over three decades of displacement rate. Each specimen was loaded until the delamination grew about 1 cm and was then unloaded. The area enclosed by a recorded load-displacement plot was used to compute G_{Ic}. This procedure was repeated for several delamination increments and an average delamination rate was then determined for each increment.

Accomplishment: The measured G_{Ic} values were found to decrease with increasing delamination rates. As shown in the figure, G_{Ic} decreased by about 35 percent over three decades of delamination rate. Examination of the fracture surfaces indicated that less plasticity, and therefore less plastic energy dissipation, accompanied delamination at the higher rates.

Significance: The data for the lowest delamination rate (0.025 mm/s) correspond to tests conducted at a proposed standard testing speed. However, impact can cause delamination at estimated delamination rates of 3000 mm/s and higher. Extrapolating the present curve suggests that impact G_{Ic} could be less than one-half that measured by the standard procedure. This comparison shows that rate dependent analyses are needed to predict impact toughness from standard DCB G_{Ic} data. At present, such analyses do not exist.

Future Plans: Fractographic analyses will be conducted to provide further insight into the mechanisms that lead to lower G_{Ic} values at higher delamination rates. Additional tests will be conducted with both brittle and tough laminates. Test results will be analyzed using viscoelastic and viscoplastic procedures.

Figure 18(a).

EFFECT OF DELAMINATION RATE ON INTERLAMINAR FRACTURE TOUGHNESS

IM7G/X8551-7 Graphite/Epoxy

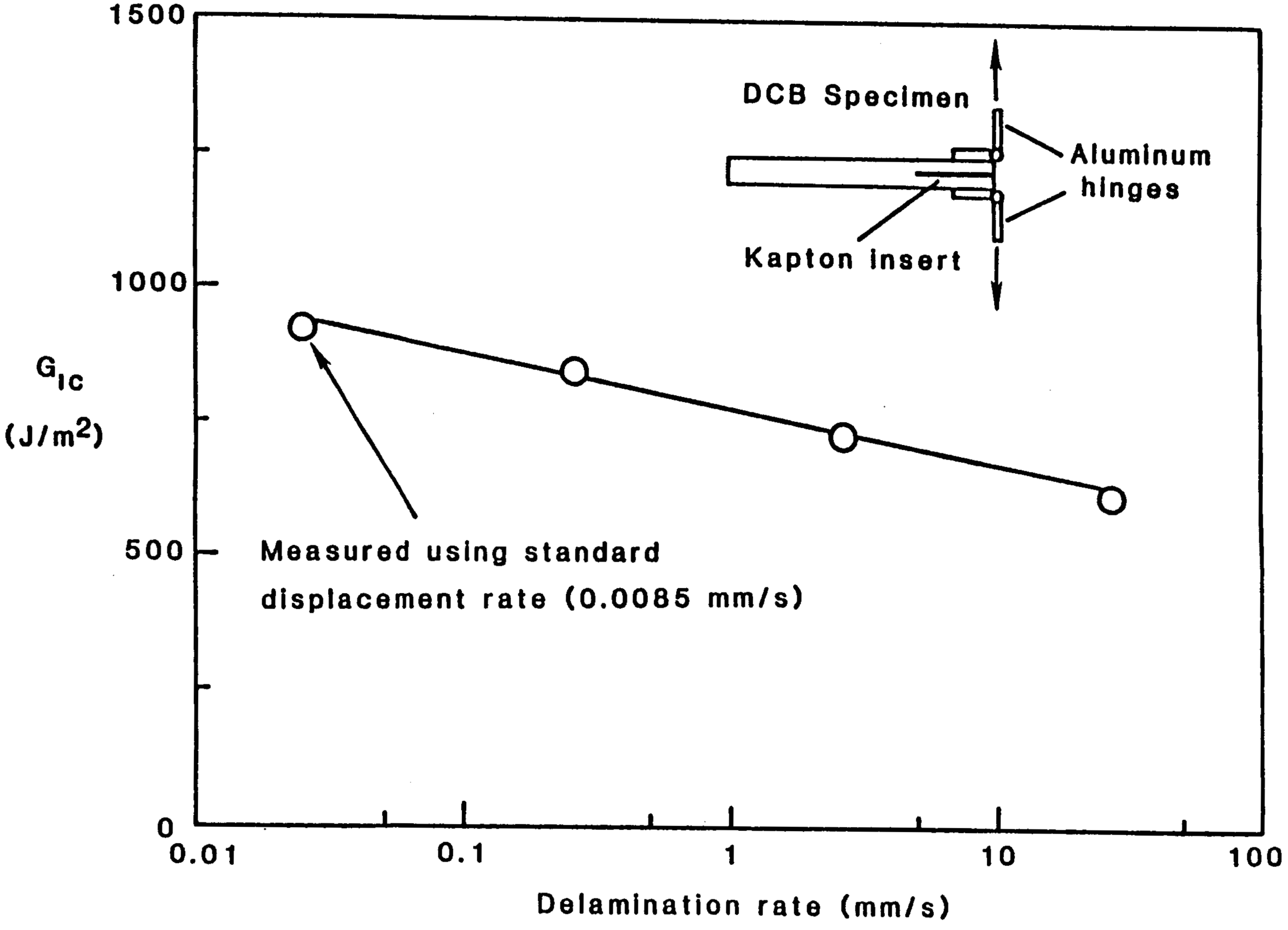


Figure 18(b).

IMPACT DAMAGE IN A THICK GRAPHITE/EPOXY LAMINATE CAUSED BY SPHERICAL IMPACTERS

Clarence C. Poe, Jr.
Mechanics of Materials Branch
Ext. 43467 January 1988
RTOP 506-43-11

Research Objective: To develop a method to predict the amount of fiber damage in a thick graphite/epoxy laminate caused by low-velocity impacts and to determine the effect of impacter shape. Impacts tend not to cause delaminations in thick laminates, and the internal damage is not visible with conventional radiography and ultrasonics.

Approach: Impacts were simulated by pressing hemispherically shaped indenters against a 3.6-cm-thick laminate made with AS4 graphite fiber and HRBF-55A epoxy resin. (See first figure.) The plate was then cut into smaller specimens (each containing a contact site), heated in an oven, and deplied to determine the extent of fiber damage. Fiber damage was also predicted using internal stresses calculated with the theory of elasticity and a maximum shear stress criterion. The onset and extent of damage was compared with the measurements.

Accomplishment: Broken fibers were found directly beneath the contact sites (second figure). The locus of broken fibers resembles a crack oriented normal to the direction of the fibers. The third figure shows contours or cross sections of fiber damage predicted with the internal stresses. The measured crack lengths are also plotted against corresponding depths. The top row of graphs shows the effect of increasing contact pressure. The analysis predicts that the damage initiates at a critical value of contact pressure, independent of indenter radius. Indeed, damage did initiate at the same contact pressure for all three indenter diameters, between 408 and 514 MPa (59.2 and 74.6 ksi). The length and depth of the cracks increased with contact pressure. The bottom row of graphs shows that the size of damage also increased with indenter diameter. The measurements and predictions are in good agreement except at the surface where the shear criterion predicts no damage. The damage at the surface was probably caused by large compressive stresses, which diminish rapidly with distance from the surface. Of more importance, the shear criterion accurately predicts the maximum depth and width of damage.

Significance: In actual impact tests, the residual strengths for a blunt indenter (large radius) were nearly as low as those for a sharp indenter (small radius), even though the surface damage was much less visible for a blunt indenter. Thus, blunt impacters will be the most critical in designing for least visible surface damage with maximum internal damage. An analysis such as the one presented here is essential to predict the most critical impact situation for design.

Future Plans: Additional experiments will be conducted on a thick laminate made from AS4 prepreg tape, which has much thinner plies than the present (filament wound) laminate. The results will be compared to determine if layup and lamina thickness affect the results.

Figure 19(a).

SIMULATED IMPACT

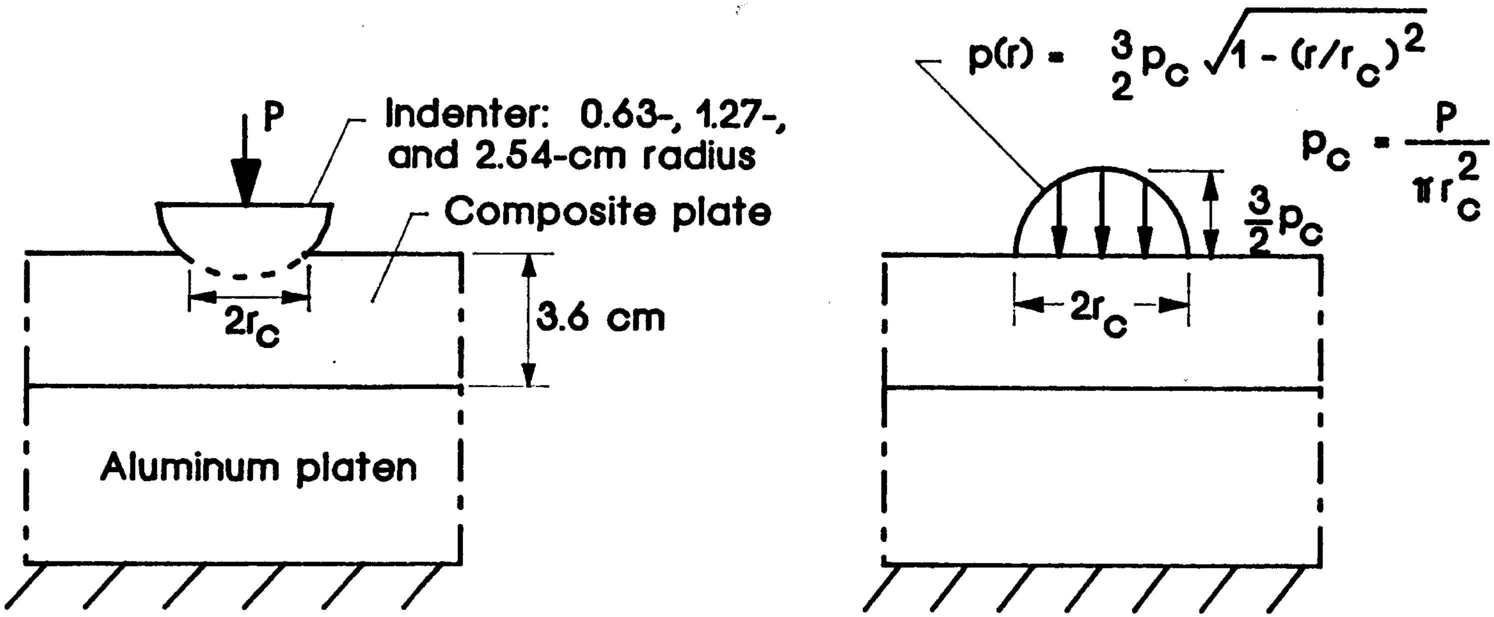


Figure 19(b).

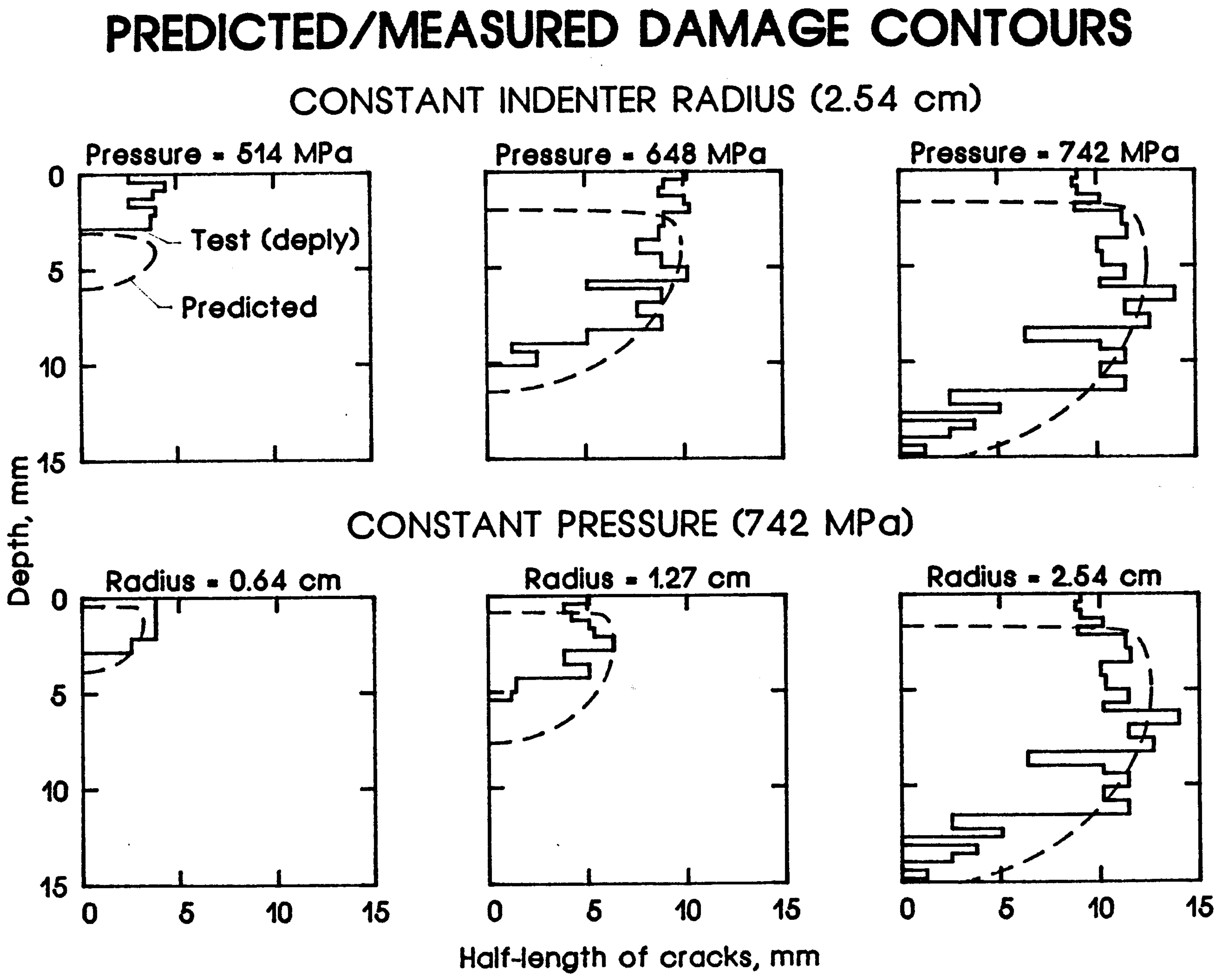

PREDICTED/MEASURED DAMAGE CONTOURS
CONSTANT INDENTER RADIUS (2.54 cm)
Pressure = 514 MPa
Test (deply)
Predicted
Pressure = 648 MPa
Pressure = 742 MPa
CONSTANT PRESSURE (742 MPa)
Radius = 0.64 cm
Radius = 1.27 cm
Radius = 2.54 cm
Depth, mm
0
5
10
15
Half-length of cracks, mm

Figure 19(c).

DAMAGED LAYERS 1-9

5.08-cm-dia. indenter and 267-kN contact force

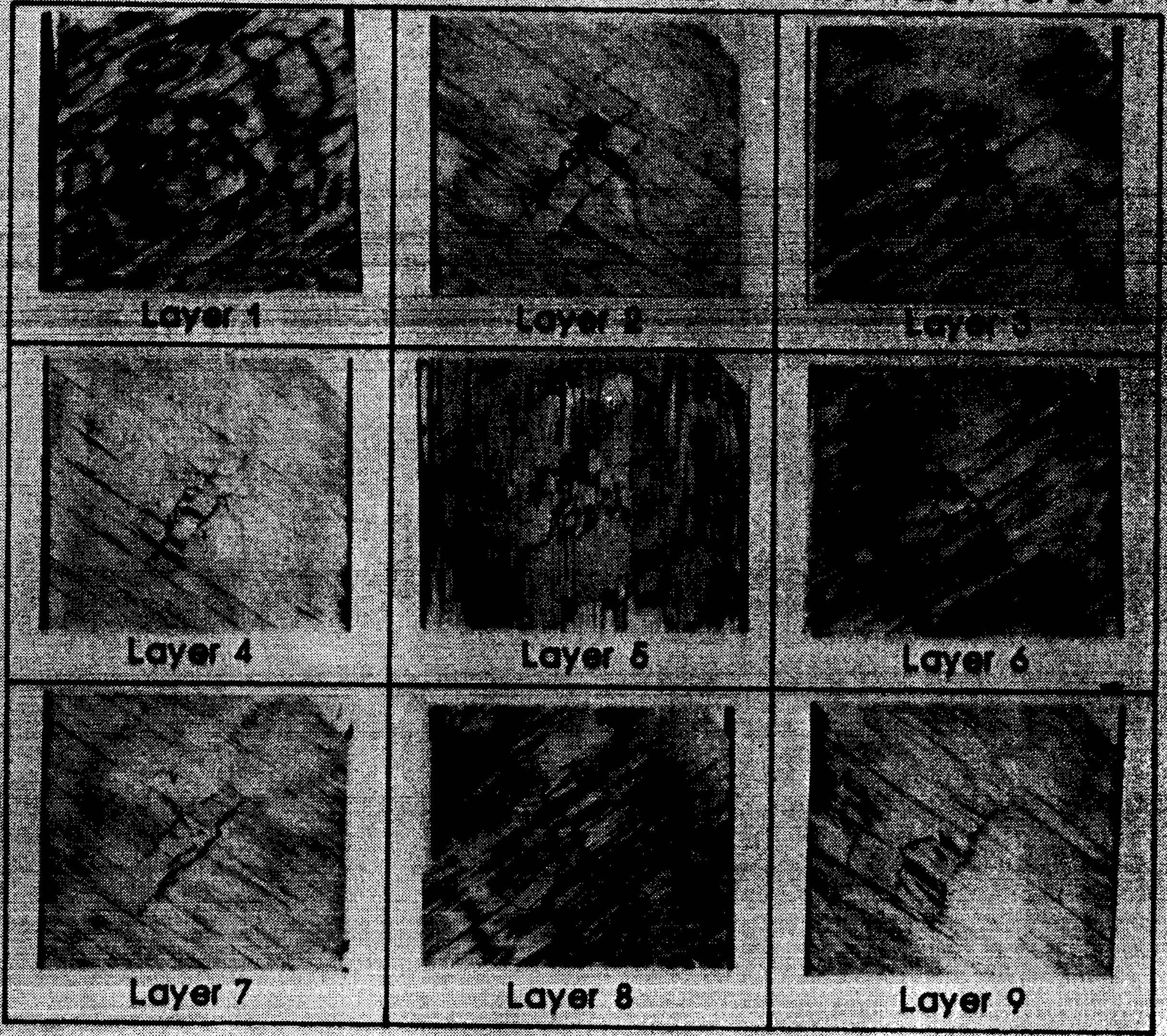


Figure 19(d).

