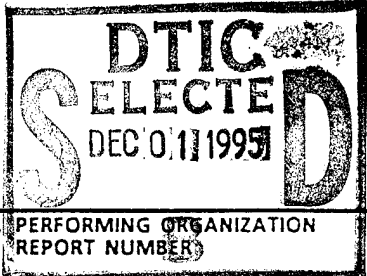


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13. ABSTRACT (Maximum 200 words) Environmentally durable high temperature polymer matrix resins are critical in the design of near-term high performance supersonic aircraft. Currently available 6F based polymers are thermally stable, but are expensive and difficult processable into void-free laminates. 3F polymers have demonstrated equivalent thermal stability and processability, but are amenable to more facile, environmentally acceptable synthetic procedures. In the current program, Semi-Interpenetrating Polymer Network (SIPN) blends of ethynyl and phenylethynyl terminated 3F polymers have been formulated, synthesized, and scaled up to quantities amenable to prepregging. Solution prepregging techniques were used by YLA, Inc. to fabricate 12" unidirectional prepreg tape. A series of test panels was fabricated from the IM7 prepreg tape, using dielectric monitoring procedures, from a 1:1 3F SIPN blend of phthalic anhydride terminated thermoplastic 3F oligomer with a phenylethynyl terminated 3F oligomer. Solution prepregging techniques were used to prepare unidirectional IM7 fiber prepreg tape. The primary goals of the program, including conception, synthesis development, scaleup, prepregging and panel fabrication, were all met. The void content of the laminates was somewhat higher than acceptable, probably due to the high melt viscosity and solvent inclusion. A plan, using powder prepregging, was offered to alleviate the void problem.				
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August 1994

Contract DAAL03-92-C-0021

# **THERMALLY STABLE ORGANIC POLYMERS FINAL TECHNICAL REPORT**

Dr. R. H. Boschan

U. S. Army Research Office

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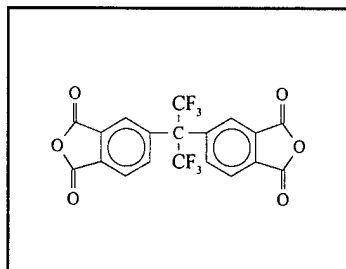
THERMALLY STABLE ORGANIC POLYMERS (TSOPS)  
U.S. ARMY RESEARCH OFFICE CONTRACT NUMBER DAAL03-92-C-0021  
FINAL TECHNICAL REPORT

STATEMENT OF THE PROBLEM

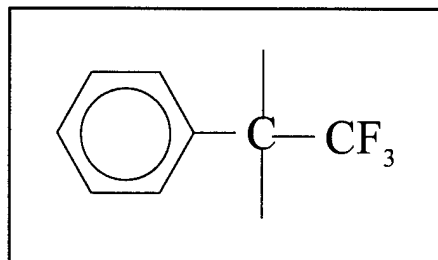
High temperature polymers for use as matrix resins in processible high performance composite materials are of critical importance in the design of near-term high performance military and commercial supersonic aircraft. Utilization of composite materials in place of metals in aircraft structures results in higher specific strength and stiffness, reduced corrosion, and, in the case of military aircraft, suppressed radar signature. Current NASA sponsored developmental research at Boeing, McDonnell Douglas, Northrop and Lockheed is directed toward composite matrix resins and adhesives for application on primary and secondary structures for the High Speed Civil Transport (HSCT), a commercial transport to be manufactured by Boeing with a projected cruising speed of Mach 2.4, capable of carrying 300 passengers. The elevated service temperatures of the HSCT carry a long-term durability requirement of 60,000-120,000 hours. Since "real-time" data on composite service for these extended time periods does not currently exist, high performance materials are currently being subjected to accelerated testing. In the NASA Advanced Composite Technology (ACT) and High Speed Research (HSR) Programs, state of the art powder prepreg and towpreg techniques, including advanced towpreg, prepreg tape and powder preforms are being utilized in fabrication of complex composite structures.

Composite matrix resins for elevated temperature service, particularly in the temperature range from 400°F(204°C) to 700°F(371°C), are all polyimides. Polyimides with the highest thermooxidative stability generally contain the hexafluoroisopropylidene group,  $\text{CF}_3\text{CCF}_3$ , (6F) as a connecting entity between aromatic structural groups in the polymer backbone. Recently reported work has shown that substitution of the phenyltrifluoroethylidene moiety,  $\text{C}_6\text{H}_5\text{CCF}_3$ , (3F) for the 6F group results in a polyimide matrix resin with comparable thermooxidative stability and processability, but with less expensive prepolymer materials and with synthetic procedures that are less labor intensive and more environmentally acceptable.

