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PILOT LINE DEVELOPMENT OF HIGH-PERFORMANCE THERMAL INSULATION

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BY

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SEPTEMBER 1989
FINAL REPORT
SEPTEMBER 1987 - FEBRUARY 1989

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Prepared for

UNITED STATES ARMY NATICK
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REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b. RESTRICTIVE MARKINGS None		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Distribution authorized to U.S. Government agencies only; Test and Evaluation, June 1989. Other requests for this (over)		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S)			5. MONITORING ORGANIZATION REPORT NUMBER(S) NATICK/TR-89/041L		
6a. NAME OF PERFORMING ORGANIZATION Albany International Research Co.		6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION U. S. Army Natick R, D & E Center		
6c. ADDRESS (City, State, and ZIP Code) 777 West St. Mansfield, MA 02048-9114			7b. ADDRESS (City, State, and ZIP Code) Kansas Street Natick, MA 01760-5000		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION		8b. OFFICE SYMBOL (If applicable) STRNC-ITFR	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Contract No. DAAK60-87-C-0061		
8c. ADDRESS (City, State, and ZIP Code)			10. SOURCE OF FUNDING NUMBERS		
			PROGRAM ELEMENT NO. 62723	PROJECT NO. AH98	TASK NO.
11. TITLE (Include Security Classification) Pilot Line Development of High-Performance Thermal Insulation (U)					
12. PERSONAL AUTHOR(S) James G. Donovan					
13a. TYPE OF REPORT Final Report		13b. TIME COVERED FROM Sept 87 to Feb 89		14. DATE OF REPORT (Year, Month, Day) 1989 September	
15. PAGE COUNT 75					
16. SUPPLEMENTARY NOTATION					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	synthetic insulation, spread continuous-filament tow, waterfowl down, fiber opening, bonded staple-fiber batt, thermal conductivity. (YES) ←		
19. ABSTRACT (Continue on reverse if necessary and identify by block number) A synthetic alternative to waterfowl down for use as an insulator in military clothing and sleeping bags was developed by Albany International Research Co. under a previous contract with U.S. Army Natick R, D and E Center. The objective of the subject contract has been to demonstrate that two distinctly different forms of the previously developed alternative insulator can be manufactured. These forms are: (1) a bonded staple-fiber batt and (2) .. batt of spread continuous-filament tow. Manufacturing processes have been developed and/or adapted to permit the continuous production of high performance, synthetic alternatives to down in each of these two forms and 100 square yards of each have been delivered to the Natick Center. A series of laboratory measurements have been made to assess the performance of each insulator form. The data obtained show that the bonded staple-fiber batt is equivalent to waterfowl down in terms of insulating efficiency and is superior to down on the basis of wetting resistance. The spread, continuous-filament tow configuration is a somewhat less efficient insulator but it does offer significant advantages in certain end-uses.					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input type="checkbox"/> UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED		
22a. NAME OF RESPONSIBLE INDIVIDUAL Deirdre Rapacz/Stephen Fossey			22b. TELEPHONE (Include Area Code) (508)651-4273		22c. OFFICE SYMBOL STRNC-ITFR

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PREFACE

This report was prepared by Albany International Research Co. under U.S. Government Contract No. DAAK60-87-C-0061. The study reported was made between September 1987 and February 1989. Ms. Rita M. Schnair of the Natick Center Procurement Office was the Contracting Officer. The Project Officer (the Government's technical representative) at the outset of the program was Mr. Stephen A. Fossey and in October, 1988 Ms. Peggy Goode replaced Mr. Fossey in that capacity. Ms. Deirdre T. Rapacz of the Natick Center staff provided technical assistance throughout the program.

Several Albany International Research Co. staff members shared responsibility for and contributed to the success of the study, as follows: Ms. Zivile M. Groh was responsible for all laboratory evaluations and assisted in many of the processing trials, Mr. James G. Donovan was the Program Manager and supervised the day-to-day activities of the program and Dr. John Skelton held overall administrative responsibility for the contract and frequently advised on technical matters. Messrs. John K. Gschwind, Carl V. Leunig and Alan L. Billings of Albany International Corp., Albany, New York, were largely responsible for development of the bonded, fine (small diameter) staple-fiber batt pilot-line and they were assisted in this effort by Ms. Groh and Mr. Donovan of Albany International Research Co. (AI).

Development of a process for making insulating batt from fine (small filament diameter), spread, continuous-filament tow was the result of cooperation from several companies in addition to Albany International Research Co. They were: Northern Feather Co. of Elizabeth, New Jersey, Hoechst Celanese Corp. of Charlotte, North Carolina and Reliance Products Co. of Oakland, California. Messrs. Arne Lind-Hansen and Joachim Jacinto of Northern Feather contributed their time and equipment for the initial spreading trials; Messrs. Robert B. Averell and H. M. Nguyen and Ms. Alice W. White and Ms. Beth Levy of Hoechst Celanese contributed their tow making and tow spreading expertise; and Messrs. Stanley Greitzer and Walt Davis of Reliance Products were generous with their time and equipment during the final tow spreading trials.

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TABLE OF CONTENTS

I.	INTRODUCTION	1
II.	DEVELOPMENT OF A MANUFACTURING PROCESS FOR A HIGH PERFORMANCE INSULATOR OF BONDED STAPLE-FIBER BATT	5
	A. Introduction and Summary	5
	B. Configuration of the Bonded Staple-Fiber Insulator	6
	C. Assembly of the Pilot Production Line and Initial Trials	8
	D. Pilot Production of Bonded Staple-Fiber Insulating Batt	12
III.	DEVELOPMENT OF A MANUFACTURING PROCESS FOR A HIGH PERFORMANCE INSULATOR OF SPREAD CONTINUOUS-FILAMENT TOW	13
	A. Introduction and Summary	13
	B. Trials 1 and 2 at Northern Feather Co.	14
	C. Trial 3 at Reliance Products Co.	26
	D. Trial 4 at Reliance Products Co.	30
IV.	LABORATORY CHARACTERIZATION OF PILOT LINE INSULATOR SAMPLES	35
	A. Performance Goals and Test Methods	35
	B. Laboratory Evaluation	39
V.	SUMMARY OF INSULATOR LABORATORY EVALUATION, OVERALL FUNCTIONALITY AND MANUFACTURING FEASIBILITY	53
	A. Summary of Laboratory Evaluation	53
	B. General Functionality and Manufacturing Feasibility	55
VI.	RECOMMENDATIONS FOR ADVANCEMENT OF BOTH INSULATOR FORMS	59
	LIST OF REFERENCES	61
	BIBLIOGRAPHY	61



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LIST OF FIGURES

- | | | |
|---|---|----|
| 1 | Schematic Diagram of Pilot Line for Production of Bonded Staple-Fiber Batt | 10 |
| 2 | Schematic Diagram of Northern Feather Company's Tow Opening, Spreading and Lapping Line | 17 |

LIST OF TABLES

1	Description of 0.5 Denier/Filament Tow Used in Trial 2 (Northern Feather, Chicago)	16
2	Description of 4 Denier/Filament, Side-by-Side Binder-Fiber Tow Used in Trial 2 (Northern Feather, Chicago)	16
3	Minimum Density, Compressional Strain and Compressional Recovery Data for Insulating Batts Made Entirely from 0.5 Denier/Filament Spread Tow During Trial 2 (Northern Feather, Chicago)	24
4	Work of Compression, Work of Recovery and Resilience Data for Insulating Batts Made Entirely from 0.5 Denier/Filament Spread Tow During Trial 2 (Northern Feather, Chicago)	24
5	Thermal Conductivity of a Lightweight Batt Made Entirely from 0.5 Denier/Filament, Spread, Continuous-Filament Tow During Trial 2 (Northern Feather, Chicago)	25
6	Description of 1.2 Denier/Filament Tow Used in Trial 3 (Reliance Products, Oakland)	27
7	Minimum Density, Compressional Strain and Compressional Recovery Data for Insulating Batts Made Entirely from 1.2 Denier/Filament Spread Tow During Trial 3 (Reliance Products, Oakland)	29
8	Work of Compression, Work of Recovery and Resilience Data for Insulating Batts Made Entirely from 1.2 Denier/Filament Spread Tow During Trial 3 (Reliance Products, Oakland)	29
9	Thermal Conductivity of a Lightweight Batt Made Entirely from 1.2 Denier/Filament, Spread, Continuous-Filament Tow During Trial 3 (Reliance Products, Oakland)	30
10	Description of 1.2 Denier/Filament Tow Used in Trial 4	31
11	Thermal Conductivity of Two Insulator Prototypes	41
12	Compressional Properties of Bonded Staple-Fiber Batt; Individual Test Results Obtained with 0.5 lb/ft ³ Test Density and 2.00 Inch Gauge Length	42
13	Compressional Properties of Batts of Spread Continuous-Filament Tow; Individual Test Results Obtained with 0.5 lb/ft ³ Test Density and 2.00 Inch Gauge Length	43
14	Compressional Properties of Bonded Staple-Fiber Batt; Individual Test Results Obtained with 4 oz/yd ² (nominal) Samples	44
15	Compressional Properties of Batts of Spread Continuous-Filament Tow; Individual Test Results Obtained with 4 oz/yd ² (nominal) Samples	45

LIST OF TABLES (cont)

16	Changes in Two Insulator Prototypes, Sewn in Cover Fabrics, Due to Laundering	47
17	Water Absorptive Capacity of Two Insulator Prototypes After Twenty Minutes of Immersion	49
18	Wet Loft Retention of Two Insulator Prototypes	50
19	Summary of Performance Properties for Two Insulator Prototypes	54

PILOT LINE DEVELOPMENT OF HIGH-PERFORMANCE THERMAL INSULATION

I. INTRODUCTION

A synthetic alternative to waterfowl down for use as an insulator in military clothing and sleeping bags was recently developed by Albany International Research Co., under a previous contract with U.S. Army Natick R, D and E Center^(1,2). Refinement and application of the theories of heat transfer through lightweight fibrous assemblies and laboratory analysis of waterfowl down, commercially available synthetic insulators, and many proposed alternatives led to development of a practical, high performance, down substitute. The fibrous configuration of the down alternative is described in U.S. Patent No. 4,588,635, "Synthetic Down"⁽³⁾. In simple terms, it is an open network of relatively stiff and elastic polyester microfibers (fibers with diameters less than 12 μm) with a proportionately small number of supporting macrofibers uniformly distributed through it.

The objective of the program that is the subject of this report has been to develop commercially viable processes for production of two variants of the general insulator form described in the "Synthetic Down" patent. Although adherence to the precise configuration of the patented insulator was not a strict requirement, the Government's insulator performance goals made utilization of the results of the previous study a very logical, if not inevitable, approach.

At the outset of the program, Natick R, D and E Center technical personnel met with AI Research Co. staff members to discuss and agree upon two specific insulator configurations for which manufacturing processes were to be developed. Specific consideration was given to each of these factors:

1. Insulating efficiency at the low use-density of waterfowl down (approximately 0.5 lb/ft³),
2. Compressional and water repellency characteristics, which greatly influence insulating efficiency under adverse field conditions,

3. Insulator durability, especially after exposure to relatively severe military launderings,
4. Suitability of insulators for "shingle construction," a sleeping bag assembly method that provides overlap between insulating-batt layers and stitch-lines and thus prevents "cold spots."
5. Adaptability of currently available processing methods to manufacture of the new insulating forms.

Awareness of these essential considerations, together with the experience of the previously mentioned contract and other recent Albany International insulator development efforts, led to ready agreement among Natick Center and AI Research staff members regarding the two insulator forms that offered the greatest potential for process development. These were:

1. Bonded staple-fiber batt of the configuration described in Patent No. 4,588,635, "Synthetic Down," and
2. Spread continuous-filament tow configured to utilize as much as possible of that which has been recently learned and documented regarding high performance, high loft insulation.

The process development effort for the bonded staple-fiber batt took place in an Albany International Felt Division plant in Albany, New York. All capital investment costs and nearly all on-site labor costs were borne by Albany International. Contract costs were limited to those incurred by AI Research Co. personnel involved in specific sample production for the Government and in laboratory evaluations made to ensure compliance with the Government's objectives. The pilot production line now in place is capable of continuous production of bonded staple-fiber batt, now trade-named "Primaloft^R," that has performance characteristics that are, with a single exception, equal to or better than those set forth by the Government as targets in the subject contract.