DAMAGED LAYERS 10-18

5.08-cm-dia. indenter and 267-kN contact force

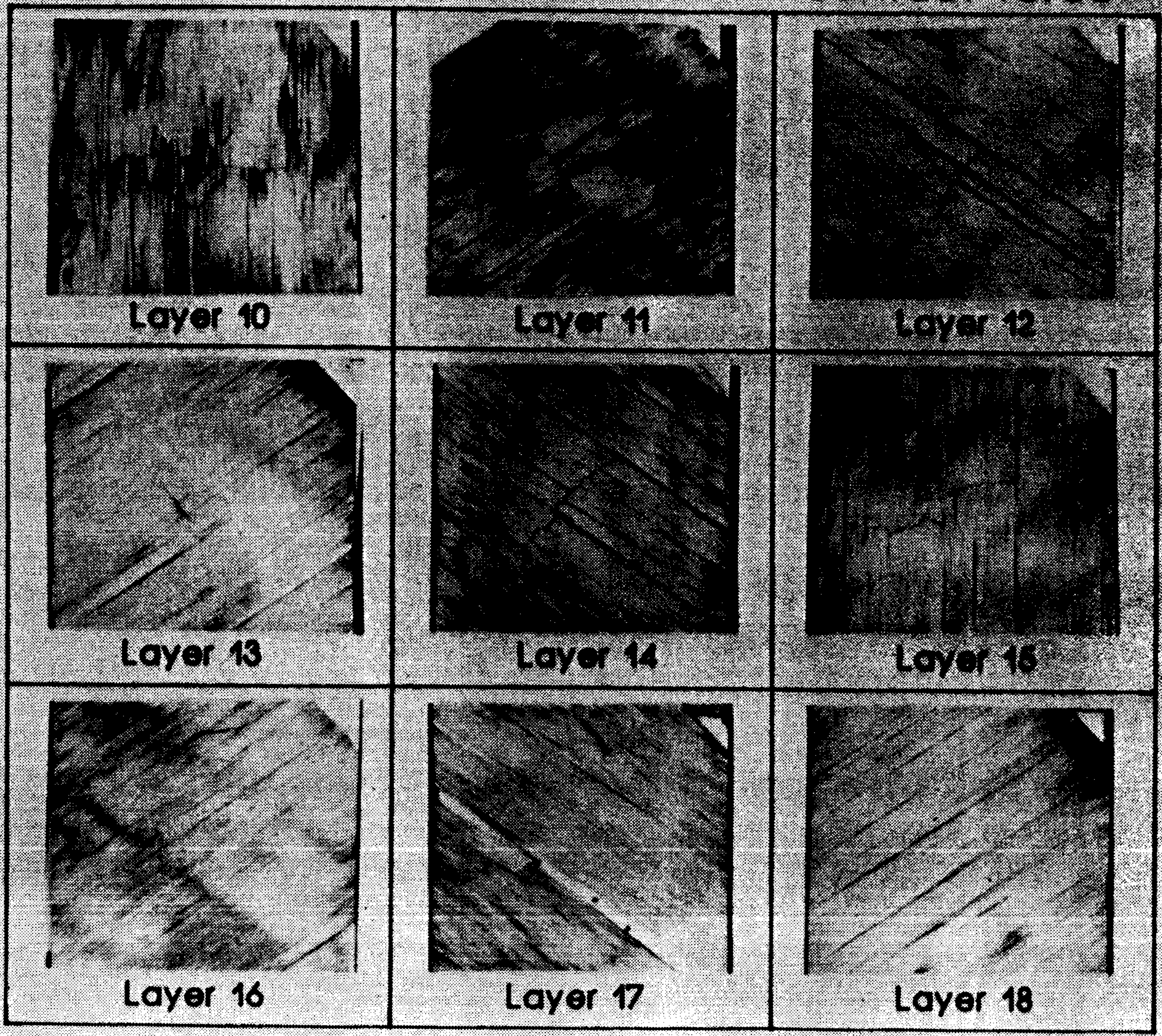


Figure 19(e).

DEVELOPMENT OF A DAMAGE-THRESHOLD/FAIL-SAFETY ANALYSIS FOR COMPOSITE MATERIALS AND STRUCTURES

T. K. O'Brien
Mechanics of Materials Branch
Ext. 43465 April 1988
RTOP 505-63-01

Research Objective: To ensure that composite structures are both sufficiently durable for economy of operation, as well as adequately fail-safe or damage tolerant for flight safety.

Approach: Develop a methodology for predicting damage onset and growth in composites, and assessing fail safety in the damage condition, for a variety of loading conditions. This methodology includes the following steps: (1) Matrix cracks are assumed to exist throughout the off-axis plies. (2) Delamination onset is predicted using a strain-energy-release rate characterization. (3) Delamination growth is accounted for in one of three ways: analytically, using delamination growth laws in conjunction with strain-energy-release rate analyses incorporating delamination resistance curves; experimentally, using measured stiffness loss; or conservatively, assuming delamination onset corresponds to catastrophic delamination growth. (4) Fail-safety is assessed by accounting for the accumulation of delaminations through the thickness and calculating their influence on residual properties.

Accomplishment: A tension fatigue life prediction for composite laminates was developed as a case study to illustrate how this approach may be implemented. A fracture mechanics analysis of edge delamination was used to generate a delamination onset criterion for the material as a function of fatigue cycles. Then, strain-energy-release rates were calculated for local delaminations that formed at matrix ply cracks through the laminate thickness and were compared to the criterion to predict local delamination onset. Delamination growth was accounted for experimentally using measured stiffness loss. Finally, fatigue failures were predicted, as shown in the figure, by accounting for the local strain concentration on the zero degree plies resulting from delaminations forming at matrix cracks through the laminate thickness.

Significance: The damage-threshold/fail-safety methodology provides a generic framework for analyzing the damage tolerance of composite structures under a variety of loading conditions.

Future Plans: Apply the damage-threshold/fail-safety approach to compression fatigue, tension/compression fatigue, and compression strength following low velocity impact.

Figure 20(a).

FATIGUE LIFE PREDICTION BASED ON LOCAL DELAMINATION ACCUMULATION THROUGH THE THICKNESS

$[\pm 45/0/90]_s$ X751/50 E-glass Epoxy

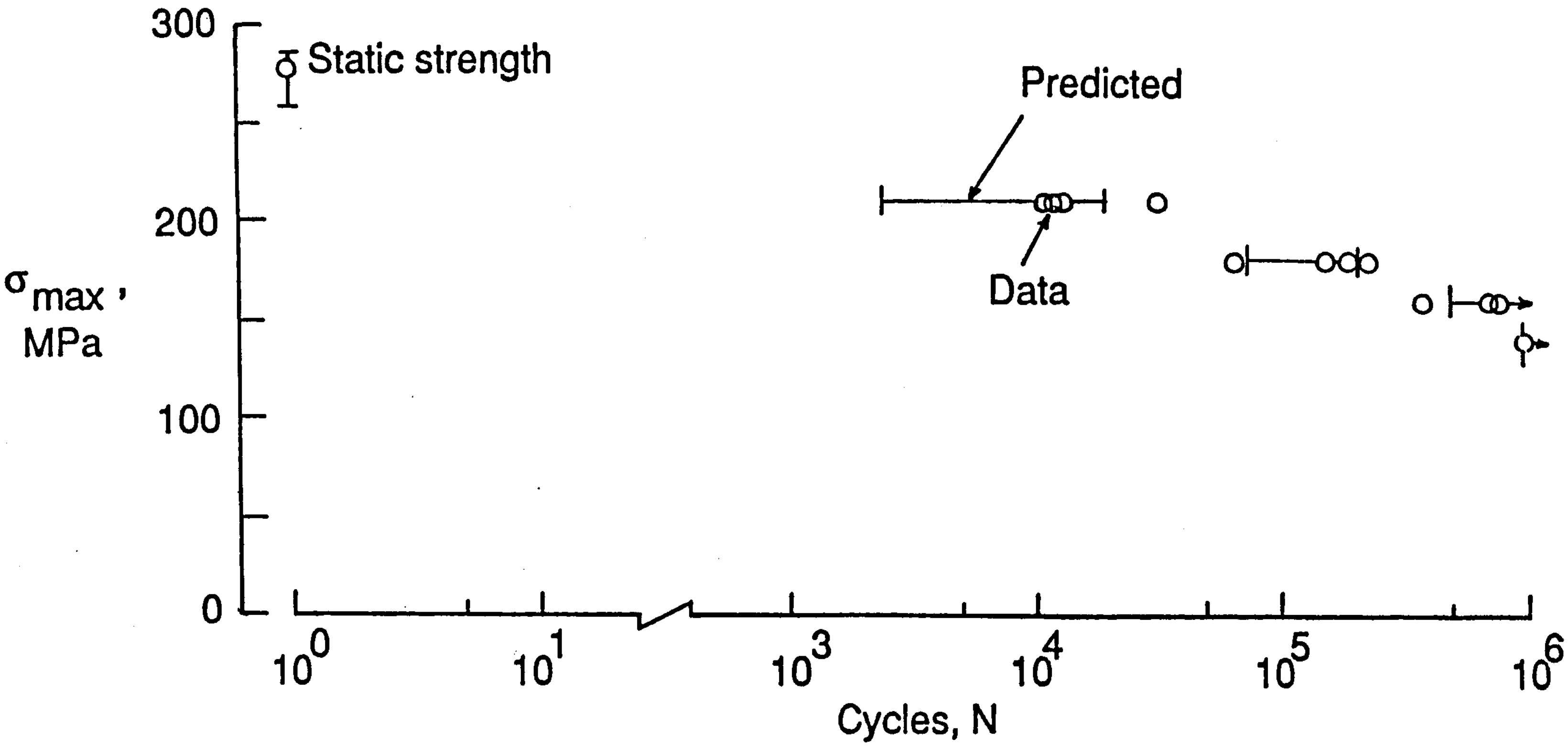


Figure 20(b).

MODE I DELAMINATION FATIGUE THRESHOLD FOR GRAPHITE/PEEK

Gretchen B. Murri and Roderick H. Martin
Fatigue and Fracture Branch
Ext. 43466 June 1988
RTOP 506-43-11

Research Objective: To find a mode I strain energy release rate threshold, G_{Ith}, below which no delamination growth occurs in a graphite/PEEK double cantilever beam (DCB) specimen.

Approach: The DCB specimen is a 36-ply unidirectional specimen. To simulate a delamination, an insert is placed at the midplane at one end of the specimen. When the DCB specimen is loaded under displacement control, the strain energy release rate, G_I, decreases with increasing delamination length. Thus, during a fatigue test the delamination growth rate will decrease with time and the tests can be continued until delamination growth arrests. Alternatively, the specimen can be monitored to determine the number of cycles at which delamination growth begins. A threshold value of strain energy release rate, G_{Ith}, was determined from the maximum cyclic load for which delamination did not occur until at least one million cycles. Both methods were used and the G_I values compared.

Accomplishment: At delamination arrest, a G_{Imax} of 3.0 in-lb/in^2 was measured. However, as the figure shows, testing to delamination growth onset gave G_{Ith} values of 1.0 in-lb/in^2, which was significantly below the arrest value. For metals, this growth arrest value has typically been considered a "threshold" value. However, for composites a more conservative value is a threshold for no delamination growth onset before one million cycles.

Significance: The usual method of obtaining G_{Ith} by cycling to delamination growth arrest over-estimates the value at which there will be no delamination growth. If G_{Ith} is to be used for life prediction it must be defined as the threshold for no delamination growth onset, rather than the threshold at delamination arrest.

Future Plans: Mode I and mode II values of delamination onset threshold for graphite/PEEK must be combined to develop a mixed-mode no-delamination-growth criterion. Initial comparisons show that the threshold values for the two modes are equivalent. This result could lead to a simple mixed-mode, no-growth criterion based on total G, thus eliminating the need to calculate the individual mode I and II components.

Figure 21(a).

Mode I Delamination Fatigue Threshold for Graphite/PEEK

(Displacement Control, R=0.1 f=5Hz)

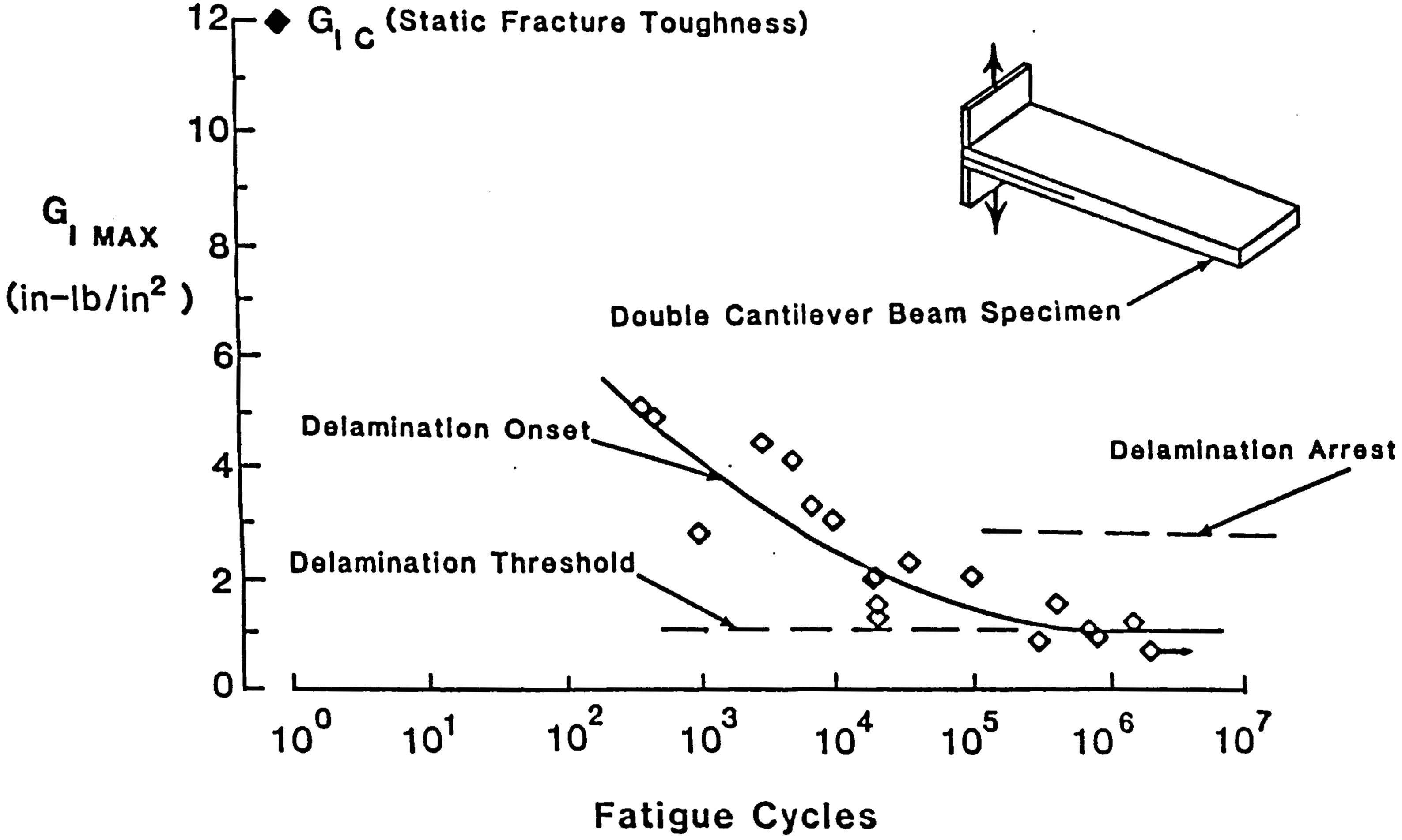


Figure 21(b).

FAILURE MODES FOR LAMINATES UNDER BEARING-BYPASS LOADING

J. H. Crews, Jr. and R. A. Naik
Mechanics of Materials Branch
Ext. 43457 August 1988
RTOP 505-63-01

Research Objective: To determine the laminate failure modes for combined bearing-bypass loading.

Approach: Typical loading for a bolt hole in a multi-fastener composite joint can be expressed in terms of the bearing load on the hole and the load that bypasses the hole. A Langley-developed test machine (Patent 4,718,281) simulates multifastener loadings using single-fastener coupons. Each end of the coupon is loaded independently and the difference between these two loads is reacted at the bolt which is clamped between bearing-reaction plates. The local clampup conditions caused by the bolt head and nut are simulated by inserts held against the coupon. The present study focused on analyzing the laminate failure modes for combined bearing-bypass loads. A previous study dealt with the corresponding laminate strengths.

Accomplishments: Single-fastener coupon tests were conducted with T300/5208 graphite/epoxy laminates subjected to a wide range of bearing-bypass loading in both tension and compression. The laminate failure modes were determined for damage onset and for coupon failure. These tests showed that damage usually initiated in one failure mode and then progressed in the same mode until the coupon failed. As expected, for tension bearing-bypass loading, net-section tension and bearing failure modes were found for the bypass-dominate and bearing-dominate cases, respectively. However, for compressive bearing-bypass loading, a new failure mode was identified.

As shown in the second figure, the failure was offset from the hole and extended across the coupon width. This unusual "offset-compression" failure mode is believed to be caused by bearing-induced delamination that extends beyond the clampup region around the hole and then initiates ply-buckling across the compressively loaded coupon. The bright areas shown next to the fracture are caused by a dry lubricant that transferred from the bearing-reaction plate to the coupon when it failed. The dry lubricant also vaguely outlines the clampup region around the hole.

Significance: Results from this study suggest that compressive bearing-bypass strength cannot be predicted from simple test data combined with stress analyses, which is the generally preferred approach in structural analyses. The compressive bearing-bypass failures involve a unique failure mode and prediction procedures usually cannot transcend failure mode differences.

Future Plans: At present, there are no plans for further bearing-bypass testing.

Figure 22(a).

COMBINED BEARING AND BYPASS LOADING

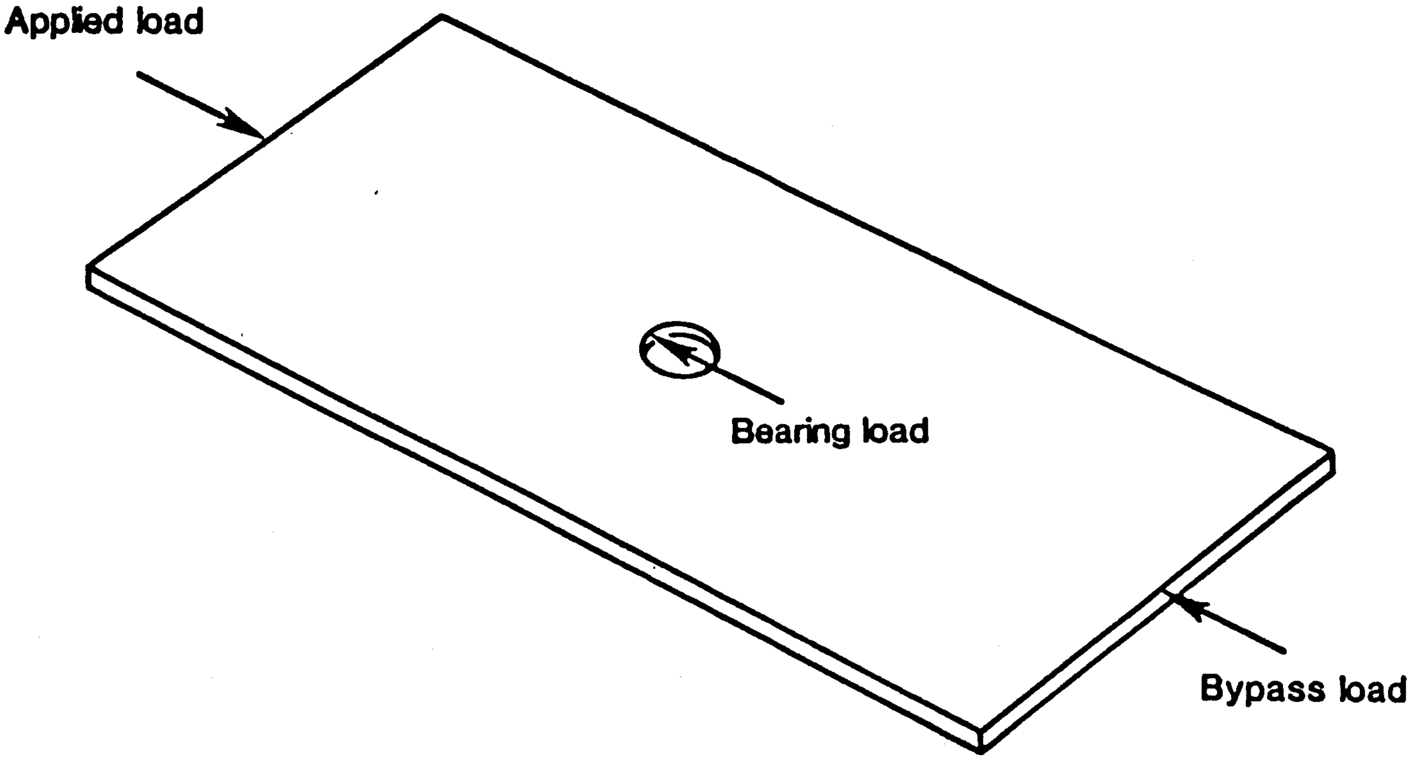


Figure 22(b).