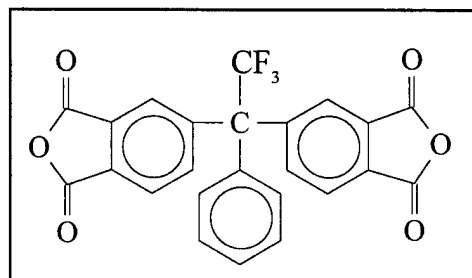
The most stable commercial organic matrix composite materials all contain the (6F) moiety as a key portion of the polymer backbone. These materials are represented by Avimid N, PMR-II, and AFR700B. An essential monomer for all of these products is the 6F anhydride I. A key intermediate in the manufacture of this anhydride is hexafluoroacetone, which is expensive, toxic, and available in limited supply. To preclude the necessity for utilization of 6F anhydride, intermediates containing the phenyltrifluoroethylidene (3F) group (II) have been synthesized. Thus, in earlier work at United Technologies, the 3F anhydride (III) has been synthesized.



I. 6F DIANHYDRIDE



II. PHENYLTRIFLUOROETHYLIDENE GROUP



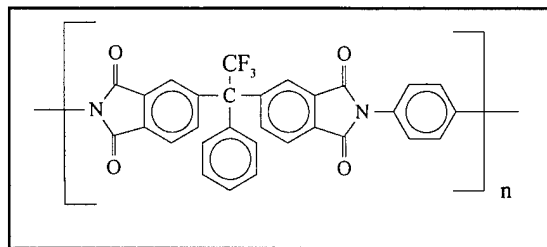
III. 3F DIANHYDRIDE

The 3F anhydride III has been used to provide a portion of the backbone in a polyimide polymer (IV), analogous to the duPont Avimid N (V). Polymer IV, with the 3F group II substituted for the 6F group in Avimid N (V), has been shown to have a thermooxidative stability comparable with (V).

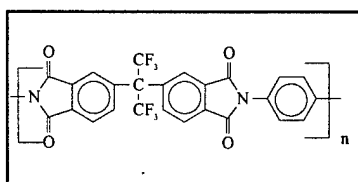
#### RESULTS OF PROGRAM STUDIES

The very high melt viscosities and process temperatures of linear thermoplastic polymers such as IV and V make it very difficult to process high quality laminates of these materials, due to the restricted resin flow and fiber wetting created by the low flow characteristics of these polymers. To address this problem, a two component semiinterpenetrating polymer network (SIPN), consisting of a thermosetting, ethynyl terminated component VII, blended with a thermoplastic component VIII was initially proposed for the current program. The thermoset component oligomer VII has a backbone structure made up of the 3F diamine VI and the commercially available biphenyldianhydride (BPDA), endcapped with 3-aminophenylacetylene, a commercial product of National Starch and Chemical Corporation. In work performed at Virginia Tech and more recently at Maxdem, Inc., synthetic procedures for 3F monomers, particularly 3F diamine (VI), have evolved which are amenable to large scale production of 3F polyimides. The synthetic procedures for the key 3F intermediate, trifluoroacetophenone, and its conversion into 3F diamine VI, have been modified and scaled up by Maxdem, Inc., one of the subcontractors on this Program. These procedures are summarized in Figure 1 and in the appendix of this report.

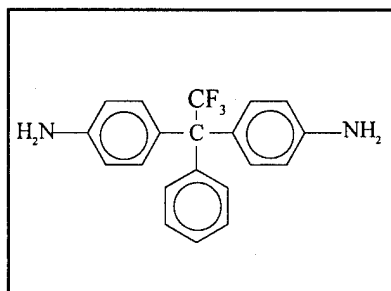
In addition, a summary of the preparation of four batches of 3F polyimides VII and VIII, synthesized from diamine VI and biphenyl dianhydride (BPDA), is included.