The process employed for the pilot-manufacture of high performance, spread, continuous-filament tow was adapted directly from one that has been successfully used to produce PolarGuard^R insulation for many years. Preliminary experimentation with tow opening and spreading equipment designed and owned by Northern Feather Co. was followed by experimental tow-producing trials at Hoechst Celanese Corp. and finally, two successful opening and spreading trials were made, using the Hoechst Celanese tow, on a modified PolarGuard production line at Reliance Products Co. in Oakland, California. The spread continuous-filament tow insulator samples produced during the second and final trial at Reliance were recently delivered to the Government. They meet most of the contract performance targets and a change in fiber finish appears to be all that is required to produce a wholly satisfactory insulator using the process that is now available.

High loft insulator samples produced by each of the two distinctly different methods employed are now on hand at Natick R, D and E Center in quantities greater than 100 yd² each. We anticipate that samples of this size will make possible thorough laboratory and field analyses and ensure continuation of effort with these high performance insulator configurations.

II. DEVELOPMENT OF A MANUFACTURING PROCESS FOR A HIGH PERFORMANCE INSULATOR OF BONDED STAPLE-FIBER BATT

A. Introduction and Summary

In the interim between the completion of AI Research Co./Natick R, D and E Center Contract No. DAAK60-83-C-0022^(1,2) and the start of the subject contract, internally funded AI Research Co. efforts led to development of a bonded staple-fiber batt insulator. This insulator was similar to the microfiber/macrofiber blends developed under the initial contract, but was a distinct improvement in that some or all of the macrofiber component was binder fiber. The preferred binder fiber was of a bicomponent, side-by-side configuration that contributed structural integrity to the insulator without compromising performance properties. Further work at AI Research during the interim between contracts led to a relationship with Teijin Ltd. of Japan, who developed unique capabilities in the manufacture of both the microfiber (0.5 denier polyester staple) and macrofiber (4 denier polyester/polyester bicomponent binder) elements required to produce the optimal form of the bonded staple insulator.

Developmental work between contracts also led to an understanding of the processing method that would be required to combine the fibrous components, open and orient them properly, and bond them to obtain a cohesive and serviceable insulator. Soon after award of the subject contract, Albany International, using self-funding, began the design of a pilot production line based upon the experience of previous processing experiments. The pilot line was assembled in an Albany International Felt Division plant in Albany, New York and was used for an extensive series of processing experiments that led to several changes in equipment configuration and to a change in fiber finish. These processing experiments all took place during the term of this contract, but without cost to the Government. The results are a high performance, bonded staple-fiber batt insulator and a production method that is commercially viable.

The bonded staple-fiber insulator samples that were recently delivered to the Government were evaluated to confirm compliance with the performance objectives of the contract. The data obtained, which is reported in Section IV, shows that the performance of the bonded staple insulator compares very favorably to program targets and to the performance of waterfowl down.

B. Configuration of the Bonded Staple-Fiber Insulator

Developmental work with spun and drawn polyester microfibers (fibers with diameters $\leq 12\mu\text{m}$), with binder macrofibers (diameters $\geq 13\mu\text{m}$), with fiber finishes, and with fiber blends in insulating batts was nearing completion, under AI corporate sponsorship, at the time the subject contract was awarded. The data generated during this development effort provided ample guidance for selection of a fibrous configuration that would possess the set of properties defined by performance goals delineated in the Work Statement of the contract. Target values for the following insulator properties were given:

1. Thermal Conductivity
2. Density
3. Launderability
 - a. Thickness Decrease
 - b. Thermal Resistance Decrease
 - c. Shrinkage
4. Work to Compress
5. Resilience
6. Compressional Recovery
7. Absorptive Capacity
8. Compressional Strain and
9. Wet Loft Retention

It seemed evident that an 85/15 blend of 0.5 denier, spun and drawn, polyester staple and 4 denier, bicomponent, polyester binder fiber would, if processed properly, provide an insulating batt that would meet performance

objectives in all 11 categories. Consequently, 85/15 blended fiber hand samples were prepared for laboratory evaluation to confirm compliance with performance goals.

It was found that 10 of the 11 performance objectives cited in the Work Statement were met or surpassed by the 85/15 blended fiber hand samples. The target for thermal resistance decrease due to laundering was the only one not met; a decrease $\leq 10\%$ was the goal but an average decrease of approximately 20% resulted from three launderings made in accord with the severe, hot water, military method prescribed. However, absolute values of thermal conductivity and thermal resistance after laundering indicated excellent insulating performance (the post-laundering thermal conductivity value was well within the overall thermal conductivity objective of ≤ 0.300 Btu-in/hr-ft²-°F). Opportunities were seen for improvement to laundering resistance as pilot production trials progressed and this further reduced concern over the short--fall measured in only one of the 11 performance parameters.

Excellent agreement between the laboratory performance of the 85/15 hand samples and contract performance objectives made adoption of the specific configuration of the hand samples a logical and easy decision. This configuration was an intimate, uniform blend of two fibers, as follows:

1. Staple polyester fiber, 0.5 denier x 1.5 inches long, 15 to 20 crimps/inch, treated with polydimethylsiloxane finish (this fiber comprises 85% of the insulating batt, by weight), and
2. Staple, bicomponent, polyester/polyester fiber, side-by-side type, 4 denier x 2 inches long. This fiber functions in the batt as both binder and stiffener and comprises 15% of the batt weight.

Both fibers are now in production by Teijin Ltd. of Japan. Their specifications have been matched to the needs of the bonded staple-fiber batt insulator during the past two years, making them truly unique. The 0.5 denier staple is, to the best of AI's knowledge, the only spun and drawn polyester

microfiber (diameter $\leq 12\mu\text{m}$) that is available, although the prospects for American production of such fiber appear to be good. The polydimethylsiloxane finish used on the 0.5 denier fiber is similar to, but an improvement over, the silicone finish that was used on the hand samples delivered to Natick Center at the conclusion of Phase I of the contract, "Development of Synthetic Down Alternatives"⁽¹⁾. Its contribution to hand is approximately the same, the wetting resistance it imparts is somewhat greater, and its laundering durability, a factor not considered previously, is very good. The fact that it is now applied directly by the fiber manufacturer is, of course, a major advantage in terms of the pilot production objective of this program.

After preparation and evaluation of insulator hand samples made with the fiber blend described, full attention was given to the problems of pilot production.

C. Assembly of the Pilot Production Line and Initial Trials

At the outset of the contractual effort, Albany International was planning to subcontract out an initial manufacturing run of bonded, staple-fiber batt that would include the 100 yd² required for delivery to the Government. However, visits and preliminary trials with several high-loft insulation processors and machinery manufacturers made apparent the poor chances for success with this approach. It was learned that little latitude existed in requirements for: (1) fiber mixing, (2) fiber pre-opening and feeding, (3) carding, (4) cross-lapping and (5) bonding. The most inflexible of these was the carding machine configuration needed to form opened webs of the microfiber blend. It was evident that the prospects for locating an operational production line that included the correct card configuration and all other required elements were virtually nonexistent. This obstacle threatened Albany International's corporate objectives for development of a bonded microfibrinous insulator as well as the success of the subject contract. Consequently, a decision was made to purchase all of the required machinery and make initial manufacturing runs in-house. Plans were made to install the

pilot line in an Albany International Felt Division plant in Albany, New York, where a work force experienced in carding and related processing was already in place.

A cooperative effort among AI Research Co. and AI Felt Division staff members led to design and assembly of the pilot production line that is shown schematically in Figure 1. Its primary elements are as follows:

1. Fiber mixing station. Although fiber mixing is the first step in the process, it remains, as of this writing, the least developed step in the AI pilot line. Mixing for the batt samples delivered to the Government was accomplished with a great deal of inefficient but effective hands-on effort. This approach will be replaced by an optimal, automatic weighing and blending station during the next month.
2. Pre-opening and feeding station. Several experiments with pre-opening and feeding systems for carding machines led to selection of a CMC Even-Feed. This equipment appears to be uniquely suited to handling the fine (small diameter) fiber mix in that it transports fiber, internally, on moving aprons rather than through sliding induced by pressure differentials. It was discovered that static electricity generation within the microfiber mix in feeders that transport by sliding makes further processing virtually impossible.
3. Carding machine. Experiments with a wide variety of carding machines prior to the start of the subject contract identified a card configuration that is essential to successful opening and web formation with the microfiber mixture. It is a tandem cylinder type manufactured by J. D. Hollingsworth Co. that has stationary, flat tops and extremely fine metallic clothing (on the order of 400 points/in²).

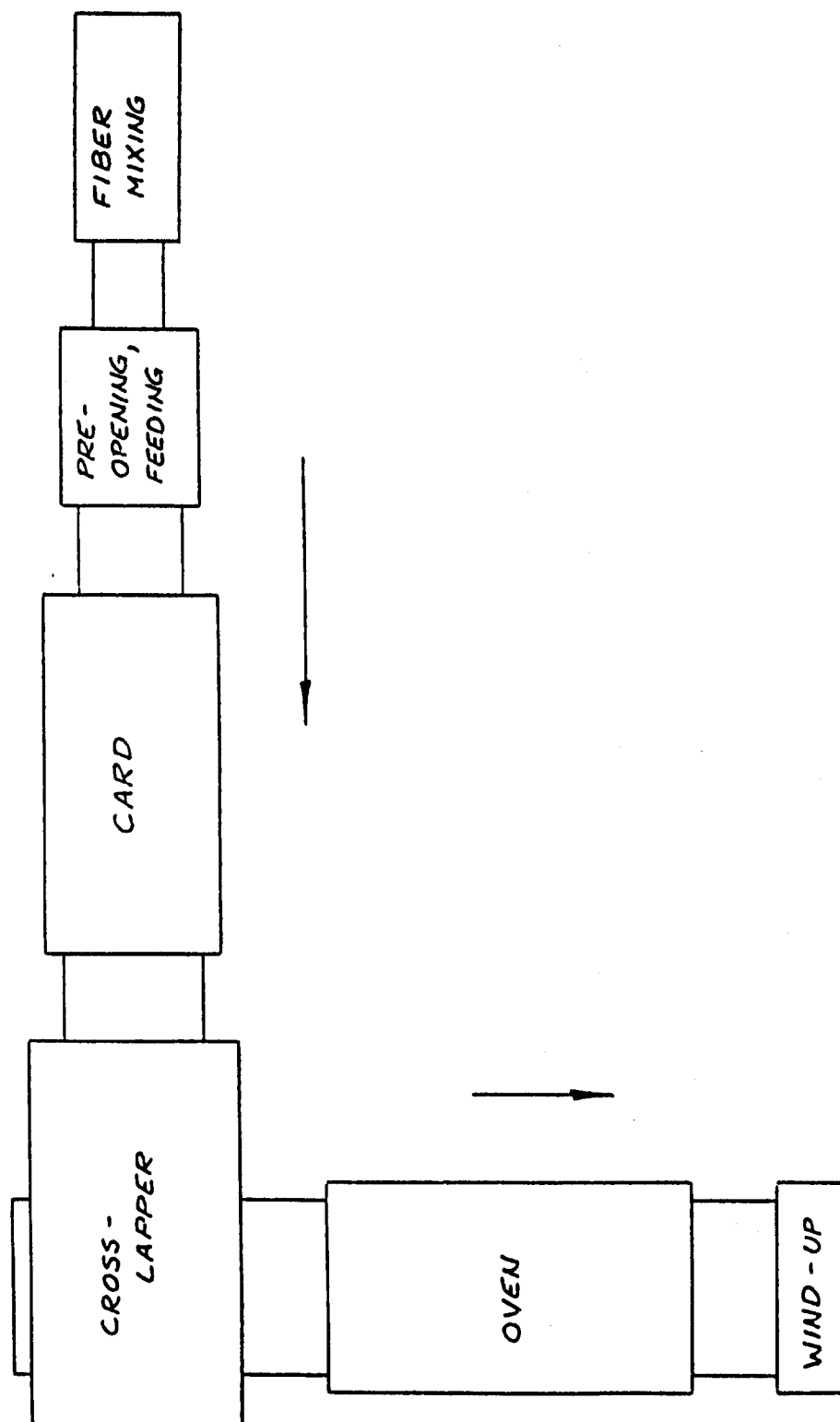


Figure 1. Schematic Diagram of Pilot Line for Production of Bonded Staple-Fiber Batt

4. Cross-lapper. The cross-lapper used to ply the card web into a batt is equipped with smooth, continuous conveying surfaces and independent control of each drive section to ensure that there is no drafting (loss of loft).
5. Bonding oven. A radiant heat conveyor oven having six independently controlled heater sections (three above and three below the conveyor) was manufactured for AI by Casso-Solar Corp. Independent heater zone controls provided greater experimental range for both temperatures and dwell times.
6. Bonded batt wind-up. The wind-up section has thus far had several experimental forms and will probably be changed again when more experience is gained with reinforcing scrims and packaging methods.