OFFSET COMPRESSION FAILURE IN BEARING-BYPASS TEST

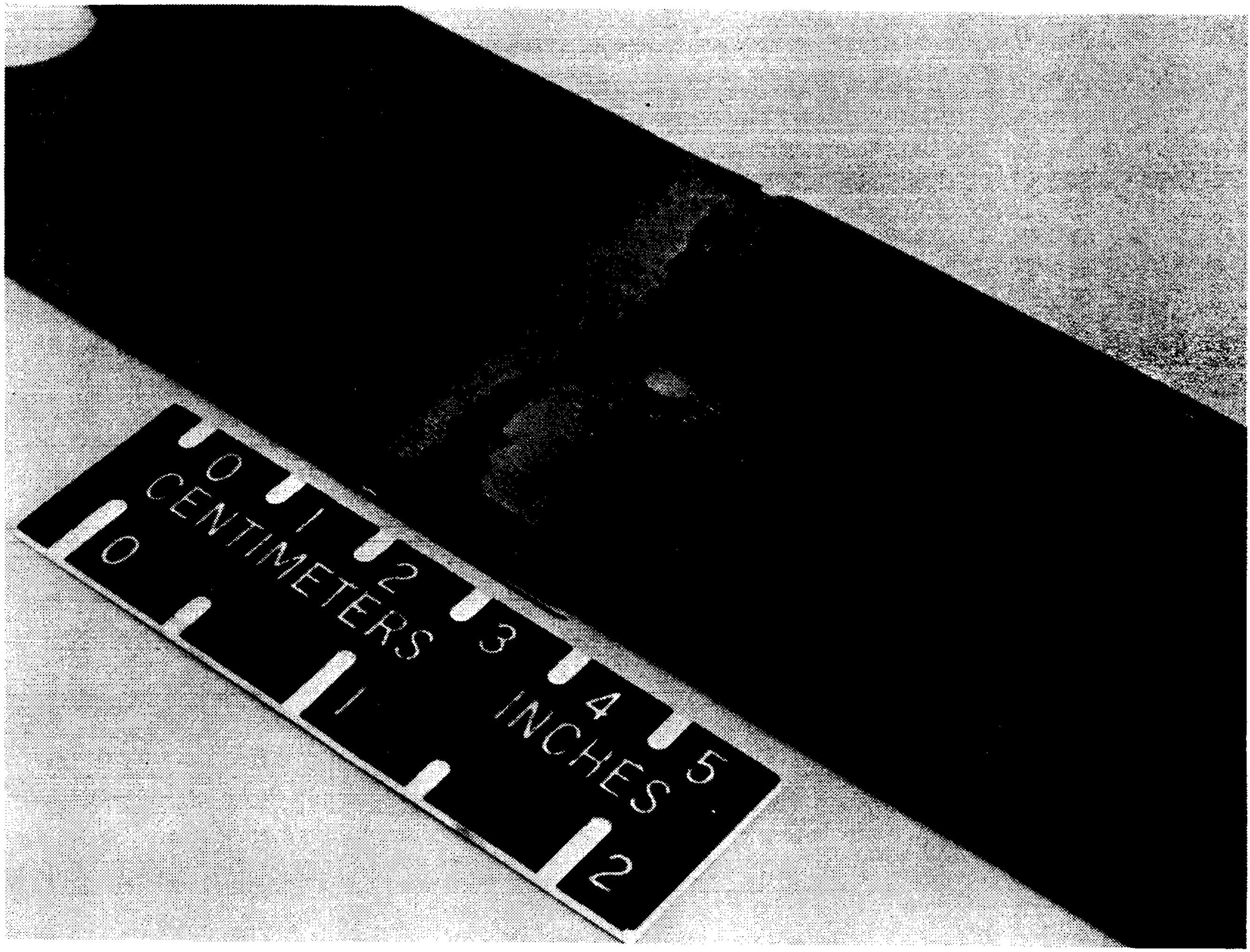
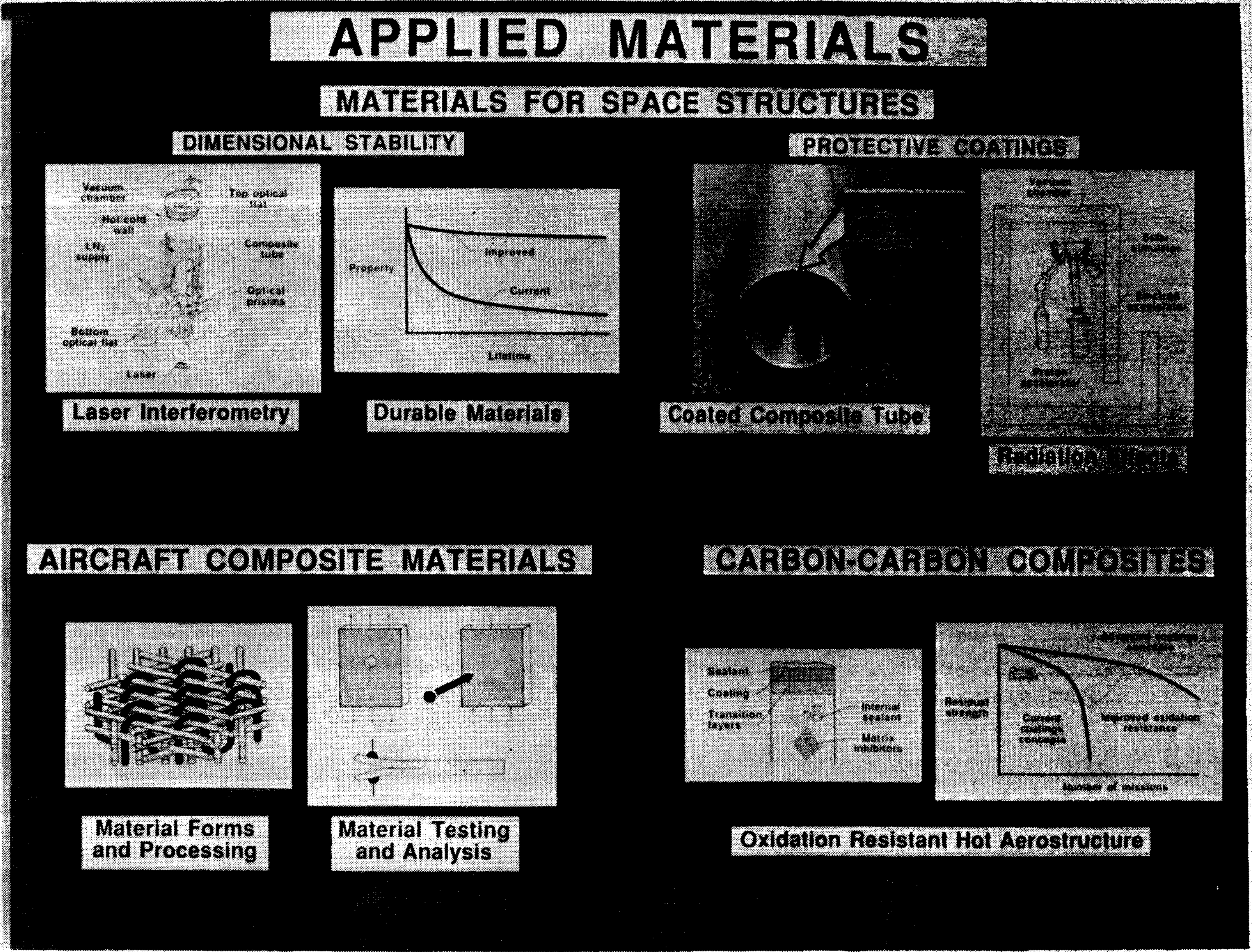


Figure 22(c).

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



APPLIED MATERIALS

MATERIALS FOR SPACE STRUCTURES

DIMENSIONAL STABILITY

Laser Interferometry

Durable Materials

PROTECTIVE COATINGS

Coated Composite Tube

Radiation Effects

AIRCRAFT COMPOSITE MATERIALS

Material Forms and Processing

Material Testing and Analysis

CARBON-CARBON COMPOSITES

Oxidation Resistant Hot Aerostructure

Figure 23.

APPLIED MATERIALS BRANCH
FIVE YEAR PLAN

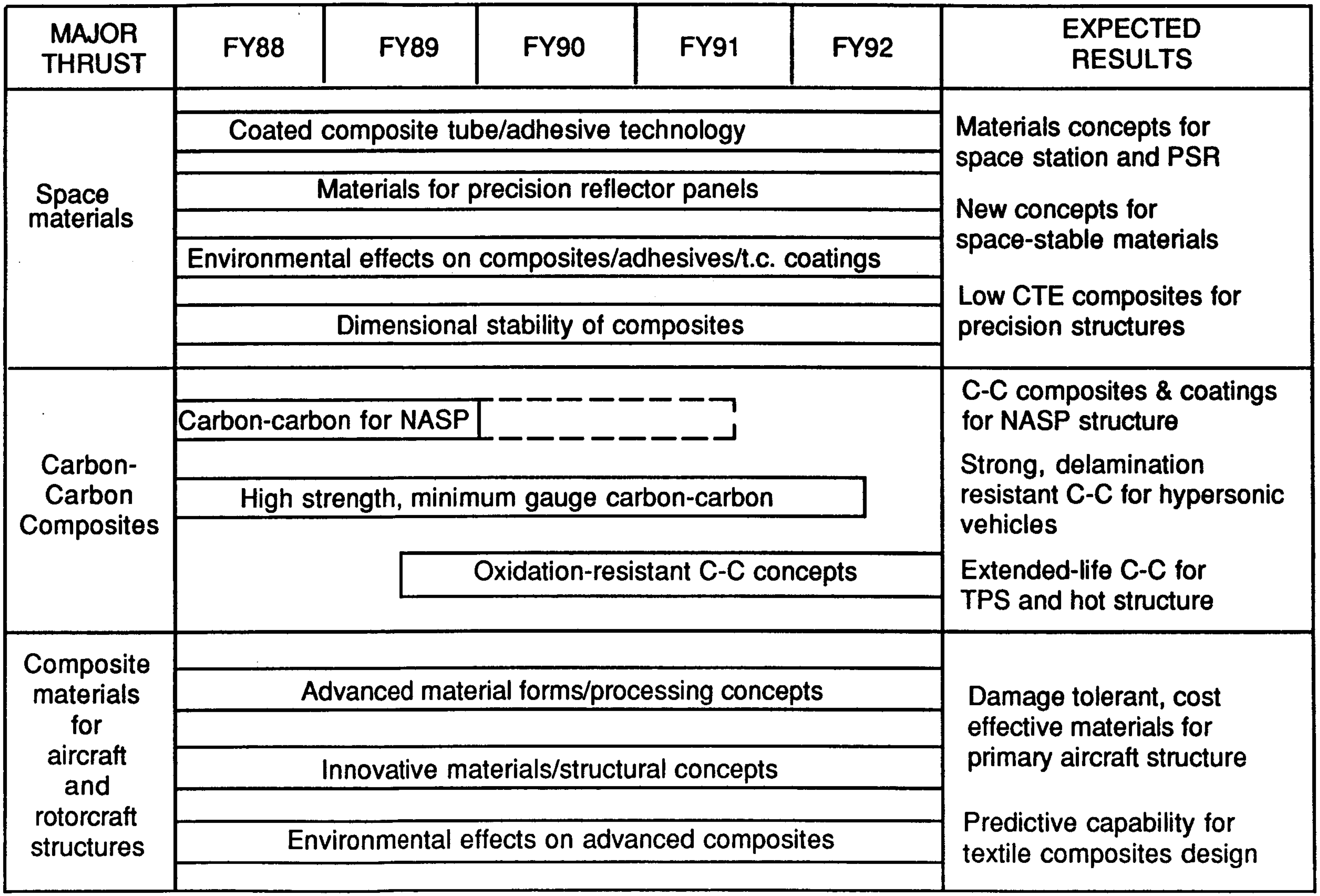


Figure 24.

ANALYSIS OF ADVANCED COMPOSITE MATERIALS FOR PRECISION SEGMENTED REFLECTORS

David E. Bowles
Applied Materials Branch
Ext. 43095 December 1987
RTOP 585-02-21

Research Objective: To identify and evaluate advanced composite materials for precision segmented reflector (PSR) applications such as the Large Deployable Reflector (LDR).

Approach: Surface roughness and weight are two of the primary design considerations for the reflector panels on LDR. Graphite/epoxy (Gr/Ep) is the current baseline material for these panels. However, Gr/Ep composites have large internal residual stresses which can cause unwanted surface distortions and microcracking. Composites with a smaller mismatch in properties between the fiber and matrix lower these residual stresses and thus reduce surface distortions and microcracking. A preliminary analysis was conducted to compare the relative surface distortions of Gr/Ep with three such composite systems: Gr/Low CTE Ep, quartz/epoxy (Quartz/Ep), and graphite/glass (Gr/Glass).

Accomplishments: A generalized plane strain finite element analysis of a single layer of fibers was used to evaluate the effect of material properties on thermally induced surface distortions. Comparisons between Gr/Ep and the alternate epoxy and Gr/Glass systems are shown in the first and second figures, respectively. The Gr/Low CTE Ep exhibits the smallest surface distortion. The coefficient of thermal expansion (CTE) of the epoxy was assumed to be 1/10 of its original value. Quartz/Ep exhibits a moderate improvement over Gr/Ep. Both Gr/Glass systems exhibit less surface distortion than Gr/Ep, even though the ΔT's (use temperature - stress free temperature) are much larger. The Gr/modified glass represents a system in which the glass chemistry has been modified to lower the stress free temperature.

Significance: Preliminary analytical investigations have shown that the alternate advanced composite systems being considered for PSR applications offer potential for improvements in surface roughness.

Future Plans: Further analytical investigations will be conducted to determine the optimum material properties and laminate construction for minimizing thermally induced surface distortions. Experiments will be performed to verify the analytical predictions.

Figure 25(a).

MODELING OF THERMALLY INDUCED SURFACE DEFORMATIONS IN COMPOSITE LAMINA

Epoxy Matrix Systems, Vf = 0.60, $\Delta T = -450°F$

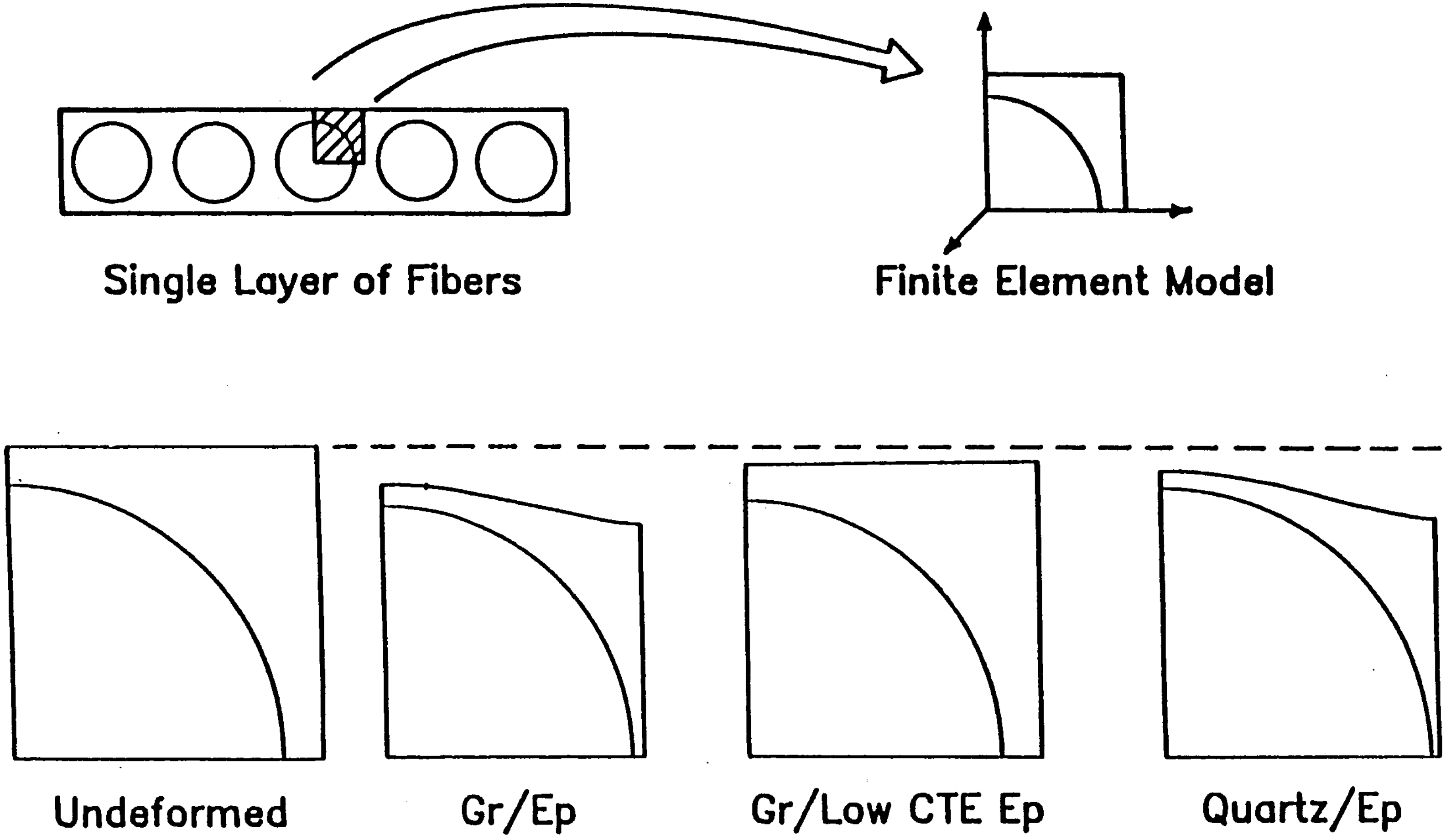


Figure 25(b).