Soon after these components were assembled to form the pilot processing line, bonded staple-fiber batt of good quality was produced using a relatively small shipment of fiber from Teijin's pilot spinning line. However, a change to fiber from a new, larger Teijin shipment began a long and arduous period in which static generation within the fiber stock prevented satisfactory processing. Prior experience had led us to expect difficulty due to static generation, which manifests itself in fiber and webs becoming uncontrollable and clinging to machinery at points where clean separation is necessary. Recognizing that static generation would be an inherent difficulty in 0.5 denier fiber processing, a concerted effort was made to adapt the pilot line to process the fiber of the larger Teijin shipment. Static control bars, which ionize the air within an inch or two of their surface, were first mounted at all points where fiber webs must transfer without clinging. Next, an air ionizing device and blower were mounted on the feed box and an automatic water misting system was mounted over the entire length of the line. All of these static control measures, operating together, eventually made processing of the new fiber shipment possible. However, some compromise in web quality was necessary and stoppages due to clinging webs remained a problem, although a much less frequent one.

Satisfied that virtually all possible static control steps had been taken, we presented the problem to the fiber manufacturer, Teijin. They responded by supplying a series of fiber samples in which small finish changes had been made in an attempt to better balance the conflicting requirements of water repellency and minimal static generation. These samples were, in turn, evaluated by us and a new, optimal, prototype finish combination was identified. It is a cured polydimethylsiloxane (0.1 to 0.2% add-on, by weight) that includes approximately 5%, by weight, of an antistatic detergent. After curing of the finish, a spray of Teijin anti-stat T-1 is also applied to the fiber. The water repellency and processability of fiber finished in this way proved to be entirely acceptable.

D. Pilot Production of Bonded Staple-Fiber Insulating Batt

The pilot production line that was shown schematically in Figure 1 and described above was used to produce 100 yd² of 60 inch wide, bonded, staple-fiber batt that were delivered to the Government in December, 1988. The line was operated continuously during production of the 5-roll sample set, as static generation within the fiber was no longer a problem. Bonding was achieved by heating the batt to approximately 375°F, with a dwell time of about 2 minutes. Four of the five rolls were wound with a 0.5 oz/yd², non-woven polyester scrim on both sides of the batt; the fifth roll was wound with the same scrim on only one side. Both options were provided with the anticipation that the experience of the Natick Center staff in handling them would help us to identify a preferred scrim arrangement. Although we are confident that the configuration of the insulating batt itself is nearly optimum, some refinement in packaging may be necessary.

Laboratory data that characterizes the performance of the 100 yd² bonded staple-fiber insulator sample will be reported in Section IV, as will corresponding data for the spread tow insulator. Both data sets will be compared to program targets.

III. DEVELOPMENT OF A MANUFACTURING PROCESS FOR A HIGH PERFORMANCE INSULATOR OF SPREAD CONTINUOUS-FILAMENT TOW

A. Introduction and Summary

Machinery for opening and spreading continuous-filament tow to form high-loft batts is not now in widespread use and our best efforts to locate tow spreading equipment in this country provided only two alternatives. The first was a high-loft tow spreading line designed, built and operated by Northern Feather Co., Inc., a Danish company with United States plants in Elizabeth, New Jersey and Elk Grove, Illinois. The second alternative was a Celanese-designed line at Reliance Products Co. in Oakland, California that is used to produce PolarGuard^R, the only name-branded, continuous-filament, high loft, sleeping bag and apparel insulator now sold in this country.

Northern Feather expressed a strong interest in adapting the approach disclosed in the "Synthetic Down" patent⁽³⁾ to continuous filament production and so initial development efforts were made with their assistance. Teijin, Ltd., the Japanese fiber manufacturer that is now supplying 0.5 denier/filament (dpf) polyester staple to Albany International agreed to prepare 0.5 dpf polyester tow and 4 dpf polyester binder-fiber tow for opening, mixing and spreading trials. Two trials on Northern Feather equipment showed that: (1) the Teijin tow lacked initial cohesion required for feeding into the opening unit, (2) the static electricity charge generated while processing the 0.5 dpf tow was so great that it precluded continuous operation, and (3) blending two tow types was not possible with the Northern Feather equipment.

The results of the Northern Feather trials led to a decision to concentrate on opening and spreading tow of a single filament size; the size to be intermediate between 0.5 and 4 dpf and selected using data from "Development of Synthetic Down Alternatives"^(1,2) to ensure close compliance with the insulator performance objectives of the program. Tow with a denier/filament value of 1.2 appeared to be optimal; processability would be much improved over tow of 0.5 dpf and most or all performance objectives would remain attainable. As the program progressed, discussion regarding tow requirements

for opening and spreading was initiated with representatives of Hoechst Celanese Corp. Hoechst Celanese (formerly Celanese Corp.) has over 20 years of unique experience in this field with PolarGuard and its staff members expressed confidence in their ability to make 1.2 dpf polyester tow samples that would be ideally suited for spreading and opening. They also offered to enlist the help of Reliance Products, now the sole producer of PolarGuard, with subsequent spreading and opening trials. The line at Reliance is of the same basic configuration as that at Northern Feather and cannot be used to mix tow of different filament diameters. However, the Reliance line does include an optional spray bonding section that provides a ready alternative to binder fiber.

Two tow sample production runs at Hoechst Celanese and two opening and spreading trials at Reliance Products proved to be necessary to optimize processing techniques for production of high loft insulation from 1.2 dpf, opened and spread, continuous filament tow. The 100 yd² sample that was eventually made is, on the basis of laboratory measurements, a very worthwhile alternative to most established, commercial high loft insulators.

The text that follows describes the most important observations and conclusions from each of the four tow spreading trials, with emphasis upon the fourth and final trial that produced the optimal insulator sample. Laboratory data that characterizes the performance of interim samples is included in this section. Data for the final 100 yd² sample will be reported and compared to program targets and to data for the bonded staple-fiber insulator in Section IV.

B. Trials 1 and 2 at Northern Feather Co.

At the outset of the program, a 6 lb sample of 0.5 dpf Teijin tow was available and it was taken to Northern Feather's Elizabeth, New Jersey plant for a preliminary trial. The small sample was run on a machine used for opening and spreading 5 dpf polyester tow for pillow filling. Although this trial was limited in scope, it provided us with an important introduction to the process and an opportunity to plan and prepare for a trial of greater scope. The level of fiber opening obtained with 0.5 dpf tow in Trial 1 was not great. It was limited by:

1. Inadequate tow crimp that consisted only of a coarse (about 2 crimps/inch) low-amplitude saw-tooth form. Tow prepared for opening and spreading usually has a high degree of low-modulus extension obtained by both primary and secondary crimping and the need for this was clearly demonstrated.
2. The tow opening equipment did not have adjustable roll speeds and it became apparent that this feature was necessary to accommodate differences in total tow denier, fiber diameter, fiber finish and crimp.

The opening and spreading line in Northern Feather's Elk Grove, Illinois plant does have adjustable roll speeds throughout both opening and spreading sections and primarily for this reason it became the best choice for the next trial.

Tow samples for Trial 2 were prepared to our specifications by Teijin, Ltd. The specifications were based upon our experience in Trial 1 and input from the Northern Feather staff and are summarized in Tables 1 and 2. Approximately 300 lb of 0.5 dpf, polydimethylsiloxane-treated polyester tow and 50 lb of 4 dpf, all-polyester, side-by-side, binder fiber tow were provided and most of the fiber was used during three and one-half days of trials.

Prior to our work, Northern Feather's Elk Grove tow processing line had been used exclusively for work with 5 denier fiber in automated production of comforters. It is a relatively large, high output system that is about 40 feet long (exclusive of the comforter sewing section). The widest portion of the line, the nip at the entrance to the cross-lapper, measures approximately 12 feet. The tow opening, spreading and lapping portion of the production line is shown schematically in Figure 2.

TABLE 1. Description of 0.5 Denier/Filament Tow Used in Trial 2 (Northern Feather, Chicago)

Tow Manufacturer:	Teijin Ltd., Japan
Finish:	Polydimethylsiloxane, as applied to 0.5 dpf Teijin/AI staple
Measured Fiber Diameter (μm)	7.7
Denier/Filament, calculated from measured fiber diameter	0.58
Total Tow Denier	136,000
Primary Crimp (no./inch)	18
Secondary Crimp (no./inch)	2.5

TABLE 2. Description of 4 Denier/Filament, Side-by-Side Binder-Fiber Tow Used in Trial 2 (Northern Feather, Chicago)

Tow Manufacturer:	Teijin Ltd., Japan
Fiber Diameter, approximate (μm)	20
Denier/Filament, approximate	4
Total Tow Denier, as received	70,000
Total Tow Denier, as used	15,000
Primary Crimp (no./inch)	14
Secondary Crimp (no./inch)	1.2

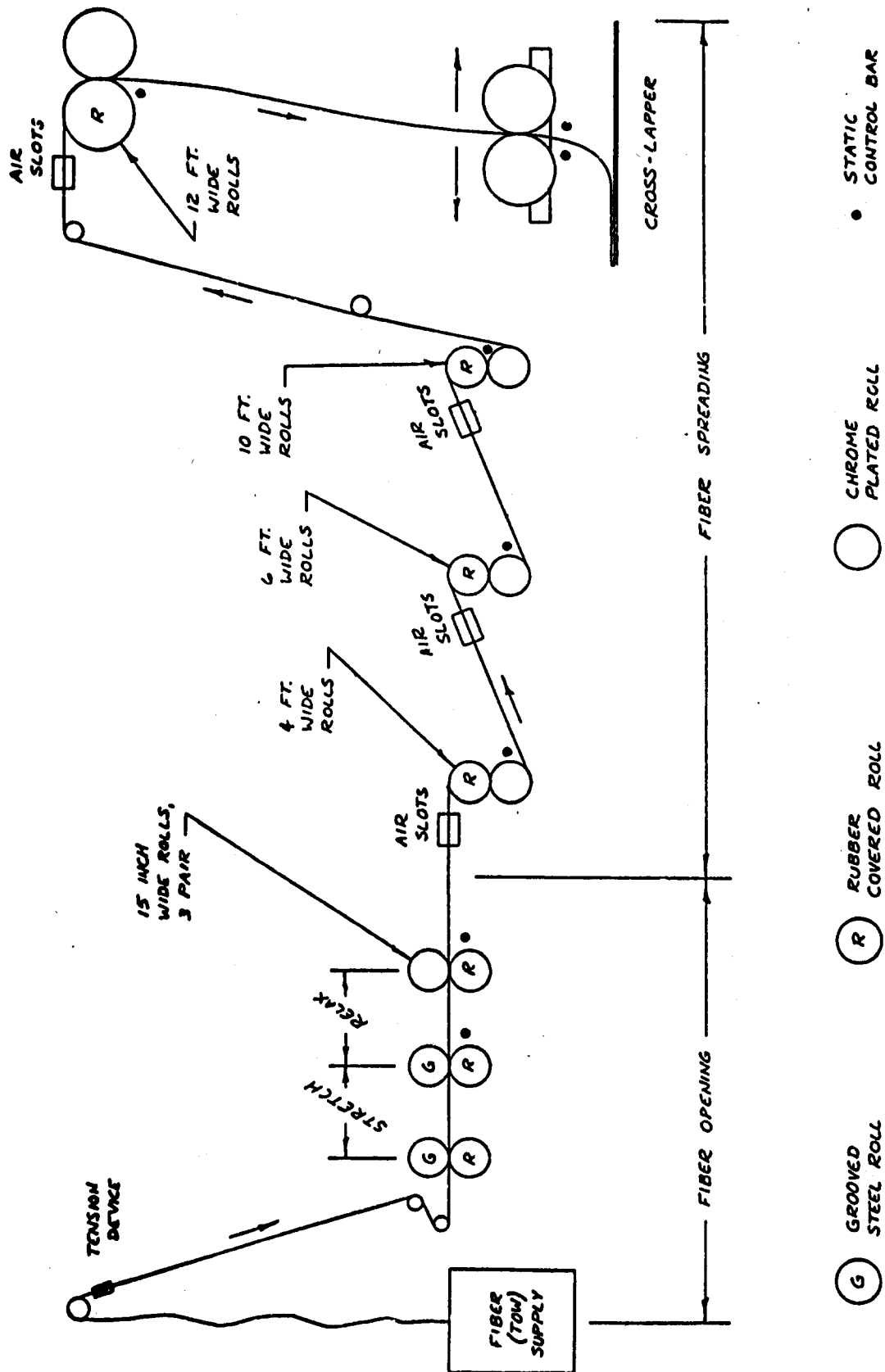


Figure 2. Schematic Diagram of Northern Feather Company's Tow Opening, Spreading and Lapping Line

The routine, continuous operation of Northern Feather's line can be best understood with reference to Figure 2 and through separating the functions, in sequence, as follows:

1. The fiber supply must be specially prepared tow with double crimp to ensure that the stock can be strained to 2.5 to 3 times its original length without stressing the fiber beyond its elastic limit.
2. Passage through the first three roll-pairs (nips) opens the tow bundle (separates individual fibers) by first stretching it, then allowing partial, controlled recovery, and finally, upon exit from the third nip, allowing complete elastic recovery. During passage through the nips, fiber gripping is nonuniform due to the varying thickness of fiber subgroups and this results in differential stretching and longitudinal motion that de-registers the crimp. The process is assisted by grooved steel rolls running on smooth rubber rolls in the first two nips. Ideally, upon total release of tension at the third nip exit, the fibers recover much of their original crimp, but the crimp in adjacent fibers is now out-of-phase, ensuring a degree of permanence to the loftiness that has been generated.
3. The opened fiber bundle is spread, incrementally, by successive passage through four sets of air slots and roll pairs. A low pressure, high volume air-supply feeds each air slot position, through which the fiber array passes without restriction, under negligible tension. Air flow through the chevron-configured slots forces the array outward from either side of its centerline and the spread width is maintained by passage through a nip at the exit from each air-spreading position.
4. The final air-spreading position is above a traversing roll-pair that cross-laps the spread, continuous-filament web onto a fabric apron moving at a right angle to the path through the opening/spreading line.

5. The fabric apron of the cross-lapper can, and usually does, serve as the bottom fabric covering of a comforter. When comforters are being produced, the upper fabric covering unrolls onto the cross-plied batt just prior to its entrance into an automatic, computer controlled Mammut quilting machine.

The tow spreading trials began with a run of 5 dpf, 350,000 total denier, silicon-treated, ICI polyester tow of the type that is customarily processed on Northern Feather's equipment. This served as a check for proper operation of the line and demonstrated to us the efficiency and thoroughness with which 5 dpf tow can be opened and spread. The only difficulty observed during this initial run was a tendency for the tow, which became charged with static electricity while sliding in the opening section, to be attracted to and wrap completely around the rolls of the spreading section. This problem was minimized through the use of static-control bars mounted in the positions shown in Figure 2.

The first attempt to open and spread the 0.5 dpf Teijin tow was quickly ended when static caused tow wind-up on the spreading rolls. It was soon realized that the static charge being generated on the tow presented a serious obstacle to making a successful experimental run. Due to very frequent roll wind-ups, the line could not be run long enough to make adjustments and determine their effects. The 0.5 denier fiber was much more susceptible to static induced problems than 5 denier fiber because:

1. For a given total tow denier, the 0.5 denier product has many more filaments and consequently, much more sliding-fiber surface area generating static, and
2. The much lighter 0.5 denier fiber (1/10 the weight per unit length) is more readily deflected by a given static charge and less affected by the often helpful effect of gravity.

It is fair to say that more than half of the time available to us was spent in trying to lessen the effects of static build-up so that a run long enough to be experimentally useful could be made. Many schemes and equipment changes were tried, including:

1. Extra hands guiding fiber off the spreader rolls,
2. Reducing the stretch ratio and thus lessening the amount of slipping in the stretch section (this had an undesirable effect upon fiber opening),
3. Repositioning all of the static control bars,
4. Spraying the tow, at various points on the line, with a fine water mist,
5. Combining two lengths of tow, and then three lengths to obtain a heavier fiber array that would be more greatly influenced by gravity, and
6. Spraying the stock with "Static Guard^R," a consumer product used to eliminate static cling on clothing. The active ingredient is: "dimethyl ditallow ammonium chloride."

Most of the above were helpful to some degree, but the last, spraying the stock supply intermittently with Static Guard, was clearly the most effective. It allowed runs of 5 to 10 minutes duration, and although each of these runs would eventually end due to static-induced roll wrap-ups, further experimentation became possible.

From the outset, the 0.5 denier tow had not been exiting the opening section fully opened. Groups of fibers with crimp still in register were readily noticeable, as was the minimal loft of the fiber bundle. Thus, the opening section received most of our attention after the static problem had been brought under partial control. Three factors were thought to be important to satisfactory opening, as follows:

1. Crimp and cohesiveness of the tow supply. Efforts prior to the trial ensured that the double crimp in the tow supplied by Teijin was appropriate. However, the tow lacked the cohesiveness of the ICI tow that Northern Feather usually runs. The Teijin tow tended to separate, twist and fold prior to entering the first nip, whereas the ICI tow ran continuously as a more-or-less flat, cohesive ribbon. This problem was minimized by trial-and-error selection of stock from the available Teijin fiber.
2. Dimensions of the grooves in the top rolls of the stretch section. Ground vee grooves with truncated crests form the surface of the top, metal rolls in the stretch section and they run against rubber covered bottom rolls. The alternating flats and voids along the nip promote parallel slip/stick motion across the width of the tow, de-registering crimp and assisting in the opening process. It was the consensus of those involved that the scale of the grooves should be reduced to accommodate the 0.5 denier fiber, which has a cross-sectional area only one-tenth that of the 5 denier fiber that is usually processed on Northern Feather's equipment. However, changes to the rolls to confirm this hypothesis were certainly not within the scope of the trial.
3. Ratios of the roll speeds among the three nips of the opening section. As mentioned previously, Northern Feather's line was unique in that most roll speeds, including those of the opening section, were adjustable. This made it possible to precisely change the level of tow strain (speed differential between first and second nips) and the degree of controlled recovery (between second and third nips) until optimal opening was achieved. After lengthy experimentation, a strain ratio of 2.81/1 (181% strain), with partial recovery to a ratio of 1.72/1 (72% residual strain) was settled upon as near-optimum.

The improvement in fiber separation that was eventually achieved through adjusting roll speed ratios in the opening section was substantial and made the preparation of a viable sample possible. Using a single end of tow, the level of opening obtained was good, and although room for further improvement existed, it was apparent that a point of diminishing returns had been reached. The lapper was set to lay down a 6 ft wide, 4 oz/yd² batt and a length of approximately 48 ft was made before static-induced roll wind-up ended the run. Surplus comforter cover-fabric was used on either side of the batt and the automatic quilting machine was used to sew four, straight through-stitch lines, including one at either edge, along the length of the sample. This stitching was estimated to be just enough to ensure that the sample would remain intact after being rolled up and shipped.

A tow mixing experiment was also tried after near-optimal roll ratios in the opening section had been settled upon. A length of 4 dpf, side-by-side conjugate, all-polyester, binder fiber tow of approximately 15,000 total denier had been prepared (see Table 2) for combining with the 136,000 total denier, 0.5 dpf tow used throughout the trials. It was learned that little or no fiber mixing could be induced by feeding the two tow bundles into the opening section together. As the fiber was spread at the air slot positions downstream, two fiber bands remained distinctly separate and were easily identifiable as groups of the two input fibers. We do not envision a means by which two fiber types could be mixed using this equipment. The most plausible approach seems to be combining tow after opening in separate, parallel opening sections, although it is doubtful that thorough fiber mixing of the kind achieved with the AI staple fiber blend can be achieved with spread tow.

Laboratory examination and evaluation of the 6x48 foot, 0.5 dpf, continuous-filament batt sample provided a good understanding of the degree of success that had been attained. Less than perfect fiber opening, as reported above, was very evident and negatively influenced AI's overall impression of the sample.

The most important mechanical characteristics of the continuous-filament batt sample were measured using the 2.00 inch gauge length and 0.5 lb/ft³ initial density combination that has been standard for virtually all prior work. This sample configuration was obtained, as it has been in the past, by plying several layers of batt. Our intention at the outset of the contract was to make most mechanical measurements using a single batt thickness and an initial density of 0.4 lb/ft³. However, the lesser loft of the incompletely opened, continuous-filament batt sample manifested itself in a minimum density of about 0.5 lb/ft³, making the originally employed gauge length conditions an inevitable choice. All compression related properties that were measured are reported in Tables 3 and 4. Most noteworthy of these, in addition to the relatively poor minimum density (loft) of 0.49 lb/ft³ mentioned above, was the low average compressional-recovery value of 79%. The compressional recovery target value given in the Work Statement is >90%.

A single thermal conductivity test was performed using a 12x12x2.06 inch sample with a density of 0.5 lb/ft³ that was prepared by hand-layering batt sections. The test method employed was the plate-to-plate technique of ASTM C518⁽⁴⁾ and all details of the test were identical to those employed during prior Contract No. DAAK60-83-C-0022^(1,2). Thermal conductivity data for the 0.5 dpf spread tow sample is reported in Table 5, together with reference data for a near-optimum bonded staple-fiber batt and the program target value. In spite of incomplete fiber opening, a relatively low and acceptable thermal conductivity value of 0.275 Btu-in/lb-ft²-/°F was measured for the batt made of spread tow.

TABLE 3. Minimum Density, Compressional Strain and Compressional Recovery Data for Insulating Batts Made Entirely from 0.5 Denier/Filament Spread Tow During Trial 2 (Northern Feather, Chicago)

Sample No.	Minimum Density (lb/ft ³)		Compressional Strain at 5 psi (%)		Compressional Recovery from 5 psi (%)	
	Target	Measured	Target	Measured	Target	Measured
1		0.50		96.3		77
2		0.47		96.5		80
3		0.51		96.4		80
Avg.	≤0.4	0.49	≥95	96.4	≥90	79

TABLE 4. Work of Compression, Work of Recovery and Resilience Data for Insulating Batts Made Entirely from 0.5 Denier/Filament Spread Tow During Trial 2 (Northern Feather, Chicago)

Sample No.	Work of Compression W _c (lb-in)		Work of Recovery W _r (lb-in)	Resilience ($\frac{W_r}{W_c} \times 100$)	
	Target	Measured	Measured	Target	Measured
1		2.24	1.54		0.69
2		2.26	1.56		0.69
3		2.25	1.46		0.65
Avg.	≤2.75	2.25	1.52	≥0.55	0.68

Note: The gauge length for these compression tests (Tables 3 and 4) was 2.00 inches; batt density at this thickness was 0.5 lb/ft³. See text.

TABLE 5. Thermal Conductivity of a Lightweight Batt Made Entirely from 0.5 Denier/Filament, Spread, Continuous-Filament Tow During Trial 2 (Northern Feather, Chicago)

Batt Type	Batt Density (lb/ft ³)	Batt Thk. (in)	Avg. Temp (°F)	Apparent Thermal Conductivity, K (Btu-in/hr-ft ² -°F)	Thermal Resistance, R (hr-ft ² -°F/Btu)
Spread, c.f. tow, 100% 0.5 dpf	0.47	2.06	74.5	0.275	7.49
Bonded staple, 85/15 blend (0.5 dpf/4 dpf binder), reference	0.50	2.06	75.8	0.259	7.94
Target value	0.50	2.00	75	≤0.300	--

The trials at Northern Feather Co. and subsequent laboratory measurements of the most important performance characteristics of the Northern Feather sample (100% 0.5 dpf tow) showed that:

1. Mixing 0.5 and 4 denier fiber is not feasible with existing equipment,
2. Generation of static charge in the tow, which appears to be a controllable problem with 5 denier fiber, makes continuous operation with 0.5 denier fiber a doubtful proposition,
3. Thorough fiber opening could not be achieved with 0.5 dpf tow and it appears that experimentation of much greater scope, probably including opening-section machinery modifications, would be required to improve opening, and
4. The 0.5 dpf spread tow sample was poor in terms of minimum density (loft) and compressional recovery, but its thermal conductivity was acceptably low.

Consideration of all of the above led to a revised approach, one based upon a batt of 100% 1.2 dpf, silicon-treated polyester tow. All that had been learned indicated that the runnability, the degree of opening attainable and the mechanical performance of a 1.2 dpf continuous-filament array would be significantly better than that which was possible with 0.5 dpf tow. Omission of 4 denier stiffening/binder fiber was regarded as a minor, perhaps negligible, factor because:

1. The larger diameter, 1.2 dpf fiber would contribute much more to insulating structure stiffness than does 0.5 dpf fiber. Fiber bending stiffness is a function of the fourth power of diameter and so the bending stiffness of 1.2 denier filament (11.1 μm diameter) is approximately 5.6 times that of 0.5 denier fiber (7.2 μm diameter).
2. The greater level of entanglement in a fully opened, continuous filament batt lessens the need for bonding and the spray adhesive that is a part of the PolarGuard process could be used, if necessary.