MODELING OF THERMALLY INDUCED SURFACE DEFORMATIONS IN COMPOSITE LAMINA

Comparison of Epoxy and Glass Matrix Systems, Vf = 0.60

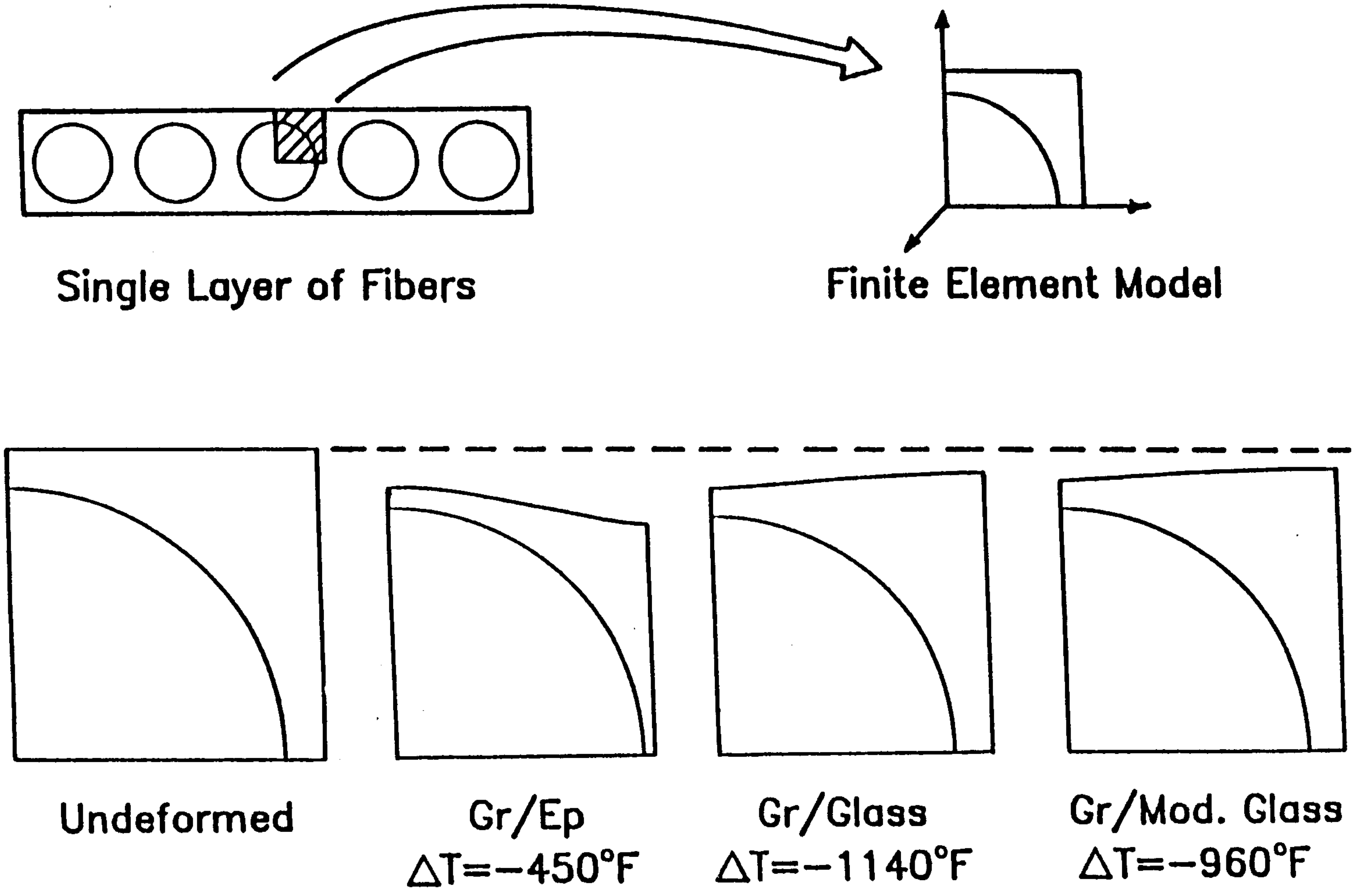


Figure 25(c).

THERMAL CYCLING INDUCED DAMAGE IN COMPOSITE TUBES

David E. Bowles
Applied Materials Branch
Ext. 43095 September 1988
RTOP 506-43-21

Research Objective: Determine whether long-term thermal cycling causes microstructural damage in composite tubes designed for large space structures, such as Space Station. Determine the effect of this damage on the thermomechanical properties of the tube.

Approach: Composite tubes of several different graphite/epoxy material systems were examined for damage formation, and tested to determine changes in properties, after 3000, 7000, and 9000 thermal cycles between ±150°F. The laminate configuration selected for evaluation is a $[\mathrm{Al/Ad}/+15/0/\pm 10/0/-15]_s$ (Al-2 mil aluminum foil, Ad-8 mil adhesive) layup, designed to maximize longitudinal stiffness, minimize thermally induced internal stresses, and provide adequate transverse strength to withstand handling and low velocity impact damage. The aluminum foil serves as a thermal control and atomic oxygen protective coating.

Accomplishment: No significant changes in axial compressive modulus were observed in T300/934, P75/934, or P75/BP907 graphite/epoxy tubes after 3000, 7000, or 9000 thermal cycles. However, cracks and delaminations at the tube ends were observed in all three material systems after 3000 thermal cycles. A photomicrograph of an end view of this damage in a P75/934 tube is shown in the first figure. A longitudinal view of the same location (first figure) shows that the crack extends only about 0.07 inches along the length of the 10 inch long tube. Further examinations showed that all of the damage occurred near the end of the tube. A preliminary finite element (FE) stress analysis (second figure) predicted a large interlaminar shear stress, T_{xz}, in the composite/adhesive interface at the end of the tube. This stress decreased to zero away from the free end of the tube. The magnitude of this shear stress is comparable to the interlaminar shear strength of this material, and is believed to be the predominate cause of the observed damage. No additional damage growth was observed after 9000 thermal cycles.

Significance: Axial compressive modulus was not degraded after 9000 thermal cycles. Thermally induced damage observed after 3000 cycles was confined to a very small region near the ends of the tube and did not grow with additional cycling.

Future Plans: Damage initiation and growth, and property changes will continue to be monitored up to 15000 thermal cycles.

Figure 26(a).

END CRACKS IN A P75/934 $[\mathrm{Al/Ad/+15/0/\pm10/0/-15}]_s$ TUBE AFTER 3000 THERMAL CYCLES

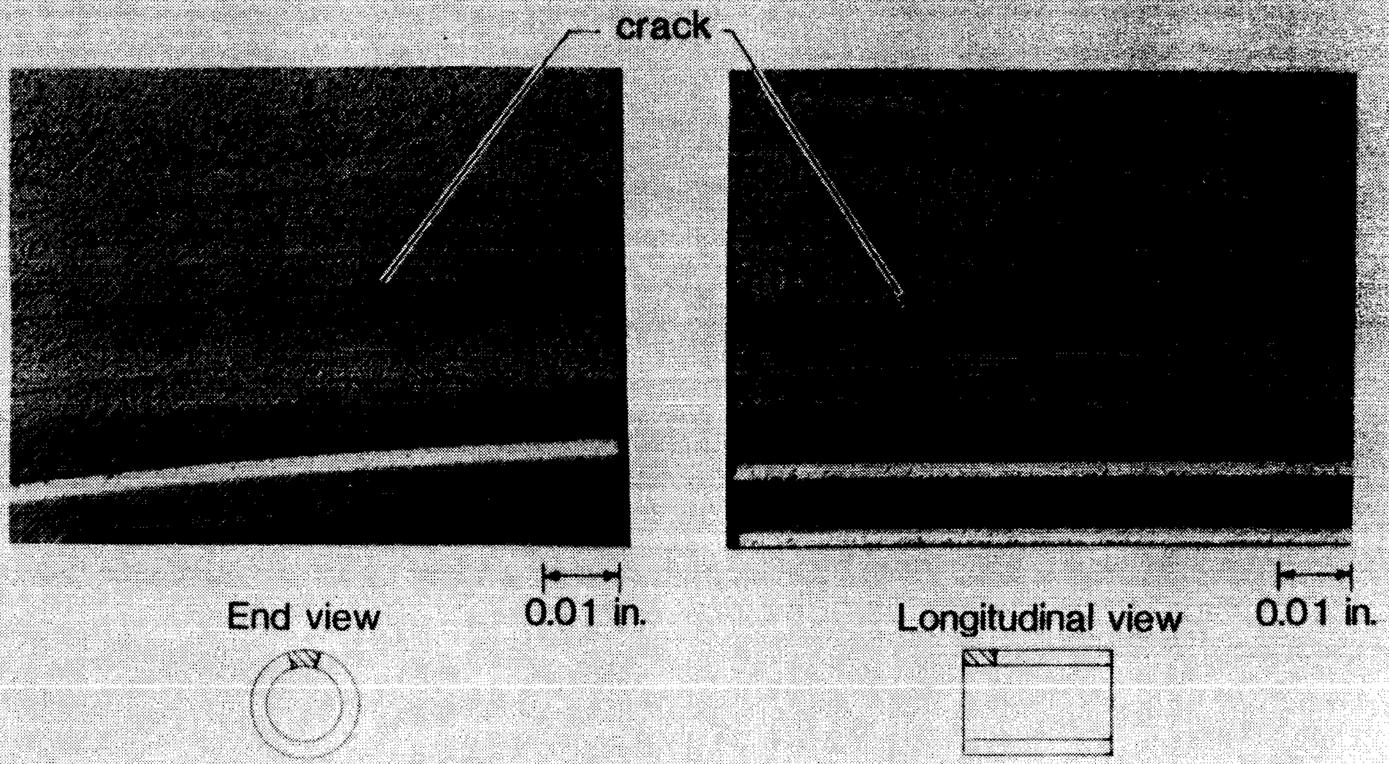


Figure 26(b).

FE ANALYSIS OF INTERLAMINAR STRESSES IN A P75/934 [Al/Ad/+15/0/±10/0/−15]$_s$ COMPOSITE TUBE

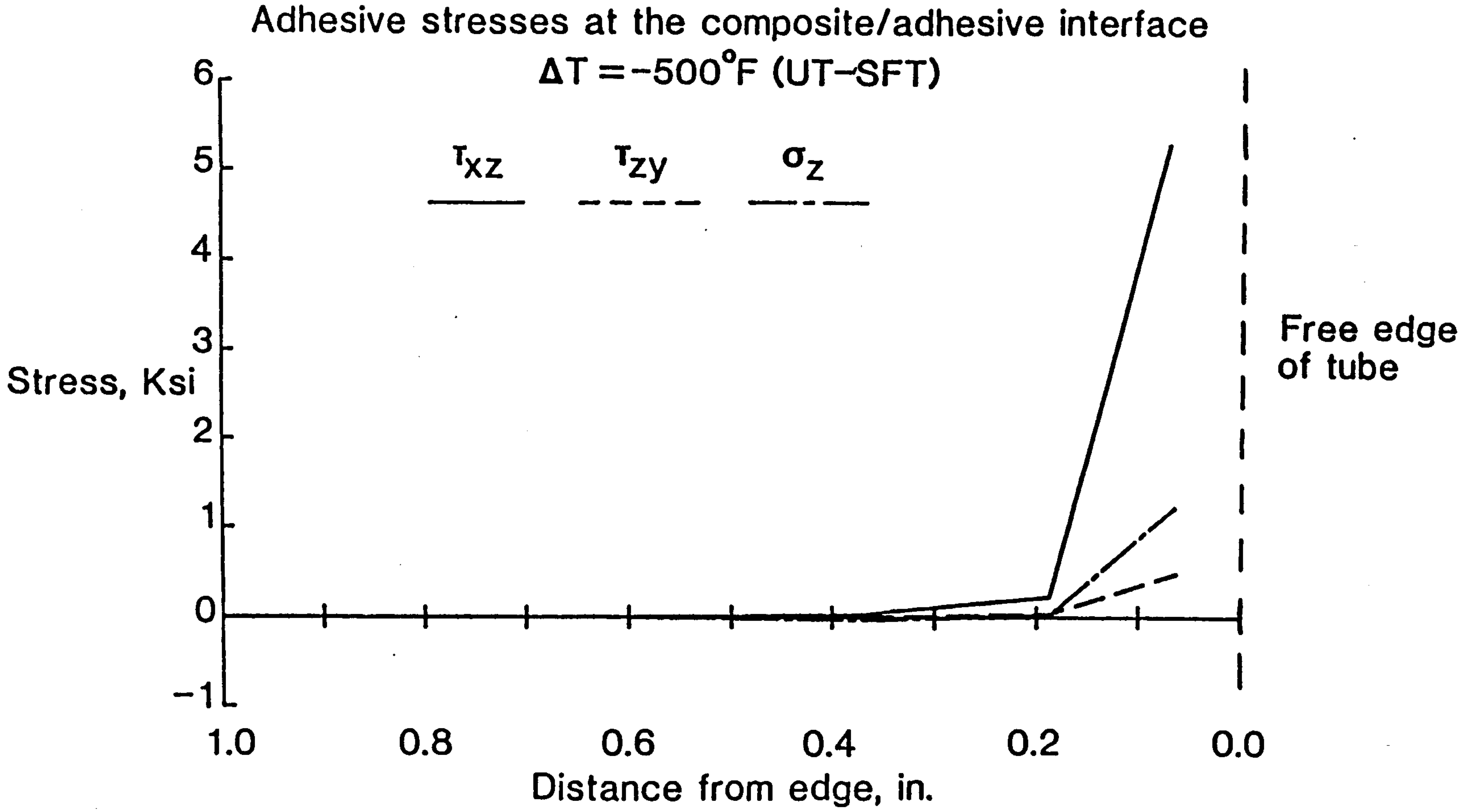


Figure 26(c).

OXIDATION-RESISTANT CARBON-CARBON COMPOSITES EVALUATION IN SIMULATED ADVANCED AEROSPACE VEHICLE ENVIRONMENTS

Craig W. Ohlhorst
Applied Materials Branch
Ext. 43502 July 1988
RTOP 763-01-41

Research Objective: To establish the potential of oxidation-resistant carbon-carbon (c-c) composites for service in high-temperature, low-pressure airframe environments representative of those anticipated for NASP and other advanced hypersonic vehicles.

Approach: State-of-the-art high-strength, high-modulus oxidation-resistant c-c composites have been developed largely for propulsion applications. Their performance has never been evaluated in simulated hypersonic airframe environments. Specimens were subjected to cruise, ascent and entry service environments in Langley's Multiparameter Environmental Simulators. Maximum temperatures on ascent and entry were 2800°F, and on cruise were 2200°F with a 1-hour hold at 1400°F. To evaluate the effect of humidity, selected specimens were equilibrated at 90 percent humidity and 80°F before testing.

Accomplishment: To date, eight specimens supplied for preliminary evaluation by various c-c fabricators have been tested. The cumulative exposure time to reach a preestablished failure criterion (75 gr/m^2) ranged from 15 to 40 hours. Moisture exposure significantly reduced lifetime. Separation of the coating from the substrate was a problem for all specimens subjected to moisture exposure. Pinhole development leading to localized oxidation of the substrate was found to be a failure mechanism for some specimens. A plot of mass change per specimen surface area for one set of specimens is shown in the accompanying figure. The plot illustrates the detrimental effect that moisture exposure can have on oxidation-protection system performance.

Significance: Oxidation-resistant c-c composites developed for propulsion applications have been shown to offer only limited life performance in hypersonic vehicle airframe environments. Major problems identified are moisture degradation of the coating, as well as pinhole development and poor coating adhesion. Results of these tests are being transmitted to material suppliers to guide future material development.

Future Plans: Continue evaluations of other oxidation-resistant c-c composite materials. Initiate research to develop improved oxidation-protection systems that will be humidity resistant and will provide adequate lifetime protection for hypersonic vehicle airframes.

Figure 27(a).

PERFORMANCE RESULTS FOR ROHR SAMPLE MATERIALS

Tested Materials: Rohr Inhibited Substrates with SFL MOD IV Coating

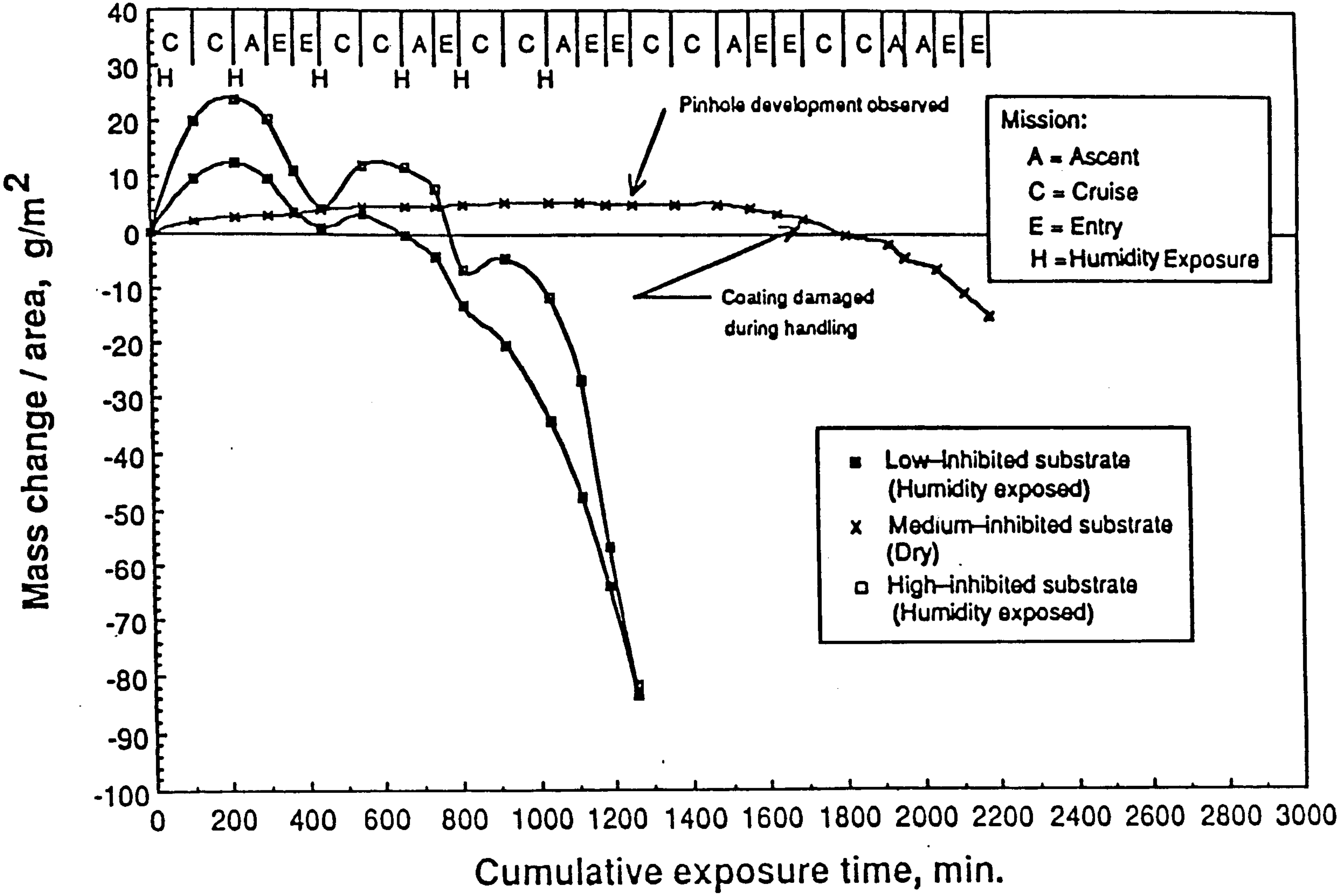


Figure 27(b).

DAMAGE-TOLERANT COMPOSITE MATERIAL CONCEPTS

Marvin B. Dow, H. Benson Dexter, and Donald L. Smith
Applied Materials Branch
Ext. 43090 October 1987
RTOP 505-63-01

Research Objective: To demonstrate and characterize promising material concepts for damage-tolerant composite structures.

Approach: Devise concepts to enhance the damage-tolerance of composite materials. Evaluate performance relative to state-of-the-art materials.

Accomplishment: Damage tolerance is an essential requirement for a composite material in aircraft applications. An accepted measure of merit is a failure strain level of 0.006 in a post-impact compression test conducted using methods given in NASA RP 1092. The first figure shows results from four graphite-epoxy materials which meet or exceed the desired strain level.

Two of the materials, IM6/1808I (American Cyanamid Corporation) and IM7/8551-7 (Hercules Corporation), are representative of the best available commercial tape materials. Both materials were specifically formulated for good post-impact performance. The other two materials result from Langley investigations of special fabric designs or stitching to enhance damage tolerance. The T300/8551-7 material incorporates a special fabric devised by Material Sciences Corporation to suppress the delamination failure mechanisms in damaged structure. The AS4/3501-6 material is stitched with Kevlar thread normal to the graphite plies with subsequent resin impregnation by resin transfer molding.

Environmental effects are important considerations in composite materials. The second figure shows that the new, toughened materials perform substantially better than earlier, more brittle materials such as AS4/3502. However, heat and moisture produce significant stress reductions in both new materials.