The only performance parameter expected to be compromised by the change from 0.5 to 1.2 dpf was thermal conductivity, but ample data was available from previous work to show that a value $\leq 0.300 \text{ Btu/hr-ft}^3\text{-}^\circ\text{F}$ (the contract target value) could still be attained.

C. Trial 3 at Reliance Products Co.

Most of the processing difficulties encountered during Trial 2 at Northern Feather were clearly attributable to the fineness (small diameter) of 0.5 dpf tow. However, the lack of tow ribbon cohesiveness described in the previous subsection (B) was another matter, one that would have caused a problem with conventional 5 to 6 dpf tow. This deficiency brought to mind the special requirements of tow used for opening and spreading and the potential advantage of working with a fiber producer having tow spreading experience. As related previously, discussion had been ongoing with Hoechst

Celanese technical staff members. Their interest and ability to produce experimental quantities of suitable polyester tow had become evident and their help was enlisted after the results of Trial 2 became clear.

Hoechst Celanese's Salisbury, North Carolina polyester fiber production plant prepared approximately 700 lb of 1.2 dpf (nominal), silicone treated, polyester tow for Trial 3. The only silicone finish that could be applied at Salisbury at that time was the one used for PolarGuard tow. Although we were aware that somewhat better water repellency could be achieved with another finish, circumstances forced this issue into the background, at least temporarily. The dimensional characteristics of the experimental tow sample that Hoechst Celanese prepared are reported in Table 6.

TABLE 6. Description of 1.2 Denier/Filament Tow Used in Trial 3
(Reliance Products, Oakland)

Tow Manufacturer:	Hoechst Celanese Corporation, Charlotte, NC
Finish:	Silicone of the type applied to Hoechst Celanese fiber used in PolarGuard
Measured Fiber Diameter (μ m)	11.8
Denier/Filament, calculated from measured fiber diameter	1.36
Total Tow Denier	459,000
Primary Crimp (no./inch)	15
Secondary Crimp (no./inch)	2.2

Hoechst Celanese (and its predecessor, Celanese Corp.) has a long standing relationship with Reliance Products Company of Oakland, California. Reliance is the only processor of PolarGuard, the continuous filament, spread tow insulator originated by Celanese and has contributed to the refinement of the PolarGuard manufacturing process. Hoechst Celanese recommended that the tow spreading trial with their tow be made at Reliance and subsequently arranged the trial on our behalf.

The configuration of Reliance Products' tow spreading line does not differ greatly from that of the Northern Feather line, which was shown schematically in Figure 2. The Reliance line has fully adjustable roll speeds at all positions, as does the one at Northern Feather, and the lines are similar in physical size. The most obvious difference is one that proved to be important to this program, i.e., the Reliance cross-lapper feeds directly to a spray-adhesive station and adhesive-curing oven. It was found that the use of a small amount of spray adhesive greatly improved the integrity of the batts formed, obviating potential handling difficulties prior to sewing them into end-use products.

A highly satisfactory level of fiber opening (separation) was obtained at the outset of the first Reliance trial (Trial 3) through adjustment of roll speed ratios in the opening section. However, a deliberate reduction in fiber opening then had to be made to allow control of the opened fiber; the opened volume of the 459,000 total denier tow could not be accommodated at the first air-spreading station immediately down-stream of the opening section. Although this reduction in fiber opening was a significant compromise in terms of the quality of the insulating batt that could be produced, it was required to ensure that the trial could continue.

The imperfectly opened fiber web proved to be relatively tractable at most points beyond the opening section, although the small fiber diameter and static generation made cross-lapping and transport of the cross-lapped webs (batt) somewhat difficult. The advantage of employing the optional spray adhesive became obvious and it was used to treat most of the sample batt produced. As the trial progressed, slight mismatches in transport belt speeds developed and/or became apparent. These caused drafting and loss of loft as the batt passed through the adhesive drying oven. Poor release from transport belts that were tacky with accumulated adhesive exacerbated drafting and loft loss and further reduced the utility of the batt samples produced. Nonetheless, insulating batt of fair quality and appearance was produced and returned to our Mansfield laboratory for evaluation. Agreement between performance test results and contract target values, as shown in Tables 7, 8 and 9, was found to be quite good and the prospects for improvement through better fiber opening and greater loft were strong.

TABLE 7. Minimum Density, Compressional Strain and Compressional Recovery Data for Insulating Batts Made Entirely from 1.2 Denier/Filament Spread Tow During Trial 3 (Reliance Products, Oakland)

Sample No.	Minimum Density (lb/ft ³)		Compressional Strain at 5 psi (%)		Compressional Recovery from 5 psi (%)	
	Target	Measured	Target	Measured	Target	Measured
1		0.49		96		83
2		0.45		96		87
3		0.49		96		82
4		0.49		96		73
Avg.	≤0.4	0.48	≥95	96	≥90	81

TABLE 8. Work of Compression, Work of Recovery and Resilience Data for Insulating Batts Made Entirely from 1.2 Denier/Filament Spread Tow During Trial 3 (Reliance Products, Oakland)

Sample No.	Work of Compression W _c (lb-in)		Work of Recovery W _r (lb-in)	Resilience ($\frac{W_r}{W_c} \times 100$)	
	Target	Measured	Measured	Target	Measured
1		4.09	2.24		0.55
2		4.03	2.06		0.51
3		4.01	2.09		0.52
4		3.74	2.19		0.59
Avg.	≤2.75	3.97	2.15	≥0.55	0.54

Note: The gauge length for these compression tests (Tables 7 and 8) was 2.00 inches; batt density at this thickness was 0.5 lb/ft³. See text.

TABLE 9. Thermal Conductivity of a Lightweight Batt Made Entirely from 1.2 Denier/Filament, Spread, Continuous-Filament Tow During Trial 3 (Reliance Products, Oakland)

Batt Type	Batt Density (lb/ft ³)	Batt Thk. (in)	Avg. Temp (°F)	Apparent Thermal Conductivity, K (Btu-in/hr-ft ² -°F)	Thermal Resistance, R (hr-ft ² -°F/Btu)
Spread, c.f. tow, 100% 1.2 dpf	0.50	2.00	75.1	0.302	6.61
Bonded staple, 85/15 blend (0.5 dpf/4 dpf binder), reference	0.50	2.06	75.8	0.259	7.94
Target value	0.50	2.00	75	≤0.300	--

The potential demonstrated during Trial 3, together with a strong sense that most of the difficulties encountered were understood and resolvable, led to plans for a previously unanticipated fourth trial. Hoechst Celanese offered to prepare 1.2 dpf tow samples of about one-half the total denier used for Trial 3 to make complete opening possible and Reliance Products Co. undertook to change several process conditions that had contributed to drafting and loft loss.

D. Trial 4 at Reliance Products Co.

The fourth and final tow spreading trial of the program was, without doubt, the most successful. We were able to apply much of what had been learned in the first three trials toward production of good quality, continuous filament, high loft insulator samples that are unique. They are, to the best of our knowledge, comprised of much finer (smaller diameter) filaments than any similar insulator and, consequently, offer much greater insulating efficiency. With one or two minor exceptions, the difficulties encountered during the previous trial at Reliance Products were successfully addressed and this minimized operational interruptions and allowed us to give full attention to fine tuning the process.

The greatest handicap during the previous Reliance trial (Trial 3) was the need to deliberately limit fiber opening in order to contain the opened tow bundle as it passed through the spreading section. A much preferred approach to controlling the opened tow was possible for the final trial; Hoechst Celanese prepared a new tow sample of much smaller total denier (about one-half) so that it could be fully opened and still be contained in the spreading section. The individual filaments in the new tow sample were the same nominal size (1.2 denier/filament) as those of the tow used for Trial 3 and the finish was the same. The essential physical characteristics of this final tow sample are reported in Table 10 below.

TABLE 10. Description of 1.2 Denier/Filament Tow Used in Trial 4

Tow Manufacturer	Hoechst Celanese Corporation Charlotte, NC
Finish	Silicone, as applied to Hoechst Celanese fiber used in PolarGuard
Measured Fiber Diameter (μm)	11.5
Denier/Filament, calculated from measured fiber diameter	1.29
Total Tow Denier	246,000
Primary Crimp (no./inch)	20
Secondary Crimp (no./inch)	3

In preparation for the final trial, we initiated discussion with Hoechst Celanese and Reliance Products personnel regarding several minor operational and equipment problems observed during Trial 3. Consequently, most of these were addressed by Reliance prior to Trial 4, and this effort ensured that the final trial progressed smoothly and efficiently. The equipment details given attention prior to the trial were as follows:

1. Conveyor speeds were matched to eliminate the drafting (and loft loss) that was a problem at several points on the processing line during Trial 3.

2. Two short conveyor sections that had been fouled with residual spray adhesive, preventing clean release and causing batt irregularities, were covered with polyethylene film. This was very effective in eliminating the difficulty. However, a similar problem existed on at least one of the through-oven conveyors, but the high-temperature and air-flow requirements made resolution more difficult. Consequently, during the final portion of the trial, when our optimal samples were being produced, the batt was continually guided off the most troublesome oven conveyor by two pairs of hands.
3. The spray adhesive application equipment was changed slightly to eliminate batt surface disturbances from the spray blast and to soften the hand of the batt. One of the two pairs of traversing spray nozzles was made inoperative; finer nozzles were installed at the two spray points that were used; and spray pressure was adjusted to the minimum that would give smooth, droplet-free operation. This pressure was found to be 25 to 30 psi.

These preparatory changes and, perhaps most importantly, use of tow of more suitable weight (total denier), enabled us to begin the final trial with the entire opening, spreading, cross-lapping, bonding and curing system operating smoothly. This was a first and a bona fide indicator of progress. With each station in the line performing reasonably well, we were finally able to concentrate upon fine tuning and the following adjustments were made:

1. Near-optimal opening was obtained by adjusting the relative speed of the stretch rolls. The roll speed ratio finally adopted was 2.4/1.
2. The traversing speed of the cross-lapper was adjusted to yield a final batt density of 4 to 5 oz/yd².

3. The angle and height of the floor apron under the cross-lapper was carefully adjusted, over time, to minimize the free-fall time of the web, which in turn minimized the negative effect of air drafts upon batt uniformity.
4. Final adjustments were made to the adhesive spray pressure (it was left at about 25 psi) to obtain a batt with minimal, but effective, bonding and a soft hand. No measurements of adhesive add-on were made, but the machine operators agreed upon an estimate of 10%. The adhesive was a Rohm and Haas acrylic latex (methylacrylate), No. TR407.
5. The adhesive curing conditions that apparently yielded the best results were an oven air temperature of 240°F and a total dwell time of approximately 8 minutes in the three-pass oven.

The spread, continuous filament insulator produced after the above adjustments had been made appeared to be of very good quality. Hand, loft, degree of fiber-opening, and overall appearance were all judged to be very good. However, careful examination of the samples shows that some minor, systematic nonuniformity exists. It is a result of: (1) a tendency of one tow edge, about one-half inch wide, to fold slightly, (2) air-turbulence induced wrinkling and folding that occurred in the lapper (this was minimized, as described above, by adjusting apron clearance) and (3) sticking on oven brattices at one or two inaccessible release points. The net effect of these irregularities is small and we are sure that they could be eliminated with minimal effort. We did not expect them to have any significant, adverse effect upon the performance properties that were to be measured.

IV. LABORATORY CHARACTERIZATION OF PILOT LINE INSULATOR SAMPLES

A. Performance Goals and Test Methods

Laboratory test methods that had been adopted during Phase I of the prior AI Research/Natick Center insulator development program and described in NATICK/TR-86/021L⁽¹⁾ were employed for this work. Their utility had been proven and their use in this program ensured that the newly obtained data could be compared directly to data for the previous, successful insulator samples. This advantage was apparently recognized in drafting the Work Statement of the subject contract, which includes the following compilation of properties targets and test methods to be employed:

- "1. Thermal Conductivity: ≤ 0.300 Btu-in/hr-ft²-°F (0.43 W/m°C) at 0.5 lb/ft³ (8.0 Kg/m³), measured by ASTM C518.
2. Density: ≤ 0.4 lb/ft³ (6.4 Kg/m³), thickness measured at 0.002 psi (0.0138 kPa).
3. Launderability: 3 cycles $\leq 25\%$ thickness decrease, $\leq 10\%$ thermal resistance decrease, shrinkage $\leq 5\%$. Prepared and laundered as specified in Cotton Procedure Method 5556 of FED-STD-191A except, one sewn on balloon cloth side of each specimen shall be marked in accordance with the procedure for marking woven cloth specimen for dimensional stability determination. Drying temperature 130 to 150°F, not moistened or pressed after drying. Thickness measured at 0.002 psi (0.0138 kPa), thermal resistance measured by ASTM C518.
4. Work to compress: ≤ 2.75 lb-in (0.113 N-m), per MIL-B-41826F section 4.3.2 except stress limits of 0.002 psi (0.0138 kPa) and 5.0 psi (34.5 kPa).
5. Resilience: $\geq 55\%$: work of recovery divided by work to compress. Work of recovery per MIL-B-41826F section 4.3.2 except stress limits of 0.002 psi (0.0138 kPa) and 5.0 psi (34.5 kPa).

6. Compressional Recovery: $\geq 90\%$ from a stress level of 5.0 psi (34.5 kPa) as per MIL-B-41826F section 4.3.2.
7. Absorptive Capacity: not more than 150% water retention after 20 min. based on ASTM D1117 as modified in NATICK/TR-86/021L p. 88.
8. Compressional Strain: $\geq 95\%$ @ 5.0 psi (34.5 kPa) per MIL-B-41826F section 4.3.2 except initial thickness at 0.002 psi (0.0138 kPa).
9. Wet loft retention: $\geq 95\%$ with 20 min. wetting and $\geq 50\%$ over 6 hrs. based on ASTM D1117 as modified in NATICK/TR-86/021L p. 88."

Most of the above test methods were followed explicitly to obtain the data that follows. However, in some cases, minor test method changes or additions were necessary to fully and accurately characterize the performance properties of the prototype insulators. The thermal conductivity test routine was expanded, several minor changes were made in the test laundering procedure, and the compression testing series was extended. These test method changes and additions will be explained below.

Thermal conductivity and thermal resistance measurements were the only ones not made in our Mansfield laboratory. Experience of the past several years has shown that this testing can be done most efficiently and very reliably by Holometrix, Inc. (formerly Dynatech) of Cambridge, Massachusetts. Early in the program, concern existed regarding meaningful measurement of thermal resistance after laundering by the severe military method prescribed in 3., above. We anticipated, and confirmed through preliminary evaluations, that fiber shifting and forming of thick and thin sections within the insulator would be the principal mode of deterioration. This consideration, together with the relatively small 4x4 inch measuring area of the Rapid K instrument that Holometrix has used for most of our insulator work, posed a potential problem. Due to the long time required for each test, the subsequent cost, and the relative reliability of the method, very few test replications are usually made. This approach, however, appeared much less valid for evaluation of the thermal resistance of batts in which fiber had shifted.

Our alternative approach was to employ an instrument with a larger measuring area to better average the net effect of nonuniform fiber distribution. Such an apparatus, the R-Matic, was available at Holometrix. Its measuring area was one of 12x12 inches, in the center of a 24x24 inch sample (in contrast to 4x4 and 12x12 inch measuring and sample areas, respectively, for the Rapid K). Both instruments are plate-to-plate types that are used in compliance with ASTM Method C518⁽⁴⁾. The most significant difference is that the larger format R-Matic can be operated only with heat flow upward, whereas most data that we have previously reported⁽¹⁻³⁾ was obtained on the Rapid K with heat flow downward. Consequently, to provide data of greatest utility, we chose: (1) to test some samples with the Rapid K in the heat flow downward mode to facilitate comparison with previous work and (2) to test the laundering samples, before and after laundering, with the R-Matic with heat flow upward. In both instances, the temperature of the hotter plate was 100°F and that of the cooler was 50°F.

The laundering method used as part of the test procedure for characterizing the launderability, or the resistance to laundering, of the insulator prototypes was specified in the Work Statement of the contract. It is described as the "Cotton Procedure" of Method 5556 of Federal Test Method Standard No. 191A⁽⁵⁾. Each washing cycle consists of six operations, as follows:

1. Washing for five minutes with a water temperature of 100°F,
2. Washing for five minutes with a water temperature of 140°F,
3. Rinsing for three minutes with a water temperature of 140°F,
4. Rinsing for three minutes with a water temperature of 120°F,
5. Rinsing for three minutes in a sour solution with a temperature of 100°F, and
6. Rinsing for three minutes with a water temperature of 100°F.

The washer is drained and refilled between each of the six operations that comprise one laundry cycle, and this is followed by machine drying. Three such washing and drying cycles are the test treatment specified in the Work Statement.

At the outset of the program, all of the essential details of the laundering procedure were discussed with Natick staff members and several minor deviations from the "Cotton Procedure" of Method 5556 were agreed upon. They were as follows:

1. The cover fabric used to make quilted fabric/insulating batt/fabric washing samples is specified as "cotton balloon cloth" but we were advised that, to comply with current Natick Center practice, a nylon taffeta should be used. The taffeta is 2.0 oz/yd² fabric described in MIL-C-21852E, Int. Amendment 1(GL), Type III, Class 1(6).
2. Method 5556 prescribes the use of a specific, large, commercial-laundry scale wash wheel and dryer, but it was agreed that the standard household units in our laboratory could be effectively substituted. Care was taken to ensure that each step in the laundering cycle complied with that specified in terms of duration, water temperature and dryer stack temperature.
3. We were advised that the synthetic detergent specified, Igepon 77, should be replaced by Igepon 73 for Natick Center evaluations and that consistent with this, the amount of detergent used should be changed as well.

By incorporating the changes suggested and developing techniques for accurately controlling wash and dry cycle times and temperatures, we established a laundering procedure that duplicates the essentials of the one that the Government will employ in subsequent evaluations.

Our experience with the laundering procedure served to emphasize its severity. Each washing cycle includes six complete machine fillings and drainings, two with water that is hotter (140°F) than is available for most home launderings, one with water that is considered "hot" (120°F) in home laundry machines, and three with "warm" water (100°F). In contrast, conventional home launderings usually consist of only two fillings and drainings,

one for washing and one for rinsing. Hang tag recommendations for Albany International's bonded staple-fiber insulator will specify this kind of conventional machine washing, using cold water for both washing and rinsing.

The compression test sample configuration that was first adopted under the prior AI Research/Natick Center⁽¹⁾ insulator development program has been in regular use in our laboratories since that time and has been used to generate a large body of reference data. This configuration is: a cylindrical disk of 5.70 inches diameter, with a height of 2.00 inches (the initial gauge length) and a density of 0.50 lb/ft³. Frequently, batt samples must be plied together, using partial batt thicknesses (separated web layers) to obtain the 2.00 inch gauge length and 0.50 lb/ft³ density combination. This is not as cumbersome or inconvenient as it may seem and its merit, in terms of facilitating many direct materials comparisons, is without question. Consequently, use of this sample configuration for measurement of all compressional properties was an obvious and logical choice. However, one compressional property target, that of work-to-compress, is a direct function of sample thickness and it is apparent that the target value given (≤ 2.75 lb-in) is for the 4 oz/yd², 0.4 lb/ft³, 0.8 inch thick batt configuration required for Government delivery. This made compression testing using delivered-sample thicknesses necessary as well. Thus, two sets of compressional data were obtained and are reported; this approach ensures completeness and the broadest utility of the data package.

B. Laboratory Evaluation

The final step in this pilot line development program was laboratory evaluation of the bonded staple-fiber batt and spread continuous-filament tow prototypes that were produced. Most of the laboratory performance data obtained for the two prototypes compares very favorably to program targets, demonstrating strong potential for both pilot processes and both insulator forms. Although some minor performance shortfalls were discovered, we think that they can be corrected and that they do not detract from the viability demonstrated for both insulator types.

The data that follows includes: individual test results, averaged results, comparisons with program targets and a data summary. Although most of this data can be readily interpreted and compared directly to program targets, some discussion regarding the most obvious performance advantages and the resolvable shortfalls mentioned above is warranted.

In accord with a fundamental finding of the previous AI Research/Natick Center insulation development effort^(1,2), relatively stiff (high modulus) microfibers with diameters in the 7 to 12 micron diameter range were utilized to the maximum degree possible, in both insulator forms, to obtain optimum insulating efficiency. Compressional performance and processability are directly affected by fiber diameter also, and so compromises, described in preceding sections, were important in the selection of fiber diameters for both insulators. Performance data obtained for the two prototypes shows that these compromises were generally successful. Thermal conductivity data is shown in Table 11, together with the program target value and reference values for MIL Spec waterfowl down, Quallofil^R and PolarGuard. While the thermal conductivity of the bonded staple blend gives it a distinct advantage over the spread continuous-filament tow, both compare favorably to the value for waterfowl down and to the program target. The insulating advantage that each offers over Quallofil, a premium, high-loft, staple-fiber insulator and over PolarGuard, the only commercially available, continuous-filament insulator, is substantial. For example, the bonded staple blend has a thermal conductivity of only 0.259 Btu-in/hr-ft²-°F, compared to 0.401 Btu-in/hr-ft²-°F for Quallofil; this indicates 55% greater insulating efficiency.

Mechanical characteristics such as minimum density (loft), compressional strain at 5 lb/in², compressional recovery from 5 lb/in², work of compression and recovery, and resilience are reported in Tables 12, 13, 14 and 15. Our use of two different gauge length conditions, one to ensure compliance with the intent of the Work Statement and one to provide data that can be compared with that of the previous contract^(1,2), doubles the scope of the compressional data. However, either data set can be used to obtain a valid understanding of the compressional characteristics of the two prototypes. Data for MIL Spec waterfowl down is included in Tables 12, 13, 14 and 15

TABLE 11. Thermal Conductivity of Two Insulator Prototypes

<u>Insulator Candidate</u>	<u>Batt Density (lb/ft³)</u>	<u>Batt Thickness (inches)</u>	<u>Avg. Temp (°F)</u>	<u>Apparent Thermal Conductivity, K (Btu-in/hr-ft²-°F)</u>	<u>Thermal Resistance, R (hr-ft²-°F/Btu)</u>
Bonded staple, 85/15 blend (0.5 dpf/4 dpf) binder	0.50	2.06	75.8	0.259	7.94
Spread continuous-filament tow (1.2 dpf)	0.50	2.00	74.2	0.282	7.09
Program Target	0.50	2.00	75.0	≤0.300	--
<u>Reference:</u>					
Duck down per MIL-F-43097G T II, Cl 1(1,7)	0.50	2.06	-75	0.271	7.62
<u>Reference:</u>					
Quallofil(8)	0.50	2.06	75.9	0.401	5.14
<u>Reference:</u>					
PolarGuard(1)	-0.50	-1.1	-75	-0.377	--

- All tests were made in accord with the plate/sample/plate method described in ASTM C518⁽⁴⁾.
- Heat flow was downward; T₁ = 100°F; T₂ = 50°F.
- A 0.5 oz/yd² non-woven scrim was used on the top and bottom of all samples.

TABLE 12. Compressional Properties of Bonded Staple-Fiber Batt; Individual Test Results Obtained with 0.5 lb/ft³ Test Density and 2.00 Inch Gauge Length

Roll Number	Minimum Density (lb/ft ³)	Compressional		Compress to 5 lb/in ² (lb-in)	Work to Recover to Zero Stress (lb-in)	Resilience ^a
		Strain at 5 lb/in ² (%)	Recovery (%)			
1	0.42	96	96	3.29	1.97	0.60
	0.41	96	99	4.01	2.23	0.56
	0.40	96	99	3.88	2.16	0.56
2	0.40	96	102	3.87	2.21	0.57
	0.40	96	105	4.14	2.31	0.56
	0.41	96	99	3.70	2.24	0.61
3	0.41	96	92	3.80	2.13	0.56
	0.41	96	94	3.88	2.15	0.55
	0.43	96	94	4.10	2.19	0.53
4	0.42	96	94	3.82	2.11	0.55
	0.40	96	98	3.98	2.13	0.54
	0.42	96	99	3.97	2.30	0.58
5	0.41	96	102	3.94	2.17	0.55
	0.40	96	99	3.77	2.11	0.56
	0.41	96	96	3.86	2.16	0.56
Average	0.41	96	98	3.87 ^b	2.17	0.56
Program Target	≤0.40	≥95	≥90	≤2.75	--	≥0.55
Reference Duck down per	0.24	95	102	4.91	2.60	0.53
MIL-F-43097G, T II, Cl 1(1,7)						

- a. Resilience equals work-to-recover divided by work-to-compress.
b. This value, obtained using an initial test density of 0.5 lb/ft³ and a gauge length of 2 inches, should not be directly compared to the Program Target Value. The value of work-to-compress is a direct function of sample thickness and so comparison with the target must be made with data for -0.8 inch thick, 0.4 lb/ft³ samples of the type delivered to the Government. See the text and Table 14.