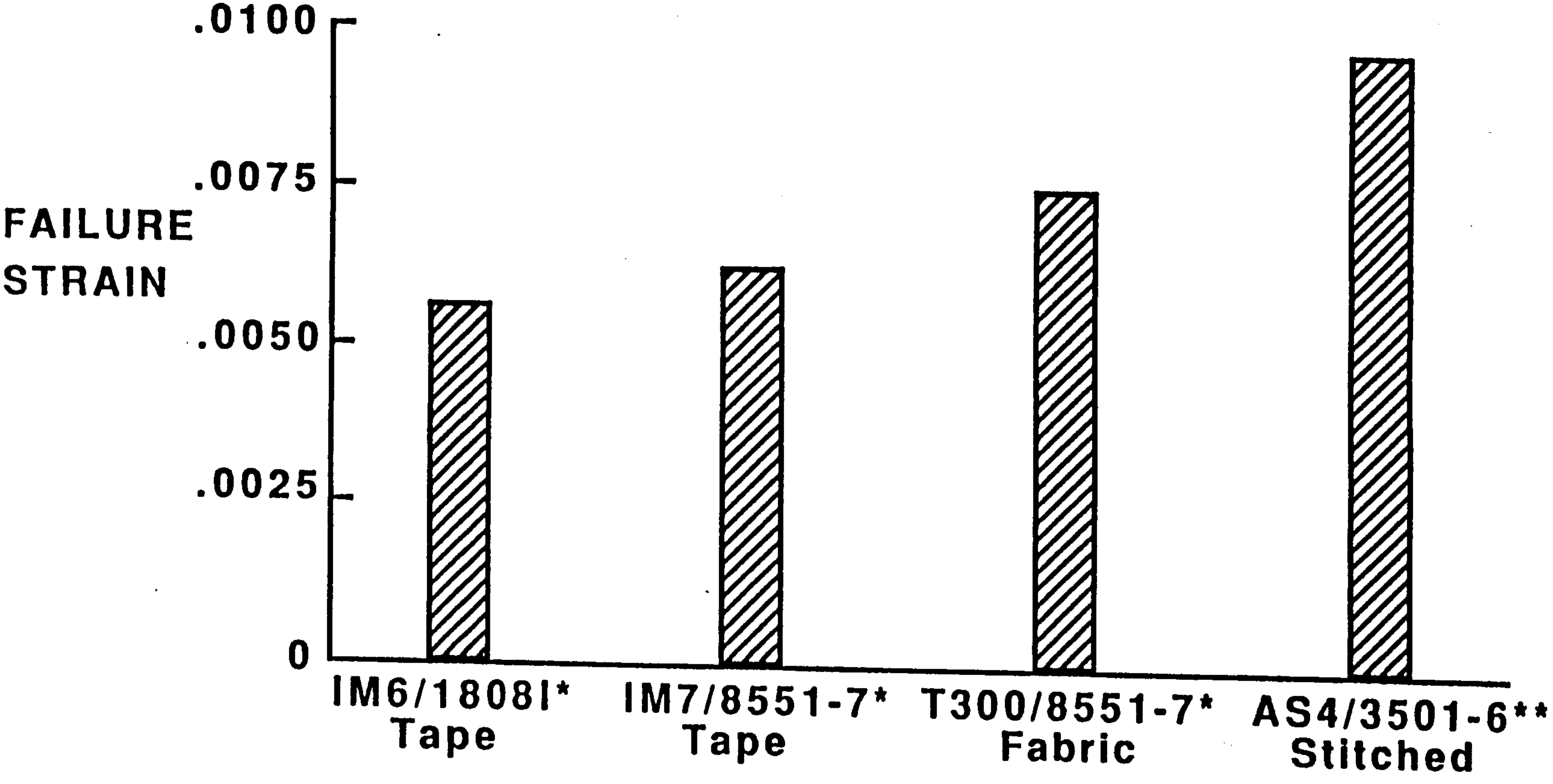
Significance: The application of composite materials must be justified on the basis of performance and cost. The results of this investigation show that the damage tolerant composite materials can be provided by ply interleaving, special resin formulations, fabric designs or stitching. All but the stitched composite involve relatively expensive prepreg material forms. The stitched material is fabricated by resin transfer molding which potentially could result in major cost savings. In static tests, the stitched material displayed outstanding damage tolerance, but the effects of moisture and cyclic loading need to be evaluated.

Future Plans: Evaluate the stitched material for moisture and cyclic loading effects. Test stitched structural elements fabricated using resin transfer molding.

Figure 28(a).

COMPRESSION AFTER IMPACT FAILURE STRAIN OF QUASI-ISOTROPIC GRAPHITE/EPOXY LAMINATES

Impact Level: 1000 $\frac{\text{in-lb}}{\text{in}}$



* NASA LARC Air Gun Impact (1/2" dia. ball)
** Drop Weight Impactor (1/2" dia. tup)

Figure 28(b).

C-2

COMPRESSION AFTER IMPACT STRENGTH OF QUASI-ISOTROPIC GRAPHITE/EPOXY LAMINATES

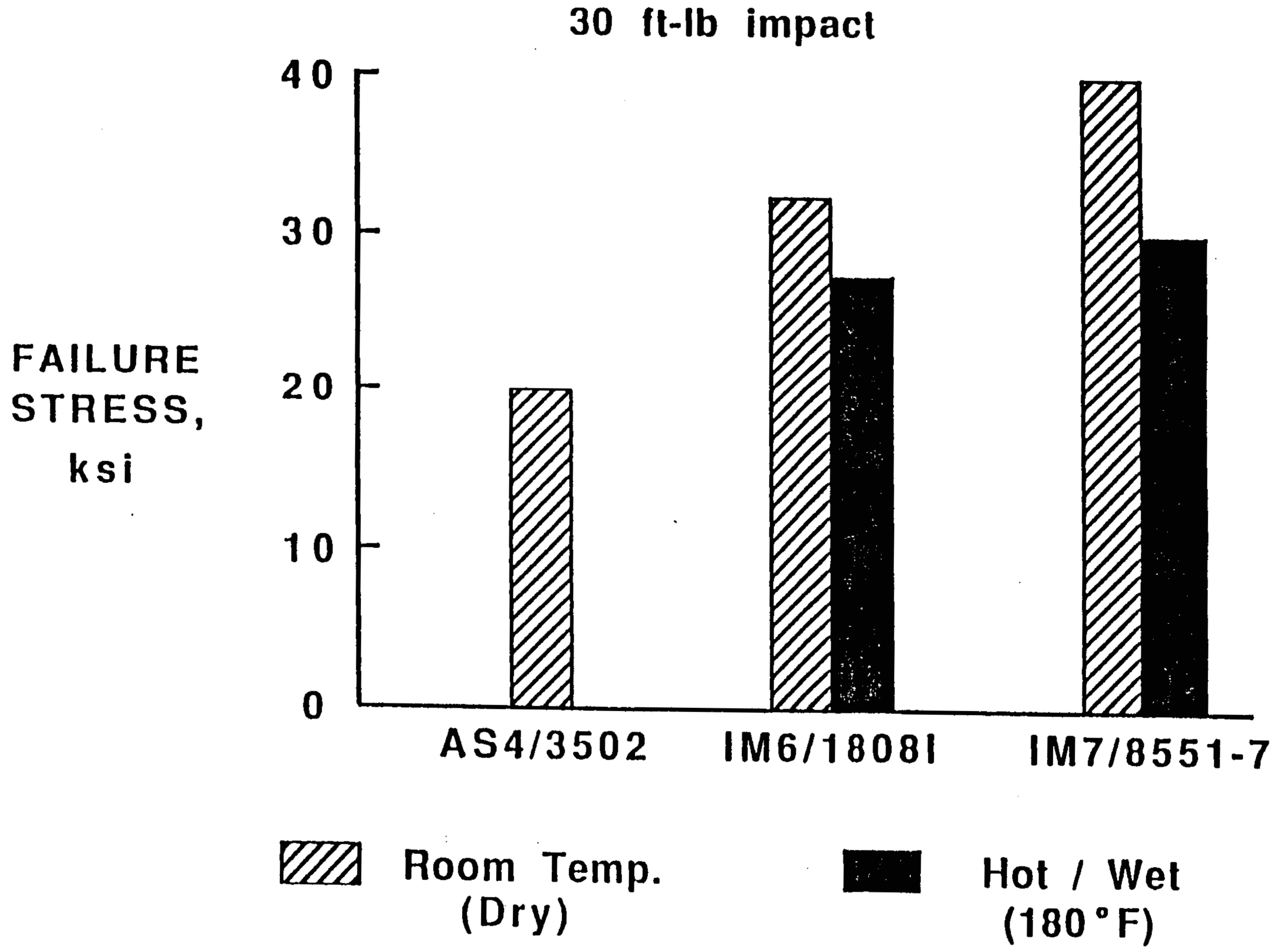


Figure 28(c).

COMPOSITE MATERIAL IN-SITU VISCOSITY MONITOR

William T. Freeman, Jr.
Applied Materials Branch
Ext. 42935 February 1988
RTOP 505-63-01

Research Objective: To develop a scientific foundation for composite material process development and reproducibility.

Approach: Devise in-situ sensor methods to interrogate the physical and chemical state of polymers during processing. Establish models to predict process requirements for high performance matrix systems.

Accomplishment: Composite material processing involves a complex thermal, chemical, and physical (tooling) environment that must be balanced within a polymer-specific, chemical reaction processing window to result in a void free flight quality part. New high performance (tough, high temperature) matrix systems require lengthy, expensive trial and error process window determination. In-process interrogation of viscosity, void content, chemical state, and reaction extent are needed to rapidly screen the large number of new material formulations and ultimately certify quality of expensive materials. Sensing methods have been developed to simultaneously measure permittivity and viscosity in a research rheometer. Correlation of the frequency dependence of the real and imaginary part of the complex permittivity provides a measure of ionic mobility which has been related to rheometer measured viscosity (first figure) for isothermal cure of an industry standard epoxy. This data has provided the required database to quantitatively measure viscosity between plies of a thick composite laminate (second figure) in a production tool and autoclave environment. The third figure shows sensor measured viscosity at the tool surface, the 32nd ply, the 64th ply, and the 96th ply for a 192 ply epoxy laminate cured in an LaRC autoclave.

Significance: This research is the first reported quantitative measure of the matrix viscosity through the plies of a graphite laminate in a production tool and high temperature autoclave environment. Apparent data resolution of approximately 10 poise over a 10,000 poise viscosity range was better than anticipated. Such measurements provide the process engineer his first measure of actual flow conditions at any location during processing of complex components.

Future Plans: Develop sensor understanding of Resin Transfer Molding processes and process window optimization methods for advanced polymer matrix composites.

Figure 29(a).

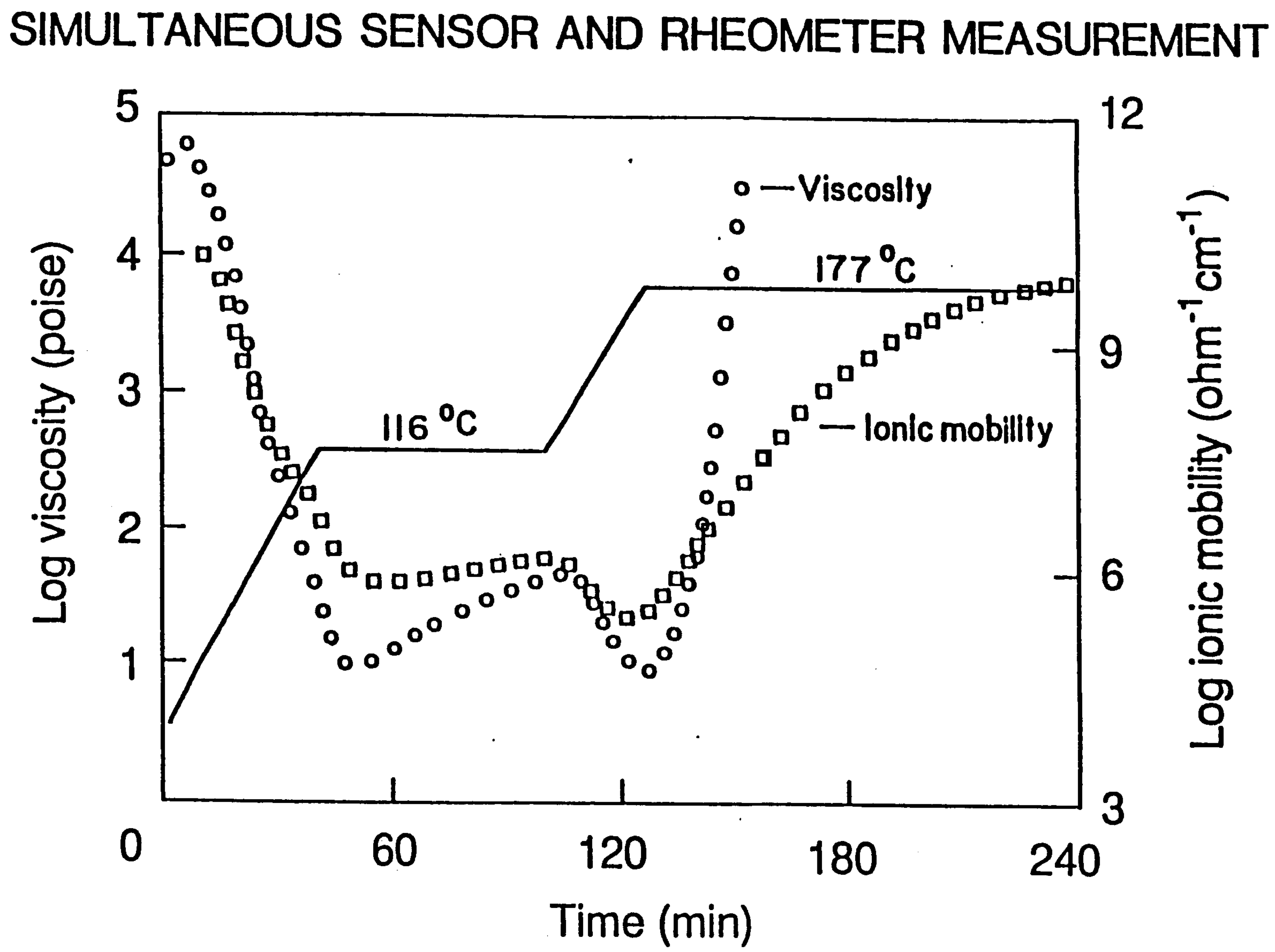

SIMULTANEOUS SENSOR AND RHEOMETER MEASUREMENT
o — Viscosity
— Ionic mobility
116 °C
177 °C
Log viscosity (poise)
5
4
3
2
1
0
Log ionic mobility (ohm⁻¹cm⁻¹)
12
9
6
3
Time (min)
60
120
180
240

Figure 29(b).

SENSOR LOCATION IN 192 PLY LAMINATE

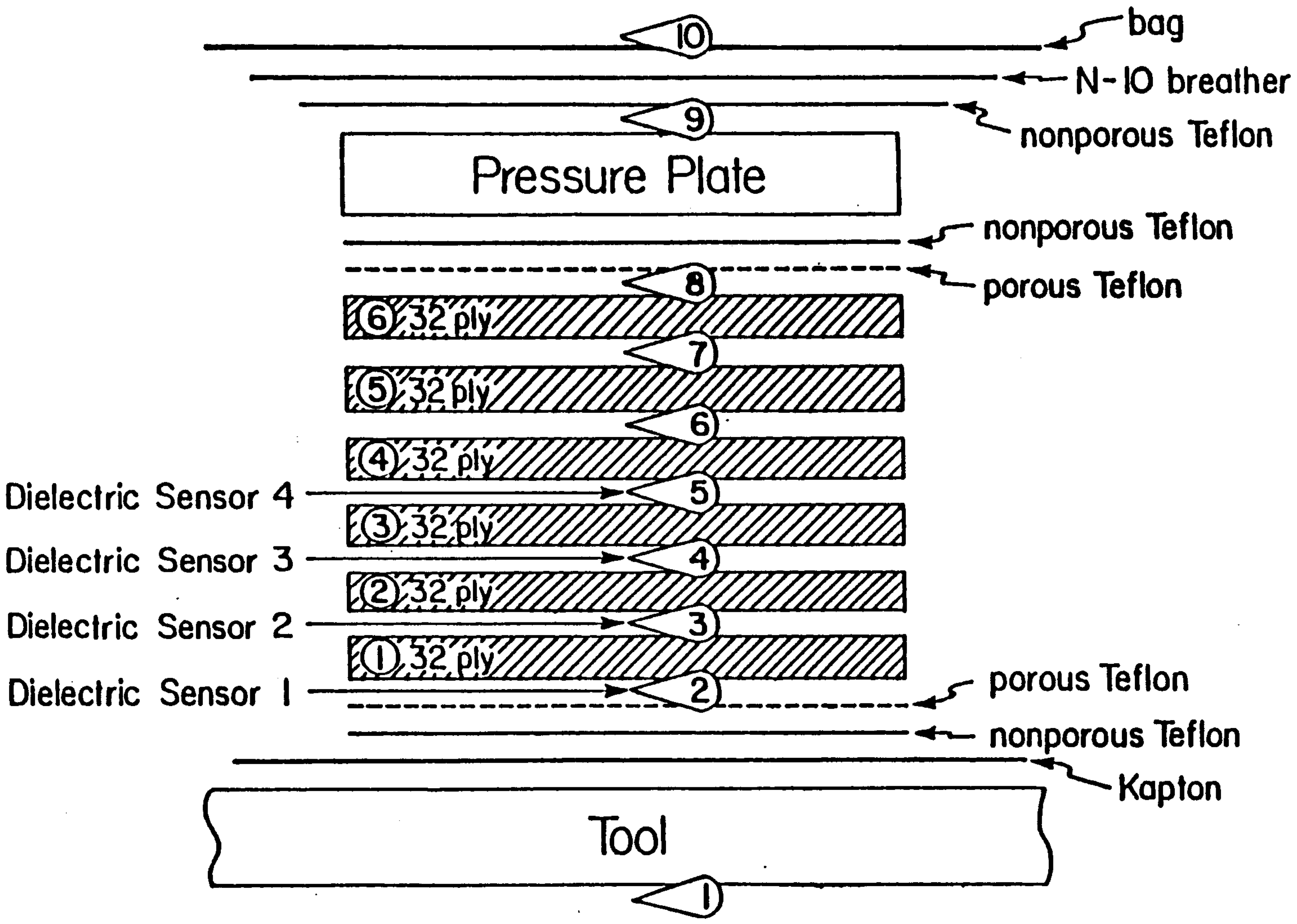


Figure 29(c).

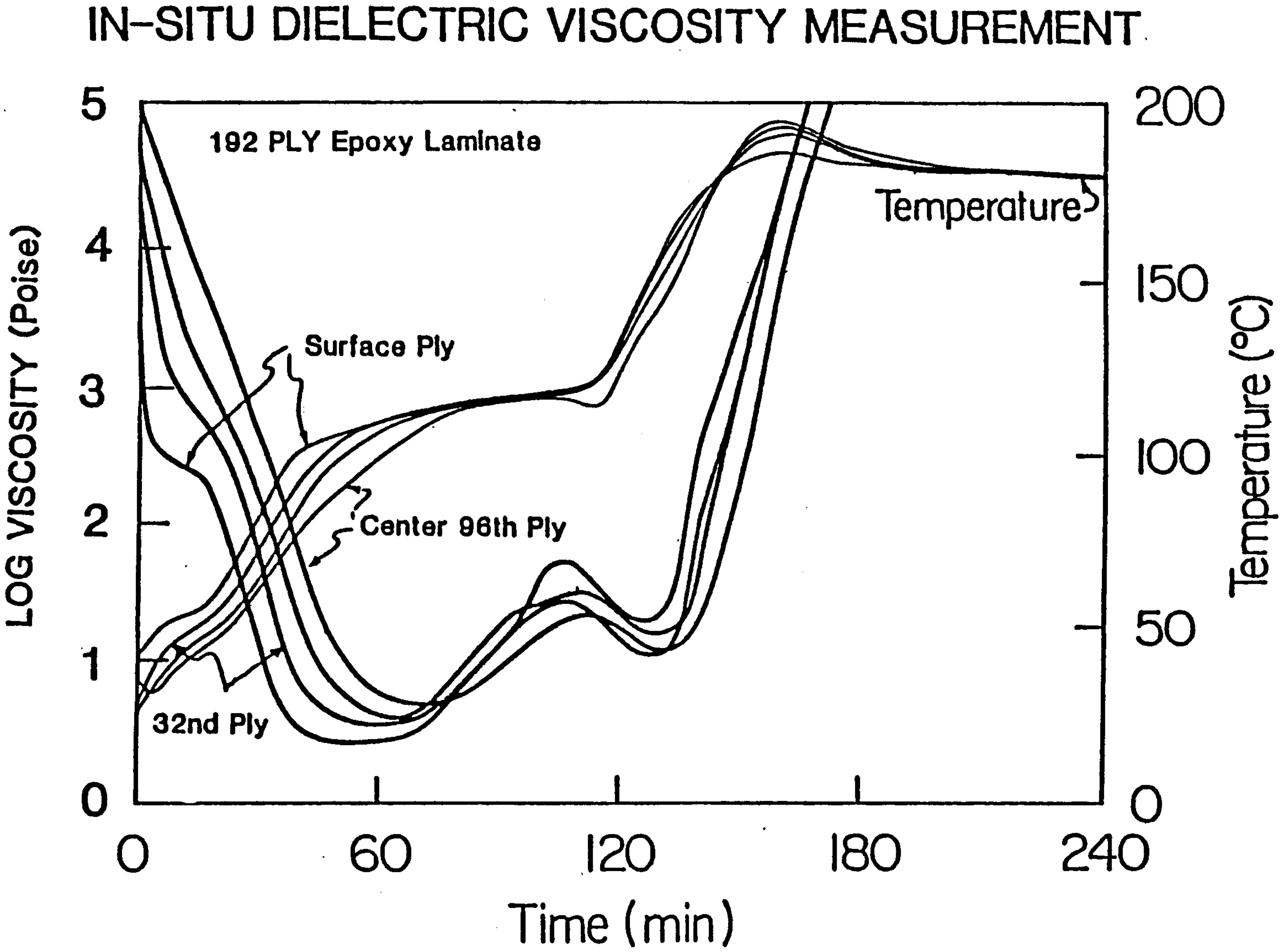

IN-SITU DIELECTRIC VISCOSITY MEASUREMENT
192 PLY Epoxy Laminate
Surface Ply
Center 96th Ply
32nd Ply
Temperature
LOG VISCOSITY (Poise)
0
1
2
3
4
5
Temperature (°C)
0
50
100
150
200
0
60
120
180
240
Time (min)

Figure 29(d).

15 YEAR FLIGHT SERVICE SUMMARY OF B-737 GRAPHITE/EPOXY SPOILERS

H. Benson Dexter
Applied Materials Branch
Ext. 43094 May 1988
RTOP 505-63-01

Research Objective: To establish confidence in the long-term durability of advanced composites through flight service evaluation of composite components on transport aircraft. Develop a data base to encourage aircraft manufacturers to commit to production of composite aircraft structures.

Approach: In 1973 the NASA Langley Materials Division initiated a series of composite flight service programs with aircraft manufacturers and airline operators. Since then 350 composite components have accumulated 4.5 million flight hours. The largest program involves 111 B-737 spoilers with graphite/epoxy skins bonded to aluminum substructure. Three graphite/epoxy material systems were used to fabricate the spoiler skins. Five airlines are currently participating in the world-wide service evaluation: (1) Piedmont, (2) Frontier, (3) Air New Zealand, (4) Lufthansa, and (5) VASP (Brazil). The total fleet has accumulated 2.5 million flight hours, and the high-time aircraft has accumulated 40,000 flight hours during 15 years of flight service.

A total of 34 spoilers have been removed from service and tested, and the residual strength results are presented in the first figure. The residual strength of most spoilers falls near or within the strength scatterband for the baseline spoilers. However, spoilers with significant corrosion damage indicated a 35 percent strength reduction after 7 and 8 years, respectively. The second figure shows a typical corrosion progression scenario. In Phase 1, moisture intrudes cracked paint and initiates corrosion. In Phase 2, the corrosion damage penetrates under the graphite/epoxy skin and, in Phase 3, skin-to-spar delamination occurs. It takes about 2 years for the corrosion to progress from Phase 1 to Phase 3. Design changes and improved sealing methods could prevent corrosion damage in composite-metal interfaces. The third figure shows a corrosion-free spoiler after 12 years of flight service.

Significance: The results of this program indicate that composite materials have good long-term durability in commercial transport operating environments. Aircraft manufacturers have started to make production commitments to composite structures for transport aircraft.

Future Plans: Conduct residual strength tests on graphite/epoxy spoilers with 15 years of service and complete contract with Boeing Commercial Airplane Company in FY 1989. Continue to monitor the service experience with secondary and medium primary graphite/epoxy components developed under the NASA Aircraft Energy Efficiency Program.

Figure 30(a).

RESIDUAL STRENGTH OF B-737 GRAPHITE/EPOXY SPOILERS

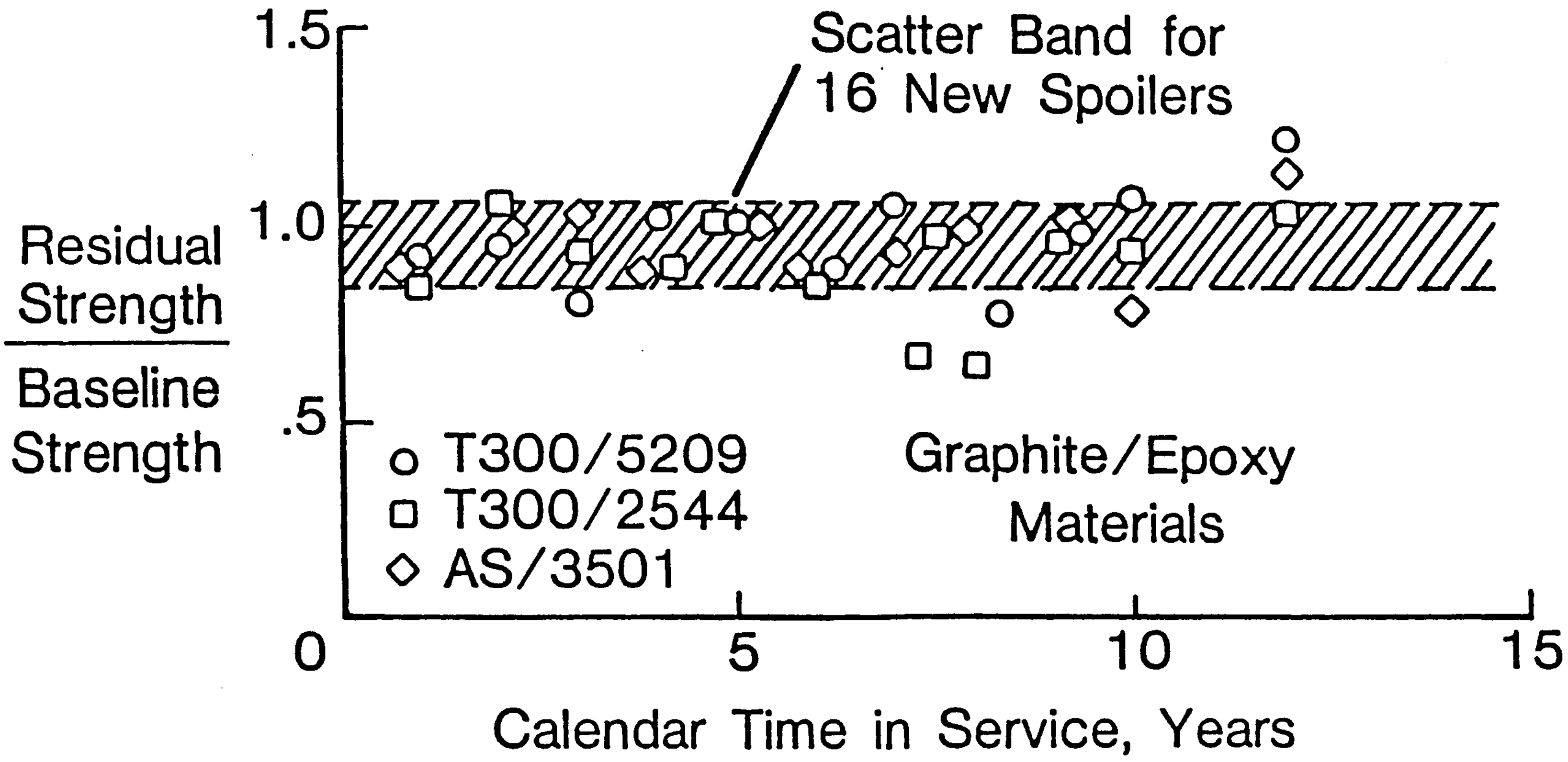


Figure 30(b).

CORROSION OF BOEING 737 GRAPHITE/EPOXY SPOILERS

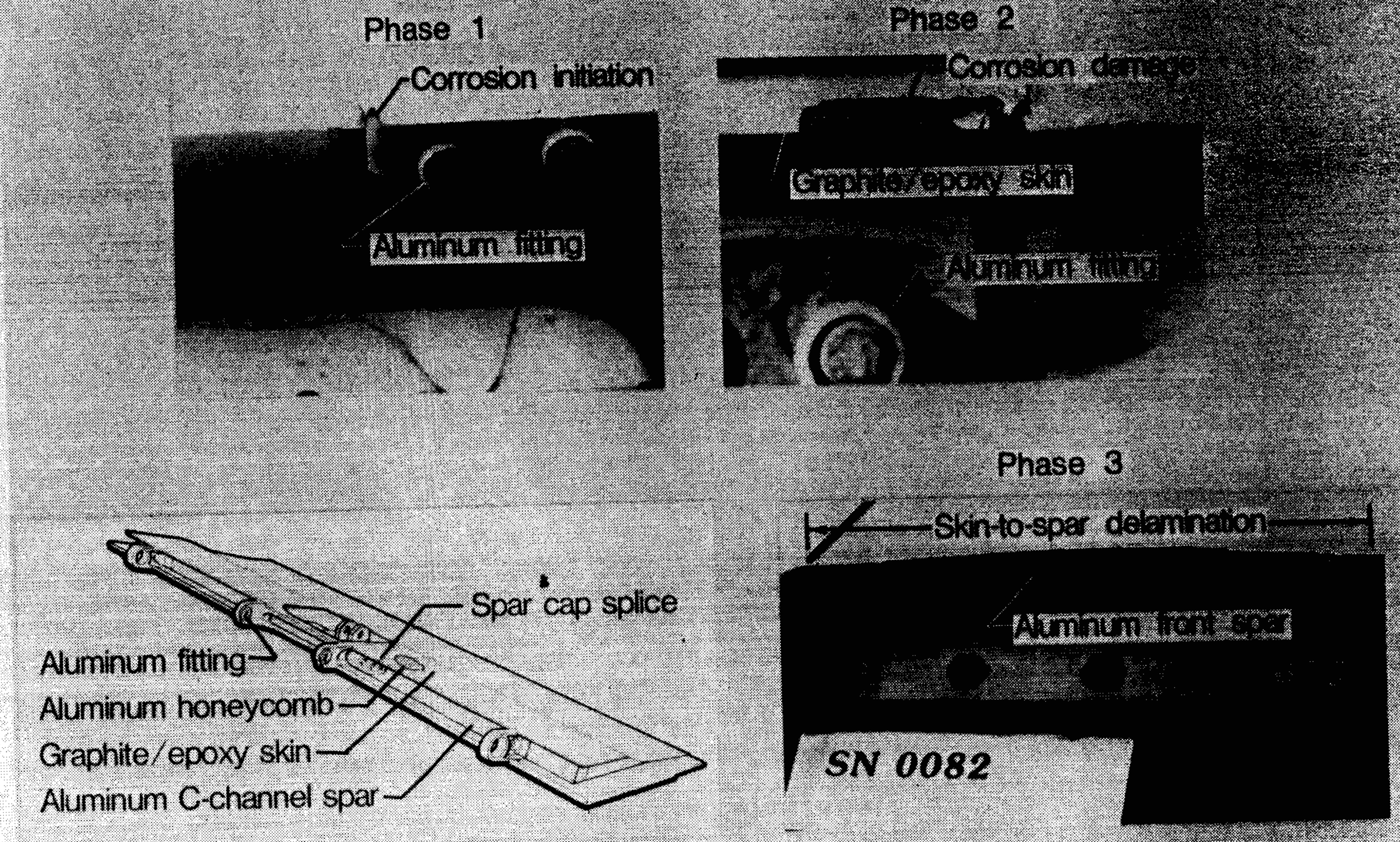


Figure 30(c).

BOEING 737 GRAPHITE/EPOXY SPOILER

WITH 12 YEARS SERVICE

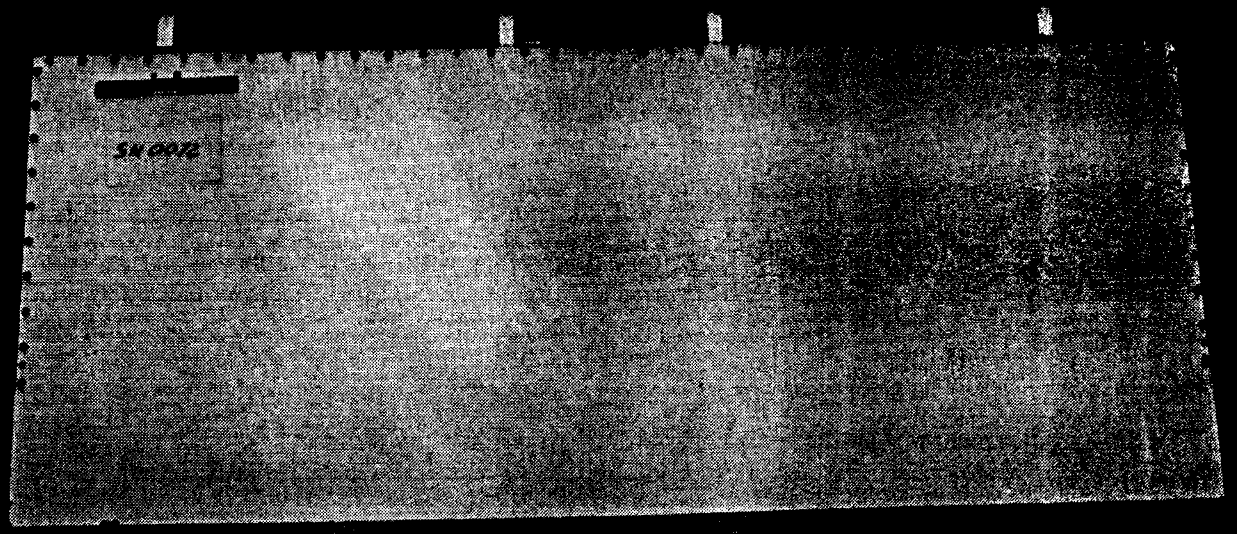
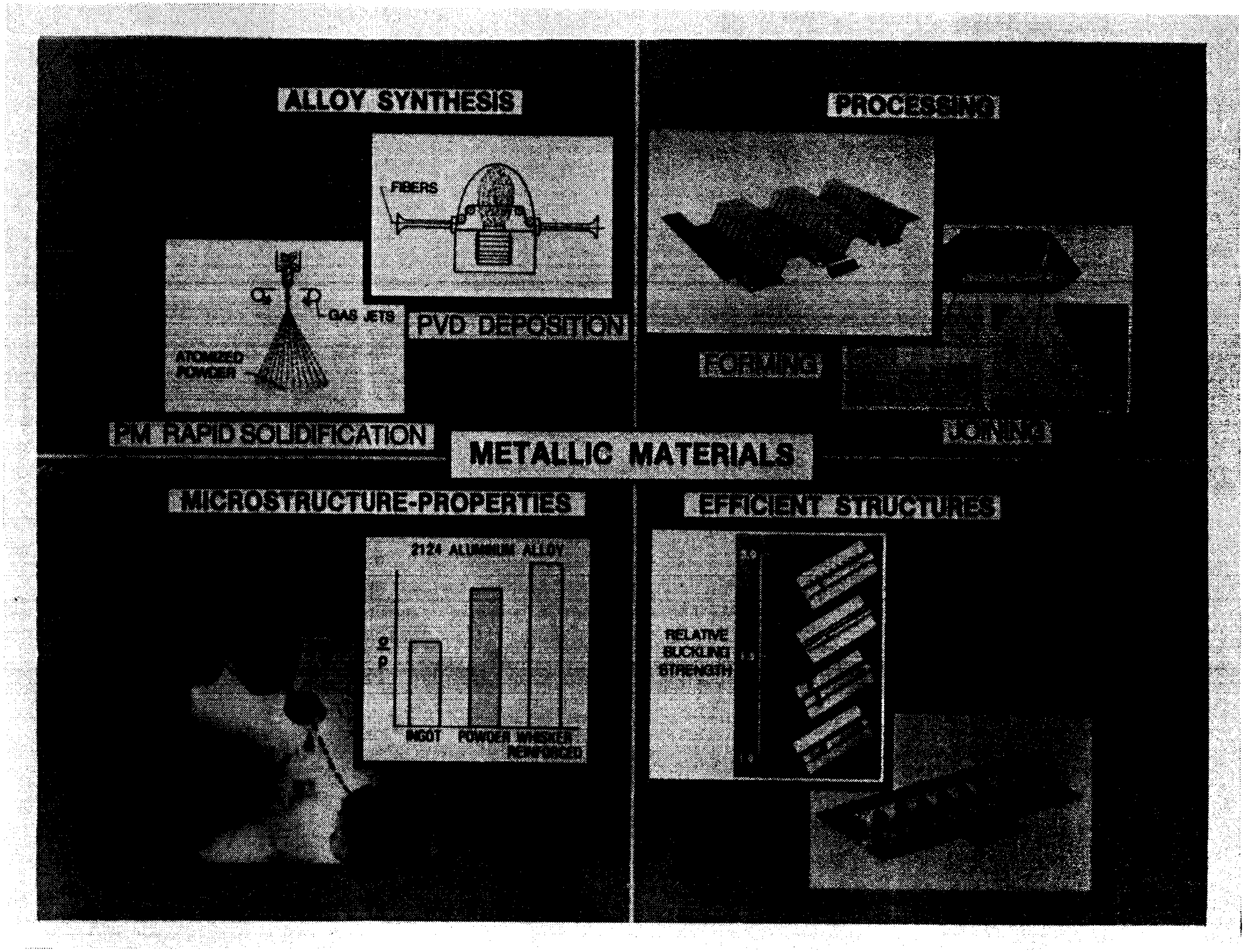


Figure 30(d).



METALLIC MATERIALS

ALLOY SYNTHESIS

PVD DEPOSITION

PM RAPID SOLIDIFICATION

PROCESSING

FORMING

JOINING

MICROSTRUCTURE-PROPERTIES

EFFICIENT STRUCTURES

Figure 31.

METALLIC MATERIALS BRANCH
FIVE YEAR PLAN

MAJOR THRUST	FY88	FY89	FY90	FY91	FY92	EXPECTED RESULTS
Advanced light alloy and MMC development	PM aluminum alloys for high temp airframe and cryotanks					Improved metallics for transcentury and high speed transport aircraft and cryogenic tanks
	Aluminum lithium alloy technology					
	Development & characterization of aluminum matrix composites					
	Secondary and thermomech. processing effects on metallurgical structure & mechanical properties of light alloys and MMC					
Innovative metals processing	Aluminum alloy modifications for enhanced superplasticity & diffusion bonding studies					Processing and joining methods for lighter weight, lower cost aerospace structures
	Suppression and control of cavitation and determination of SPF parameters for Al alloys					
High temperature thin gage metals and MMC for airframe applications	SPF/Al and Ti alloy material/structural integration studies					Higher specific strength and stiffness materials for hypersonic vehicle airframes
	High temperature brazing/diffusion bonding studies of foil gage Ti and AMMC					
	Synthesis and characterization of thin gage high temperature metal matrix composites					
	Properties and stability of intermetallic alloy substrates by deposition					

Figure 32.