TABLE 13. Compressional Properties of Batts of Spread Continuous-Filament Tow; Individual Test Results Obtained with 0.5 lb/ft³ Test Density and 2.00 Inch Gauge Length

Roll Number	Minimum Density (lb/ft ³)	Compressional Strain at 5 lb/in ² (%)	Compressional Recovery (%)	Work to Compress to 5 lb/in ² (lb-in)	Work to Recover to Zero Stress (lb-in)	Resilience ^a
1	0.42	95	99	5.83	2.58	0.44
	0.46	95	91	5.75	2.46	0.43
	0.43	95	90	6.51	2.76	0.42
2	0.42	95	92	5.99	2.50	0.42
	0.41	95	104	5.46	2.47	0.45
	0.45	95	97	5.62	2.57	0.46
3	0.47	95	97	5.38	2.34	0.43
	0.44	95	94	5.32	2.45	0.46
	0.46	95	95	5.75	2.80	0.49
4	0.42	95	104	6.10	2.80	0.46
	0.40	95	95	6.15	2.58	0.42
	0.44	95	94	6.19	2.66	0.43
Average	0.44	95	96	5.84 ^b	2.58	0.44
Program Target	≤0.40	≥95	≥90	≤2.75	--	≥0.55
Reference Duck down per	0.24	95	102	4.91	2.60	0.53

MIL-F-43097G,
T II, Cl 1(1,7)

- a. Resilience equals work-to-recover divided by work-to-compress.
b. This value, obtained using an initial test density of 0.5 lb/ft³ and a gauge length of 2 inches, should not be directly compared to the Program Target Value. The value of work-to-compress is a direct function of sample thickness and so comparison with the target must be made with data for ~0.8 inch thick, 0.4 lb/ft³ samples of the type delivered to the Government. See the text and Table 15.

TABLE 14. Compressional Properties of Bonded Staple-Fiber Batt; Individual Test Results Obtained with 4 oz/yd² (nominal) Samples^a

Roll Number	Gauge Length or Thickness (inches)	Areal Density (oz/yd ²)	Volume Density (lb/ft ³)	Compressional Strain at 5 lb/in ² (%)	Compressional Recovery (%)	Work to Compress to 5 lb/in ² (lb-in)	Work to Recover to Zero Stress (lb-in)	Resilience ^b
1	0.88	4.03	0.38	95	94	1.41	0.76	0.54
2	0.88	3.98	0.38	96	89	1.50	0.81	0.54
3	0.88	3.80	0.36	96	89	1.40	0.88	0.63
4	0.84	4.12	0.41	96	93	1.44	0.82	0.57
5	0.82	4.08	0.41	95	89	1.39	0.92	0.66
5A	0.84	3.94	0.39	96	90	1.45	0.82	0.56
Average	0.86	3.99	0.39	96	91	1.43	0.84	0.59
Program Target	--	4.0	≤0.40	≥95	≥90	≤2.75	--	≥0.55
Reference Duck down per MIL-F-43097C, T II, Cl 1(1.8)	0.80	4.00	0.42	94	109	2.11	1.12	0.53

- a. All of the above compressional properties were measured using the as-delivered insulator sample thickness as the gauge length. The same properties were also measured using a 2.00 inch gauge length and an initial density of 0.5 lb/ft³ to provide direct comparisons with previous work. See the text and Table 12.
- b. Resilience equals work-to-recover divided by work-to-compress.

TABLE 15. Compressional Properties of Batts of Spread Continuous-Filament Tow; Individual Test Results
Obtained with 4 oz/yd² (nominal) Samples^a

Sample Number	Gauge Length or Thickness (inches)	Areal Density (oz/yd ²)	Volume Density (lb/ft ³)	Compressional Strain at 5 lb/in ² (%)	Compressional Recovery (%)	Work to Compress to 5 lb/in ² (lb-in)	Work to Recover to Zero Stress (lb-in)	Resilience ^b
1	0.93	4.62	0.41	95	92	2.36	1.08	0.46
2	0.90	4.59	0.42	95	93	2.22	1.08	0.49
3	0.88	3.80	0.36	95	93	2.19	1.08	0.49
4	0.90	4.50	0.42	95	87	2.43	1.15	0.47
5	0.84	4.19	0.42	95	90	1.93	1.05	0.54
6	0.84	4.35	0.43	95	90	2.25	0.97	0.43
Average	0.88	4.34	0.41	95	91	2.23	1.07	0.48
Program Target	--	4.0	<0.40	>95	>90	<2.75	--	>0.55
Reference Duck down per MIL-F-43097G, T II, CL 1(1,8)	0.80	4.00	0.42	94	109	2.11	1.12	0.53

- a. All of the above compressional properties were measured using the as-delivered insulator sample thickness as the gauge length. The same properties were also measured using a 2.00 inch gauge length and an initial density of 0.5 lb/ft³ to provide direct comparisons with previous work. See the text and Table 13.
- b. Resilience equals work-to-recover divided by work-to-compress.

for reference. Both prototypes can be generally characterized as down-like in their compressional properties, although the bonded staple batt is more so. The compressional test data of Tables 14 and 15, for which the gauge length was set at the thickness of each 4 oz/yd² test batt, is perhaps more appropriate for comparison with program target values. The data for bonded staple batt is within all target values, and the only shortfall for the spread tow prototype is in resilience. This shortfall is not great (an average value of 0.48 was obtained; the target value was ≥ 0.55) and, through changes in fiber finish and surface bonding, could probably be eliminated.

Three program targets relating to laundering durability were given; each was an allowable decrease in dimension or performance after three of the previously described laundering cycles. Values for thickness change, planar shrinkage ("outer seam shrinkage") and change in thermal resistance (R value) are reported in Table 16, together with the corresponding target values and several related measurements. Also given in Table 16 are data sets for two bonded staple batt samples that were laundered using the AI consumer recommendation of cold water wash/cold water rinse. The quilting pattern of these samples differed from that of the "military" washing samples; the "consumer" washing samples had a 6 inch square stitch-line layout, whereas the "military" samples had parallel stitch lines (forming channels) spaced at 6 inches. The cold water washed samples with the alternative quilting layout were included to measure and demonstrate the laundering resistance of the bonded staple insulator under the much less rigorous consumer conditions. Some fiber migration occurred during laundering by both methods, but it was minimized under the consumer conditions and dimensional and performance changes were well within the program targets (see Table 16). However, use of the military method resulted in a relatively large thickness decrease of 22% (the target was $\leq 25\%$ and a decrease in thermal resistance (28%) that was greater than anticipated and significantly greater than the target of $\leq 10\%$. The prospects for improving the launderability of the bonded staple batt through improved fiber-to-fiber bonding are, we think, quite good. AI-funded experimentation toward this end is now underway and we plan to report the results to the Government, independently of this contractual effort, as soon as possible.

TABLE 16. Changes in Two Insulator Prototypes, Bonded Staple-Fiber Batt and Spread Continuous-Filament Tow, Sewn in Cover Fabrics, Due to Laundering

Sample No.	Sample Description	Laundering ^a Method	Areal Density, Batt (oz/yd ²)	Initial ^b Thk. (inch)	Thk. ^b After Wash (inch)	Thk. Change (\$)	Outer ^c Seam Shrinkage, Avg. (%)	Initial ^d K	K After ^d Wash	Initial ^e R	R After ^e Wash	R Change (\$)
3	Bonded staple-fiber batt; 6 inch channel quilting	Military	4.4	0.80	0.62	-22	1.4	0.268	0.284	2.99	2.18	-27
6	Bonded staple-fiber batt; 6 inch channel quilting	Military	4.4	0.79	0.61	-23	2.2	0.271	0.291	2.91	2.10	-28
1	Bonded staple-fiber batt; 6x6 inch square quilting	Consumer	4.1	0.71	0.69	-3	nil	0.267	0.284	2.66	2.43	-9
2	Bonded staple-fiber batt; 6x6 inch square quilting	Consumer	4.0	0.67	0.65	-3	nil	0.268	0.280	2.50	2.32	-7
7	Spread continuous-filament tow; 5 inch channel quilting	Military	4.8	0.83	0.80	-4	1.9	0.312	0.311	2.66	2.57	-3
8	Spread continuous-filament tow; 6 inch channel quilting	Military	4.5	0.86	0.82	-5	1.1	0.308	0.305	2.79	2.69	-4
	Program Target	Military	4.0	--	--	<25	<5.0	<0.300	--	--	--	<10

a. "Military" denotes the military laundering method specified in Cotton Procedure Method 5556 of Federal Standard No. 191A(5), except for minor deviations as described in the text. The dryer stack temperature was 140°F. The 24x24 inch samples were sewn between cover fabrics with 6 inch channels parallel to the machine direction of the batts. All data above was obtained after three washing and drying cycles.

"Consumer" denotes the laundering method that Albany International will recommend to consumers. It consists of: cold water wash, cold water rinse and "permanent press" machine drying. The 24x24 inch samples were sewn between cover fabrics with 6 inch quilted squares. All data above was obtained after three washing and drying cycles.

b. Average from thickness measurements at eight locations on each sample under a pressure of 0.002 psi.

c. The shrinkage value reported for each sample is the average of four determinations; two in the warp direction and two in the fill direction of the cover fabric.

d. Units for K, thermal conductivity, are: Btu-in/hr-ft²-°F. Measurements were made with heat flow up and insulators sewn in cover fabrics; see text.

e. Units for R, thermal resistance, are: hr-ft²-°F/Btu. Measurements were made with heat flow up and insulators sewn in cover fabrics; see text.

Table 16 also shows that the laundering resistance of the spread continuous-filament tow insulator, even under the severe military conditions, is very good; for example, the maximum change measured in thermal resistance was only 4%. The 6 inch channel construction, with stitch lines parallel to the insulator machine direction that is specified for the laundry samples optimizes the performance of the spread tow configuration. The orientation of the spread continuous-filaments is nearly perpendicular to the machine direction (as a result of cross-lapping) and so through-stitching parallel to the machine direction locks the filaments into place with a degree of permanence that is unique. This sewing-line/fiber orientation should, of course, be utilized in as many continuous-filament tow insulator applications as possible.

The water repellency of the two prototype insulators was characterized by measuring: (1) weight increase after 20 minutes of immersion ("water absorptive capacity;" Table 17), (2) loft (thickness) retention after 20 minutes and after 6 hours of immersion (Table 18) and (3) density increase after 20 minutes and after 6 hours of immersion (also in Table 18). The third parameter, density increase, manifests the net result of the first two. The water repellency of the bonded staple insulator, in terms of all three parameters, is extremely good. An average absorptive capacity, after 20 minutes, of 106% (6% weight increase due to water absorption) was obtained, which is low in any terms and is very low compared to the $\leq 150\%$ target. The loft retention for 3.4 oz/yd² bonded staple samples, after both 20 minutes and 6 hours of immersion, was 100%; i.e., the thickness did not change. The much heavier, standard compression samples, which are 2 inches thick and have an areal density of 12.0 oz/yd², retained 97% of their loft after 6 hours of immersion. The net effect of 6 hours of immersion on these heavy, worst case, samples was an average density increase of only 18%. All water repellency related measurements for the bonded staple batts yielded values well within the program targets. This performance is, we think, a result of finish optimization and the relatively small interfiber pores in the uniformly opened, microfibrinous batts.

TABLE 17. Water Absorptive Capacity of Two Insulator Prototypes After Twenty Minutes of Immersion

Roll No.	Bonded Staple Batt		Spread Continuous-Filament Tow	
	Wet Weight (g)	Absorptive Capacity (%)	Wet Weight (g)	Absorptive Capacity (%)
1	1.56	104	14.31	954
	1.55	103	7.83	522
	1.55	103	10.76	717
2	1.61	107	8.70	580
	1.61	107	16.57	1104
	1.58	105	11.53	769
3	1.56	104	11.66	777
	1.58	105	18.96	1264
	1.57	105	10.18	679
4	1.59	106	9.97	665
	1.64	109	15.83	1055
	1.58	105	13.28	885
5	1.59	106	--	--
	1.60	107	--	--
	1.63	109	--	--
Average	1.59	106	12.46	831
Program Target	--	≤150	--	≤150

All of the above is based upon a dry sample weight of 1.50 g. Absorptive capacity was calculated by the method implicit in the Work Statement, i.e., wet weight divided by dry weight times 100 to obtain value as a percentage.

TABLE 18. Wet Loft Retention of Bonded Staple Batt and Spread Continuous-Filament Tow Insulator Prototypes

Sample Description	After 20 Minutes Immersion				After 6 Hours Immersion					
	Dry Thickness (inches)	Dry Density (lb/ft ³)	Thickness (inches)	Loft Retention (%)	Density (lb/ft ³)	Density Increase (%)	Thickness (inches)	Loft Retention (%)	Density (lb/ft ³)	Density Increase (%)
Bonded staple, 35/15 blend; std. compression specimen (12.0 oz/yd ²)	2.18	0.46	2.13	98	0.49	6	2.13	98	0.52	13
	2.18	0.46	2.10	96	0.53	15	2.12	97	0.55	20
	2.23	0.45	2.23	100	0.49	9	2.13	96	0.54	20
Average		0.46		98		10		97		18
Bonded staple 85/15 blend; 3.4 oz/yd ²	0.64	0.42	0.64	100	0.44	5	0.64	100	0.49	17
	0.68	0.44	0.68	100	0.44	0	0.68	100	0.49	11
	0.64	0.43	0.64	100	0.46	7	0.64	100	0.48	12
Average		0.43		100		4		100		13
Spread continuous-filament tow; std. compression specimen (12.0 oz/yd ²)	2.58	0.39	2.28	88	1.12	187	2.08	81	2.21	467
	2.44	0.41	2.18	89	1.06	158	2.08	85	1.45	254
	2.46	0.41	2.18	89	0.74	80	2.04	83	1.17	185
Average		0.40		89		142		83		302
Spread continuous-filament tow; 4.2 oz/yd ²	0.93	0.42	0.88	94	1.84	338	0.73	78	3.88	824
	0.78	0.39	0.76	97	1.31	236	0.70	90	2.77	610
	0.84	0.41	0.84	100	1.37	234	0.75	89	2.85	595
Average		0.41		97		269		86		676
Target Values		≤0.40		≥95				≥50		

The water absorptive capacity of the continuous-filament tow insulator prototype was found to be surprisingly high, as reported in Table 17. The average capacity, after 20 minutes of immersion, was 831% (the target value is $\leq 150\%$); the water absorbed increased the sample weight eightfold. The loft loss of these samples (Table 18) was greater than that of the bonded staple batts, but was acceptable in terms of program targets. Density increases, due primarily to the high water absorption rate, were also very high.

Midway through the spread tow insulator development, as plans for a more appropriate tow supply were being made with Hoechst Celanese, a decision was made to employ the standard PolarGuard water-repellent finish. Later, during process development at Reliance Products, the advantage of utilizing the in-place spray adhesive system used for PolarGuard became evident and it, too, was adopted. Each of these decisions was made with the anticipation that the water repellency of the fine-denier spread tow prototype would be at least as good as that of PolarGuard. The unexpectedly poor result led to closer laboratory observation and it was discovered that the surface adhesive, a methylacrylate, was extremely hydrophilic and responsible for the insulator's low water repellency. It was found that inner portions of the continuous-filament tow batts, those unaffected by the surface adhesive, had a water absorptive capacity of approximately 125% after 20 minutes of immersion (the target value is $\leq 150\%$). Thus, we concluded that the standard silicone finish used for PolarGuard would provide the required water repellency. At this point, we cannot specifically attribute the spray adhesive deficiency. Suspicion that the curing temperature used at Reliance Products may have been too low led to several attempts at post-curing in our laboratory, but without any significant improvements in water repellency. However, we are certain that improvement in the water repellency of the adhesive could be made. We would first experiment with curing conditions and then, if a water repellency deficiency still existed, investigate hydrophobic additives for the adhesive.

V. SUMMARY OF INSULATOR LABORATORY EVALUATION, OVERALL FUNCTIONALITY AND MANUFACTURING FEASIBILITY

A. Summary of Laboratory Evaluation

The two insulator forms for which manufacturing processes were developed are similar in that the fibrous components of each were selected, with emphasis upon diameter and finish, to utilize the findings of the recent, previous AI Research/Natick Center study^(1,2). Consequently, each provides performance that approximates that of waterfowl down. In fact, the performance characteristics of the bonded staple fiber batt are equivalent to or better than those of MIL Spec down. The performance characteristics of both prototypes are summarized in Table 19, together with program target values and reference values for 80/20 down/feathers, water repellent treated, MIL Spec waterfowl down. The general compliance of the individual performance characteristics of both forms with program targets and favorable comparison of these characteristics with those of down are readily apparent in Table 19. Most noteworthy among the performance properties of the prototypes are:

1. The very low thermal conductivity values achieved for both,
2. The laundering durability of the continuous-filament tow form,
3. The excellent correlation between the compressional properties of the bonded staple batt and those of down (the down-like hand of the bonded staple form is a result of this),
4. The extremely low water absorption exhibited by the bonded staple batt, and
5. The excellent wet loft retention of both prototypes.

Each prototype form also exhibited one significant shortfall among the properties measured, as follows:

1. The bonded staple batt, although performing very well in home-consumer laundering tests, did not fully meet program targets for resistance to military laundering. The thermal resistance decrease due to laundering was 28% in comparison to a target value of $\leq 10\%$.

TABLE 19. Summary of Performance Properties for Two Insulator Prototypes

<u>Performance Property</u>	<u>Bonded Staple- Fiber Batt</u>	<u>Spread C.F. Tow</u>	<u>Program Target</u>	<u>MIL Spec^a Down</u>
Thermal conductivity (Btu-in/hr-ft ² -°F)	0.259	0.282	≤0.300	0.271
Minimum density (lb/ft ³)	0.41	0.44	≤0.40	0.24 ^b
Thickness decrease due to laundering (%)	22	4	≤25	--
Thermal resistance decrease due to laundering (%)	27	3	≤10	--
Shrinkage due to laundering (%)	1.8	1.5	≤5	--
Work to compress (lb-in) ^c	1.43	2.23	≤2.75	2.11 ^d
Resilience ^c	0.59	0.48	≥0.55	0.53 ^d
Compressional strain at 5 lb/in ² (%) ^c	96	95	≥95	94 ^d
Compressional recovery from 5 lb/in ² (%) ^c	91	91	≥90	109 ^d
Absorptive capacity; 20 minute immersion time (%)	106	831	≤150	161
Wet loft retention; 20 minute immersion time (%) ^c	100	97	≥95	77 ^d
Wet loft retention; 6 hr immersion time (%) ^c	100	86	≥50	59 ^d

- a. Reference data for down/feathers, 80/20, per MIL-F-43097G, Type II, Class 1(1,8).
- b. The minimum density that can be measured should be differentiated from the as-used density, which typically is about 0.5 lb/ft³.
- c. The compressional properties data set selected for the above summary and for final comparison with program targets is the set based upon gauge lengths equal to as-delivered sample thicknesses. Compressional data for tests made with a 2.00 inch gauge length was also included herein (Tables 12 and 13) to provide direct comparisons with previous work.
- d. This data was obtained using a 4 oz/yd² layer of down with a gauge length of 0.80 inch and an initial density of 0.42 lb/ft³ to provide directly comparable reference data.

2. The spread continuous-filament tow prototype absorbed water at an unacceptable rate. Its absorptive capacity after 20 minutes of immersion was 831%; the target value was $\leq 150\%$.

This summary of positive and negative performance characteristics, together with the data summary of Table 19, provides a realistic overview of the potential of both insulator prototypes. Although each has one deficiency that is significant in terms of the intended military application, these deficiencies appear to be correctable. In each case, focused product improvement effort will almost certainly make each insulator form an outstanding alternative to high loft insulators now in use. The insulating efficiency of the prototypes, as indicated by low thermal conductivity values of 0.259 and 0.282 Btu-in/hr-ft²-°F for bonded staple batt and spread continuous-filament tow, respectively, make them unique among synthetic insulators. Thermal conductivity reference values for Quallofil and PolarGuard, previously given herein, are 0.401 and 0.377 Btu-in/hr-ft²-°F, respectively. A thermal conductivity value of 0.271 Btu-in/hr-ft²-°F was previously measured, and also reported herein, for MIL Spec duck down.

B. General Functionality and Manufacturing Feasibility

There are other considerations, in addition to laboratory performance data, that reflect the current state-of-development and the potential utility of each insulator prototype. Although manufacturing feasibility has been clearly demonstrated for each type, and the samples produced are wholly functional insulators, brief further discussion will help to more fully characterize each insulator.

The pilot line for production of bonded, staple-fiber batt that has been assembled in our Albany, New York plant is a complete entity dedicated solely to pilot production and development of AI Primaloft^R. Primaloft is, essentially, the bonded staple prototype described herein and its current state-of-development is such that samples are now being delivered, sewn into garments and use-tested in sleeping bags and winter clothing. Initial, relatively rugged, wear/wash testing of parkas (using cold water washing) by a

large, independent merchandiser has yielded excellent results and generated considerable enthusiasm on their part. Improvements are continually being made to the pilot equipment and developmental advances are being made with the product as well. For example, a relatively minor product change that significantly improves fiber-to-fiber bonding is now being incorporated and it is expected to improve resistance to hot water washing. The advanced state-of-development of the staple batt form and the existence of a dedicated, operating pilot line make it attractive for near-term military use. A reliable fiber source exists, Teijin Ltd. of Japan, and a U.S. fiber manufacturer plans to be producing the primary fiber component, 0.5 denier polyester staple, by the end of 1989.

The bonded staple-fiber batt, as it is now being pilot-line produced and as delivered to the Government, is very uniform in terms of fiber mixing, fiber distribution and fiber separation (fiber opening). This uniformity is readily apparent to the unaided eye and can be observed on a microscopic level as well. The batt is currently being rolled and shipped with a lightweight (0.3-0.5 oz/yd²) nonwoven scrim on one or both faces. This aids all handling steps from roll-up through final fabrication and eliminates stretching. In most cases, these scrims, or cover fabrics that could be substituted for them, will remain in place and become a quilted surface. As is the case with other high-loft staple insulators, quilting is necessary to minimize fiber migration; a 6x6 inch square (or diamond) pattern works well and 6 inch channel quilting, with stitch lines parallel to the machine direction, will probably be almost as effective.

At present, the bonded staple batt form (Primaloft) is a fully functional, direct down substitute that is limited for military use only by its cold water washing requirement. This issue is now receiving attention and the prospects for lessening the importance of cold water washing and perhaps eliminating the recommendation entirely are good.

The tow spreading line used to produce the samples delivered to the Government is a PolarGuard production line that closely approximates that which would ultimately be required to produce the 1.2 dpf spread tow insulator described herein. However, detailed changes would be necessary to improve batt uniformity. A tendency for the fine-fiber web to fold erratically at the cross-lapper and slip-stick drafting at several points on the line resulted in systematic, readily observed nonuniformities in the final samples. In spite of those obvious flaws, the overall appearance and the apparent sturdiness of the samples reinforces the general potential demonstrated by the laboratory performance data. A unique advantage of the spread tow form results from its continuous-length, cross-machine fiber arrangement. When reinforced by quilting in the machine direction or by any other machine-direction sewing operation (as in shingle-construction sleeping bag fabrication), the final textile assembly becomes unusually strong and durable. The most significant performance drawback observed, the high water absorptive capacity, can almost certainly be improved through changes to the hydrophilic adhesive system. The fiber supply required, 1.2 dpf, 250,000 total denier polyester tow, is not now a commercially available product, but our fiber-sample supplier, Hoechst Celanese, has demonstrated great interest in this insulator approach.

The lack of a dedicated pilot line, the need for further product and process improvement, and the lack of a commercial fiber source combine to make the spread tow insulator's present state-of-development less than that of the blended, bonded staple batt. Its performance potential, although not as great as that of the bonded staple form, is very good and, when it can be sewn to take advantage of the spread continuous-filament configuration, it offers excellent durability.

VI. RECOMMENDATIONS FOR ADVANCEMENT OF BOTH INSULATOR FORMS

The preceding summary of laboratory performance, general functionality and manufacturing feasibility leads conclusively to a recommendation that both prototype insulator forms be fully developed to exploit their considerable potential. It is apparent that each can fulfill an important need and the development efforts that remain are, in fact, minor. This is especially true in the case of the bonded staple batt. Efforts to eliminate its cold water washing requirement, which to our knowledge is the only technical impediment to military adoption, are underway and Albany International intends to submit improved samples (at its own expense, without contractual obligation) within a month.

Additional work remains to develop the spread tow form to the commercialization level of the bonded staple insulator. Attainment of this level will require: (1) a commercial fiber source, (2) ready, regular access to a tow spreading line, (3) improvements in uniformity through fine-tuning the mechanical elements of the line and (4) improvements in water repellency.

Albany International is committed to adapting its bonded staple insulator (Primaloft) to make it wholly acceptable for military use. The potential exhibited by the spread tow insulator form and its different balance of positive and negative attributes makes it, too, worthy of continued commitment.

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