REINFORCED, WELDABLE, ALUMINUM-LITHIUM ALLOYS DEMONSTRATED

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Ext. 43136 June 1988
RTOP 505-63-01
Code RM WBS 52-3

Research Objective: To develop reinforced, weldable, aluminum-lithium alloys with improved properties for cryogenic tank applications.

Approach: Synthesize and characterize ingot metallurgy aluminum-lithium alloys with chemistries and microstructures tailored for improved weldability and for specific cryotank applications. Fabricate and evaluate composites made by XD^{TM} processing techniques using the most promising alloys.

Accomplishment: The Martin Marietta Weldalite^{TM} alloy is the first American aluminum-lithium alloy designed to be weldable, and preliminary data show weldment strengths up to 60% greater than 2219 alloy which is commonly used for cryogenic tank applications. XD^{TM} refers to a Martin Marietta developed process in which one or more reinforcing dispersoids are formed directly within the matrix metal. The result is an ultra fine dispersion of high-modulus, high strength compounds that are extremely stable in a metal and hence can allow the metal to be heat treated, remelted or welded without serious degradation of properties. One reinforced and three non-reinforced aluminum alloys were fabricated with various lithium levels. The figure shows that both the reinforced and the unreinforced materials with lower lithium levels in the T8 (stretched 3% and slightly underaged) condition had exceptionally good room temperature strengths. The fact that the reinforced alloy has comparable strengths and usable ductility at room temperature is important because of the potential for superior high temperature properties and equivalent weldability.

Significance: The development of weldable, low density materials, that have high specific properties and can be used over a wide range of operating conditions, will lead to significant weight reduction and hence bigger payloads and improved mission performance for advanced launch systems.

Future Plans: Determine effects of processing parameters and dispersoid size and volume fraction on composite behavior from liquid nitrogen temperatures to 600°F. Define welding practice for XD^{TM} reinforced aluminum-lithium alloys.

Figure 33(a).

ROOM TEMPERATURE TENSILE PROPERTIES OF WELDABLE ALUMINUM-LITHIUM ALLOYS

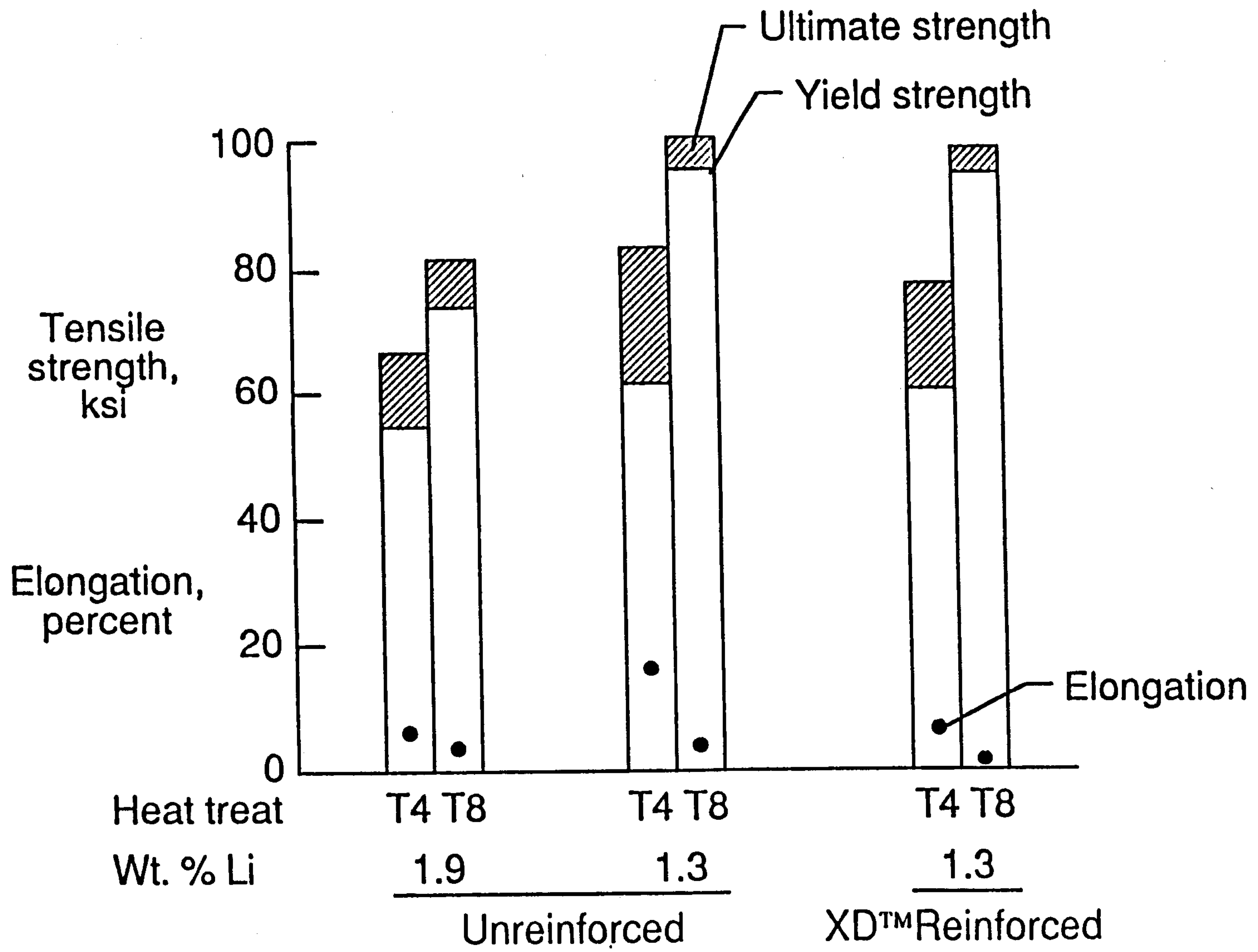

Figure 33(b).

STRESS CORROSION RESISTANCE OF PM 7091 DETERMINED WITH THE BREAKING LOAD TEST METHOD

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Ext. 43126 August 1988
RTOP 505-63-01
Code RM WBS 52-3

Research Objective: To characterize the stress corrosion cracking (SCC) resistance of powder metallurgy alloy 7091 and assess the applicability of the breaking load test method for evaluation of emerging advanced aluminum alloys.

Approach: Conduct breaking load stress corrosion tests for PM 7091 extrusions in two overaged conditions (T7E69 and T7E70). Perform statistical analyses associated with the test method to determine the threshold stress level for each condition.

Accomplishment: The breaking load test method, which was developed under an LaRC research contract with Alcoa Laboratories, is an improved accelerated technique for assessing the stress corrosion cracking resistance of aluminum alloys. The method provides more information with fewer specimens and shorter exposure times than conventional tests, and is more sensitive to small performance differences among resistant materials. Test results provide a quantitative estimate of SCC resistance which can be statistically evaluated to determine probabilities of survival, 99 percent survival stresses, and threshold stress levels for SCC. The first figure shows that both conditions of 7091 are very resistant to stress corrosion, with no effect of exposure stress level observed for the T7E70 material, and a small additional reduction in breaking stress occurring for the T7E69 material only after exposure at 90% of the material yield strength. This difference in performance between these two very resistant conditions of 7091 would not have been detected during conventional SCC testing. The second figure presents threshold stress levels determined by statistical analysis of the breaking stress data for PM 7091, compared with handbook data for IM 7075 in both the T651 and T73 conditions. The combination of material properties and stress corrosion threshold attained with 7091 in both T7E69 and T7E70 conditions is superior to that which has been achieved with 7075-T73.

Significance: Powder metallurgy 7091 provides a superior combination of mechanical properties and SCC resistance than is available with similar IM materials. The breaking load test method provides rapid, quantitative assessment of SCC performance of advanced aluminum alloys, which will lead to more accurate ranking of these materials, allowing for more efficient design of critical aerospace components.

Future Plans: Evaluate application of the breaking load test method to alternate specimen configurations for short transverse testing of thinner product forms. Determine stress corrosion performance of emerging aluminum-lithium alloys.

Figure 34(a).

BREAKING LOAD RESULTS FOR PM 7091 TRANSVERSE ORIENTATION SPECIMENS

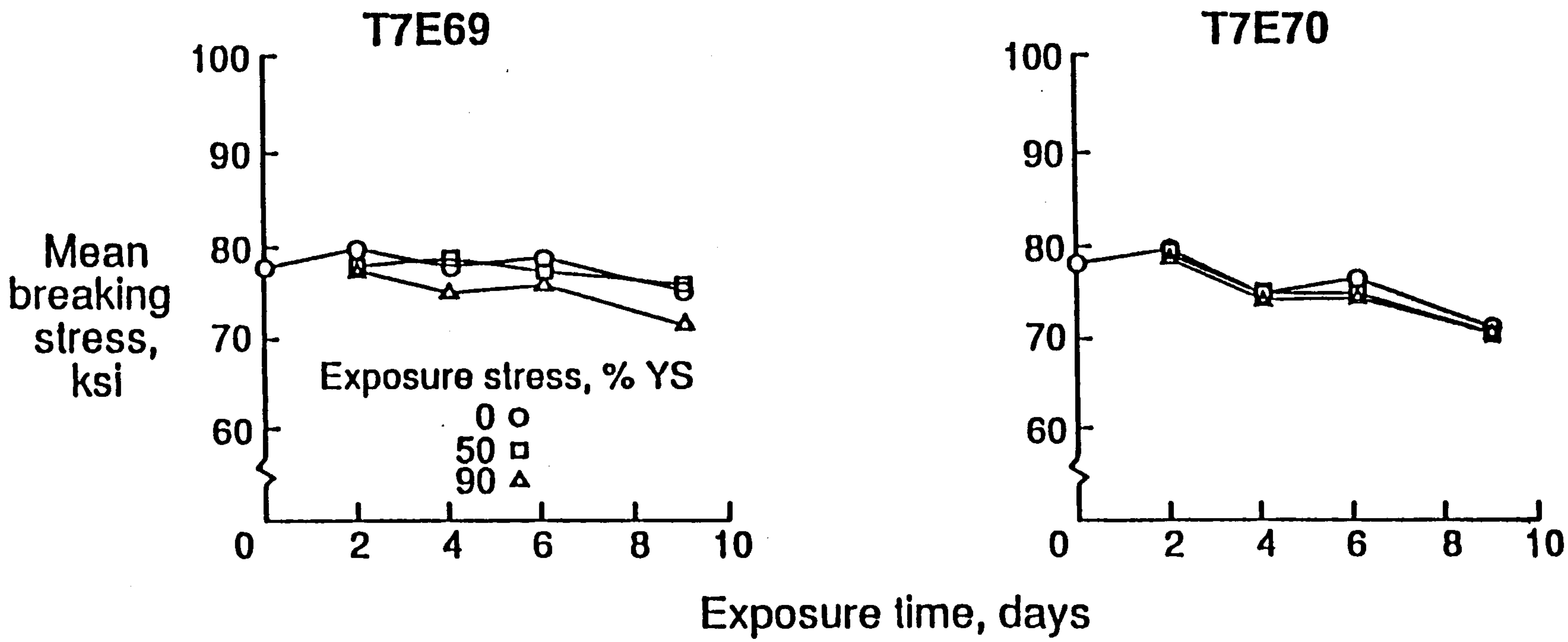

Figure 34(b).

THRESHOLD STRESSES FOR PM AND IM ALLOYS

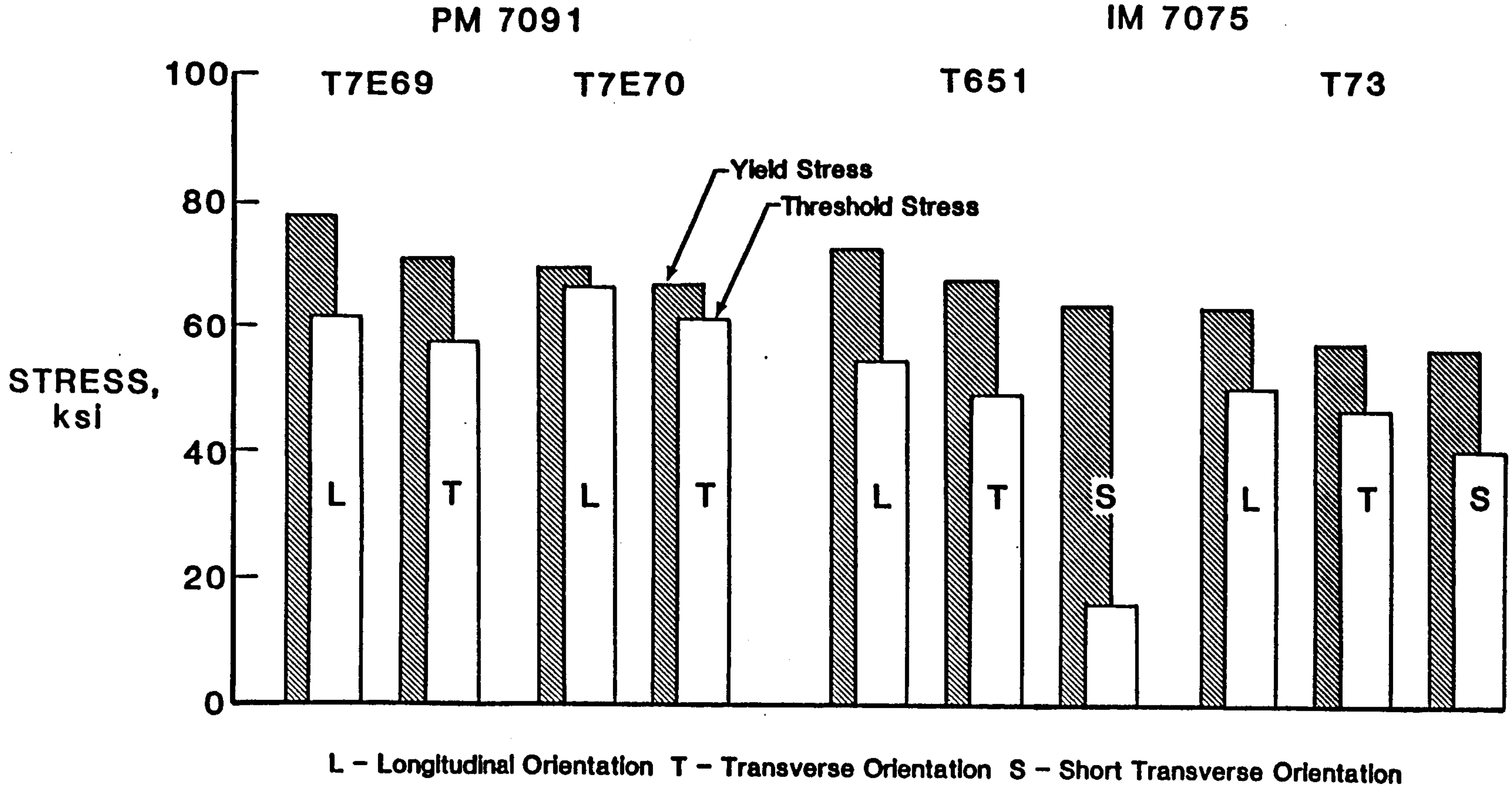

Figure 34(c).

CHARACTERIZATION OF SUPERPLASTICALLY FORMED ALUMINUM FOR STRUCTURAL APPLICATIONS

William F. James
PRC Kentron
Ext. 43140 November 1987
RTOP 505-63-01

Research Objective: To investigate the effects of superplastic forming on mechanical properties of advanced aluminum alloys processed for optimum superplastic forming behavior for use in aerospace vehicle structures.

Approach: Conduct an experimental test program to evaluate the effects of superplastic forming elongation and the resulting internal porosity or cavitation on the mechanical properties of new and emerging aluminum alloys processed specifically to produce recrystallized, equiaxed, fine-grained material. Using a unique in-house superplastic straining facility, sheets of fine-grained, specifically processed 7475 aluminum alloy were heated to 960°F and formed at a strain rate of 0.0002 per second to elongation levels of 115, 250, and 325 percent. Tensile and fatigue specimens were machined from the strained sheet and heat treated to a T6 condition.

Accomplishment: The superplastic straining resulted in cavitation levels varying from 0 to 10 percent by volume based on microstructural evaluation. The figure compares the fatigue properties of as-received and superplastically strained 7475-T6 with conventional Alclad 7475-T61 aluminum alloy sheet. The improved fatigue properties of the specially processed 7475 material were attributed to the 10-15 µm grain size. Material strained 115 percent had a fatigue limit which was 11 ksi lower than the as-received material but still above the fatigue limit of conventional Alclad 7475-T61 aluminum alloy. Material subjected to superplastic forming strains greater than 115 percent resulted in significant decreases in fatigue life as well as tensile properties.

Significance: Results of the experimental test program indicate the need to reduce cavitation for superplastic forming strains if this material is to be used in structural applications. Cavitation reducing processes such as post forming pressure or back pressure may be required for highly strained parts. Superplastic forming will result in the ability to make difficult-to-form parts with weight and cost savings.

Future Plans: Additional alloys will be evaluated including aluminum lithium alloys and titanium aluminides. The work will also include strain rate sensitivity testing to evaluate the optimum superplastic forming parameters.

Figure 35(a).

EFFECT OF SUPERPLASTIC ELONGATION ON FATIGUE PROPERTIES OF 7475 ALUMINUM

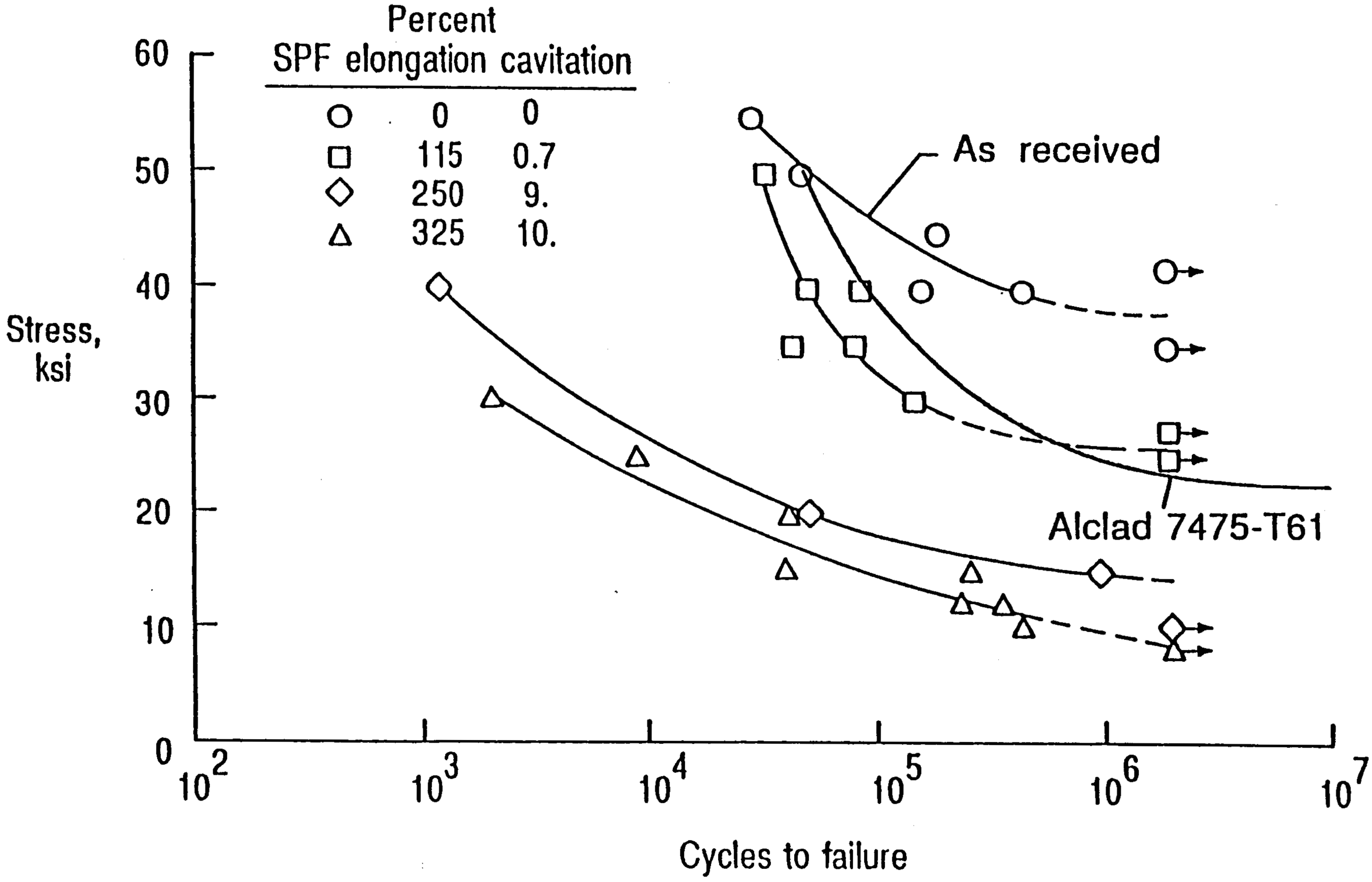

Figure 35(b).

LaRC FACILITY PRODUCES ALUMINUM ALLOY SHEET FROM POWDER

Dick M. Royster and O. R. Singleton
Metallic Materials Branch
Ext. 43135 April 1988
RTOP 505-63-01

Research Objective: To develop advanced aluminum alloys with improved strength and toughness properties for high temperature applications on high-speed civil transports.

Approach: Produce in-house research quantities of rapidly solidified, zirconium-bearing, P/M, Al-alloy sheet using small, consolidated billets prepared from powder supplied to LaRC by subcontract from Aluminum Company of America in conjunction with NASA contract NAS1-16048. Compare the material properties of LaRC laboratory produced sheet to those obtained from sheet produced from larger, pilot scale billets.

Accomplishment: Over 30 heat treated, P/M, 2XXX + Zr aluminum alloy sheets have been produced at Langley from vacuum-hot-consolidated, forged, and hot-rolled billets. Good agreement between LaRC laboratory and pilot scale produced microstructures and bidirectional tensile properties was obtained. The normalized tear strength/yield strength ratio was also in near agreement, as is shown in the attached figure. However, the unit crack propagation energy toughness measurement was lower for the laboratory produced sheet than for the pilot scale produced sheet. This study demonstrates that sheet material produced on a small laboratory scale can be utilized for advanced alloy synthesis. Results from LaRC P/M aluminum alloy evaluations will be used in guiding the continuing, contract, pilot-scale study.

Significance: A small in-house research facility will permit inexpensive and fast screening of innovative rapid solidification powder metallurgy aluminum alloy compositions. Rapid solidification appears to offer the most practical means to develop aluminum materials for use at temperatures of 600°F and above. Such aluminum alloys are not only lighter, but also potentially less expensive, than competing titanium alloys.

Future Plans: After completion of the material property sheet validation program, the methodology and equipment will be used to fabricate innovative P/M aluminum alloy sheet containing silicide additions. These aluminum alloys with potential for use at 600°F and above have densities under 2.9 g/cc. The research aluminum alloy powder has been purchased to specification through commercial suppliers and the first sheets fabricated.

Figure 36(a).

TOUGHNESS OF LABORATORY AND PILOT PROCESSED P/M ALUMINUM ALLOY SHEET

P/M 2xxx + Zr, - T8X temper sheet

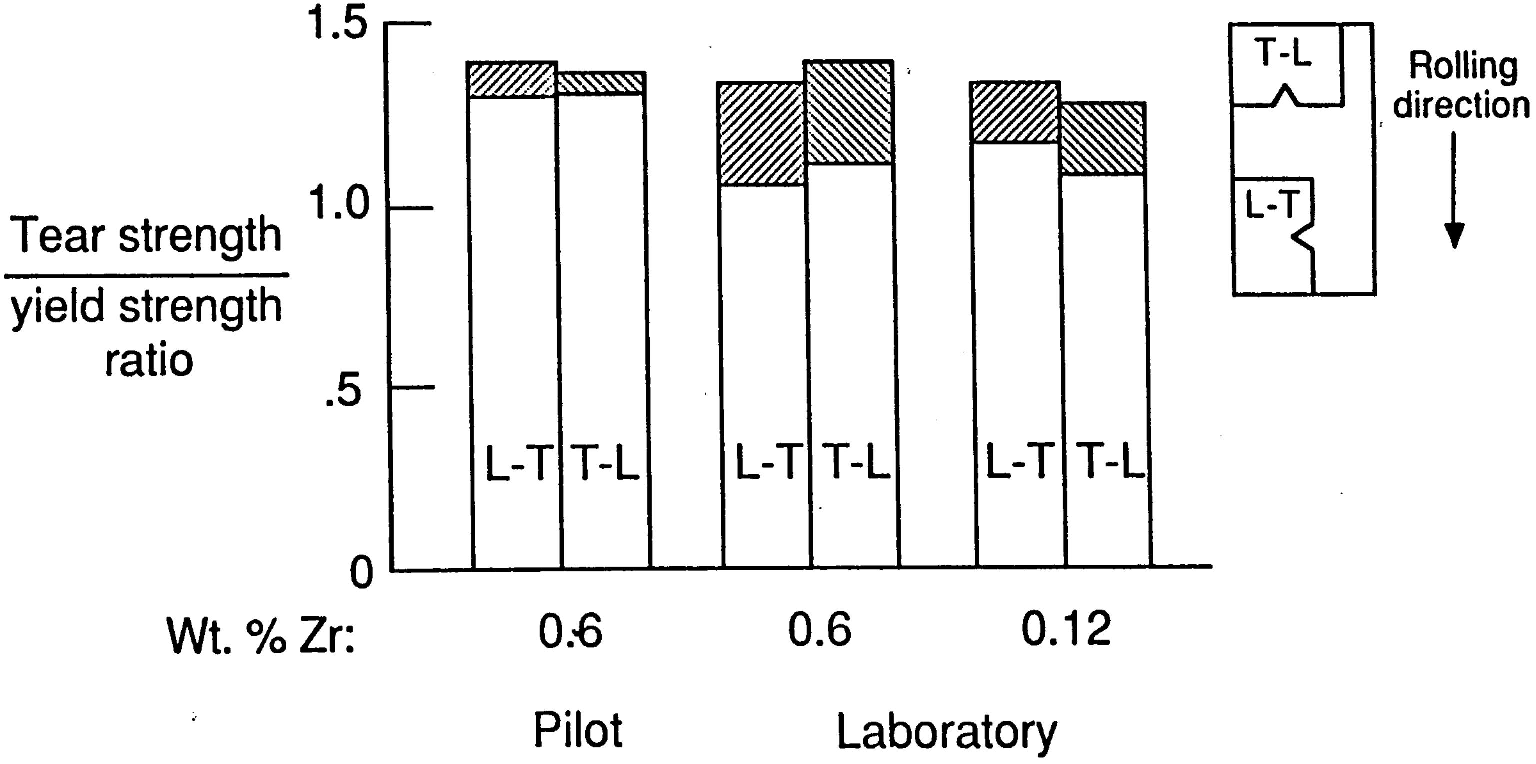

Figure 36(b).

CHARACTERIZATION OF STRUCTURAL METALLICS WITH HIGH STRENGTH AND TOUGHNESS FOR CRYOGENIC APPLICATIONS

R. Keith Bird
Metallic Materials Branch
Ext. 43512 January 1988
RTOP 505-63-01

Research Objective: To investigate advanced structural metallics for cryogenic applications and develop unique processing techniques to optimize property combinations.

Approach: Conduct a comprehensive experimental test program to evaluate the effect of temperature, composition, product form and metallurgical condition on new candidate materials. Develop tailored properties through thermomechanical processing techniques.

Accomplishment: Components of several cryogenic model systems which require a high combination of strength and toughness are being fabricated from 18Ni 200 grade maraging steel (VascoMax 200). Using materials at high stress levels and cryogenic temperatures requires that the fatigue behavior be well characterized to insure model integrity. In a current investigation at LaRC, the mechanical behavior of 18Ni steel has been characterized at room and cryogenic temperatures wih fatigue, tensile and toughness testing. The figures show the fatigue behavior of 18Ni steel at room temperature and -275°F. Both a conventional metallurgical treatment process and a grain refinement process in which grain size is significantly decreased were used to heat treat fatigue specimens in this study. A three-point bend test specimen configuration was used to better simulate the stresses associated with expected wing loading of a cryogenic wind tunnel model. The results indicate that at room temperature smooth mechanically polished specimens in the grain refined condition exhibited a higher fatigue resistance than specimens in the conventionally treated condition. At -275°F, however, the fatigue resistance of electric discharge machined specimens in the grain refined condition was lower than that of specimens in the conventionally treated condition. In other tests conducted for this study, the fatigue resistance at both room temperature and at -275°F was not affected by surface roughness. Thus, the trend reversal shown in the figures is most likely due to interactions between grain size and temperature.

Significance: Results of this experimental test program provide quantitative design information which should minimize the possibility of model failure during cryogenic testing.

Future Plans: Use laboratory and metallurgical experimentation to determine the cause of the trend reversal of the data presented in the figures. Also, investigate the cryogenic behavior of Fe-12Ni steel for application in model systems for the National Transonic Facility.

Figure 37(a).

FATIGUE BEHAVIOR OF 18 Ni 200 GRADE MARAGING STEEL

Microstructural effects at room temperature

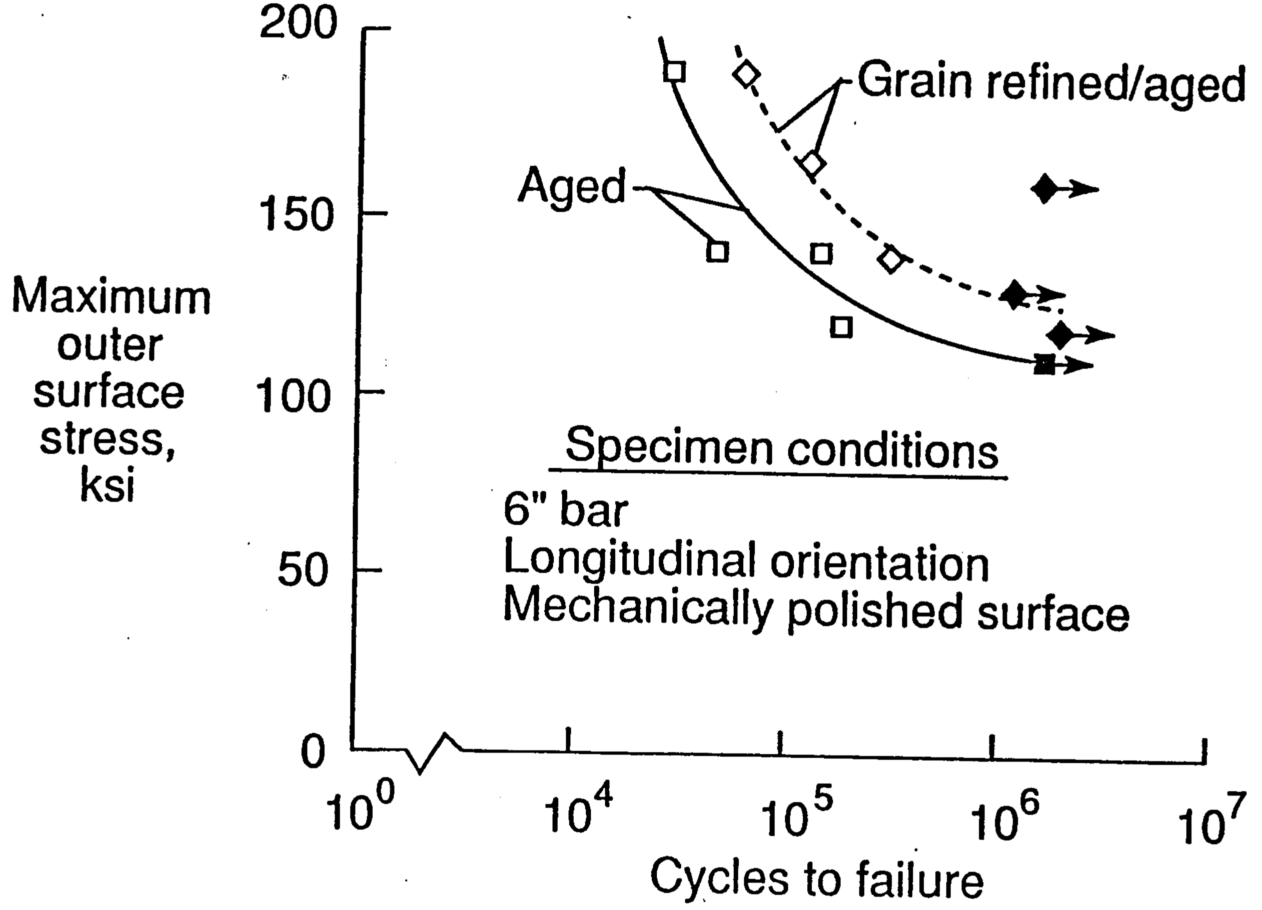

Figure 37(b).

FATIGUE BEHAVIOR OF 18 Ni 200 GRADE MARAGING STEEL

Microstructural effects at -275° F

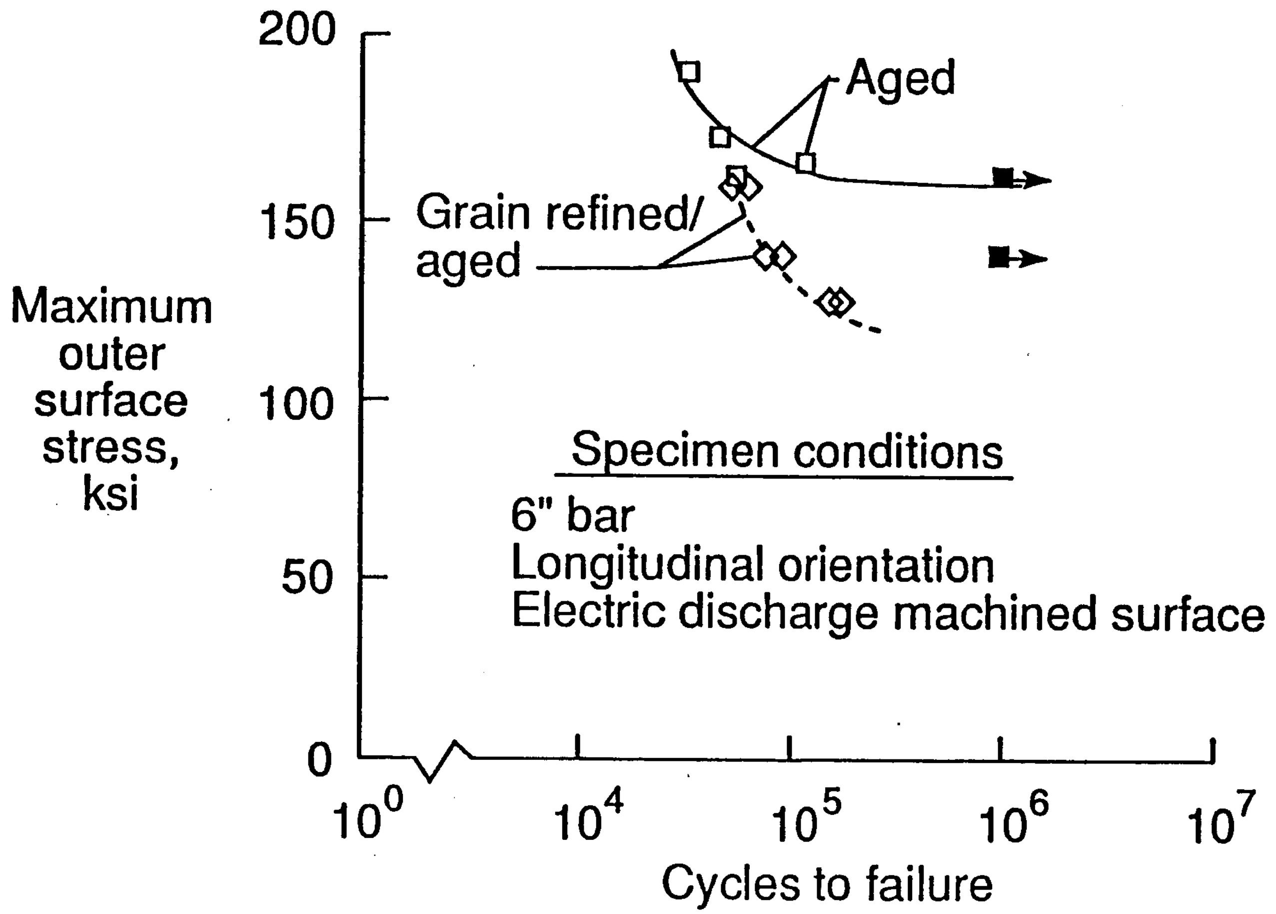

Figure 37(c).

POLYMERIC MATERIALS BRANCH

FY 89 PLANS

- Synthesis of improved polymers
    - New polyimides and poly(arylene ether ketones)
    - Thermoplastics and thermosets from reactive oligomers
    - Amorphous and semi-crystalline polyimide blends and IPNs
    - Initiate work on space stable, low CTE polymers
- Expand composite work
    - Resin and prepreg scale-up
    - Improve prepreg quality (powder and slurry coating)
    - Optimize composite fabrication processes
    - More comprehensive composite evaluation
- Structure/property relationships
    - Polymer synthesis (CTE, modulus, crystallinity)
    - Composite constituent relationships
    - Low-cost, nontoxic adhesives
    - Films

Figure 38.

MECHANICS OF MATERIALS

FY 89 PLANS

- Composite micromechanics to focus on damage initiation and propagation under local stress states
- Develop mechanics models treating materials as inelastic, nonisotropic, and nonhomogeneous
- Develop fracture mechanics methodology for crack growth under mixed-mode loadings
- Address mechanics of materials issues relevant to elevated temperature structural integrity

Figure 39.

APPLIED MATERIALS BRANCH

FY 89 PLANS

- Space materials
  - Verify durability of space station composite tubes and TC coatings
  - Initiate simultaneous thermal cycling/irradiation studies
  - Develop low expansion resins and composite concepts for PSR
- Carbon-carbon composites
  - Initiate development of oxidation protection system tailored for NASP environment
  - Develop field-applied sealant concepts for refurbishment/repair of Carbon-carbon coatings
  - Explore interface modifications for improved interlaminar properties
- Composites for aircraft/rotorcraft
  - Develop and evaluate damage tolerant composite materials
    - Multidirectional weaving technology
    - Stitched/braided/knitted material forms
  - Modeling and semi-automatic process control of resin transfer molding

Figure 40.

METALLIC MATERIALS BRANCH

FY 89 PLANS

- Advanced aluminum alloy technology
    - Alloy development for expendable cryogenic tanks (2090+In, Weldalite)
    - High temperature aluminum for reusable tank structures (dispersion strengthened, XD Weldalite)
- Innovative metals processing
    - Superplastic forming of conventional high strength and Al-Li alloys for expendable cryotanks
    - Joining of skin-stiffener structures for expendable cryotanks (resistance welding)
- High temperature thin gage materials for hypersonics
    - AMMC for NASP
    - Enhanced diffusion bonding of Ti_xAl MMC for NASP
    - Light alloy matrix composites for hypersonics

Figure 41.

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16. Abstract

The research program of the Materials Division is presented as FY 88 accomplishments and FY 89 plans. The accomplishments for each Branch are highlighted and plans are outlined. Publications of the Division are included by Branch. This material will be useful in program coordination with other government organizations, universities, and industry in areas of mutual interest.

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