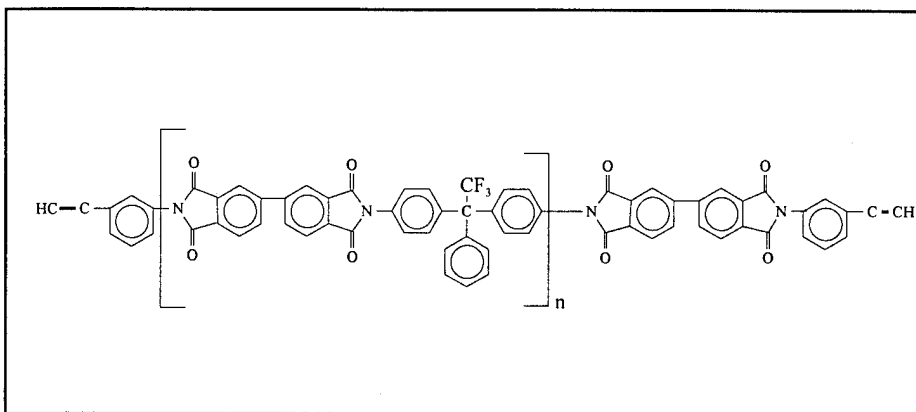
IV. 3F POLYIMIDE POLYMER



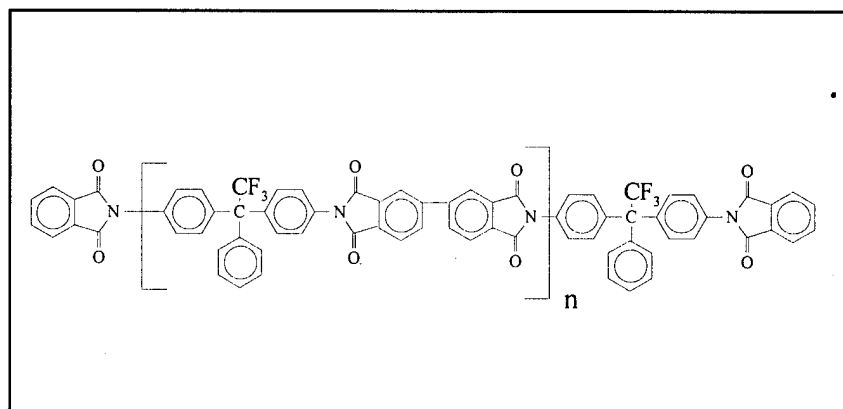
V. DUPONT AVIMID N



VI. 3F DIAMINE



VII. ETHYNYL TERMINATED 3F OLIGOMER



VIII. PHTHALIC ANHYDRIDE TERMINATED 3F OLIGOMER

## MONOMER AND PREPOLYMER PREPARATION

### Trifluoroacetophenone

Initial work at Maxdem focused on the scale-up of the synthetic procedure for trifluoroacetophenone, which was originally developed by McGrath and coworkers at Virginia Tech.

Modifications in the synthesis included elimination of the environmentally unacceptable carbon disulfide as solvent and use of ambient reaction temperature in place of the more cumbersome -40°C. 4 kilograms of trifluoroacetophenone were prepared for use in synthesis of 3F Diamine VI.

### 3F Diamine

Additional process changes were made in the synthetic procedure for VI to facilitate scale-up procedures. In particular, the hydrochloric acid catalyst was replaced by the more acidic p-toluenesulfonic acid. This change resulted in a reduction of the quantity of by-products and increased yield of purer product. By this procedure, 3 kg of monomer grade 3F diamine was prepared, accompanied by additional material requiring at least one additional recrystallization.

### 3F Polyimide Oligomers

Four batches of approximately 100g. each of endcapped 3F Polyimide oligomers were prepared in the laboratories at Maxdem, Inc. Two batches were endcapped with aminophenylacetylene, to yield the ethynyl terminated prepolymer VIII, and two batches were endcapped with phthalic anhydride, giving rise to the thermoplastic oligomer IX. Table I shows the calculated and measured (GPC) number average molecular weight, weight average molecular weight, and intrinsic viscosity for each experimental batch.

TABLE 1. ENDCAPPED 3F POLYIMIDE POLYMERS

Batch	Endcap	Calculated MW <sub>n</sub>	GPC MW <sub>n</sub>	GPC MW <sub>w</sub>	η
1	APA	4K	7140	12332	0.24
2	APA	8K	14339	25710	0.35
3	PA	15K	21471	37413	0.44
4	PA	25K	24292	42881	0.47

APA - Aminophenylacetylene Endcapped

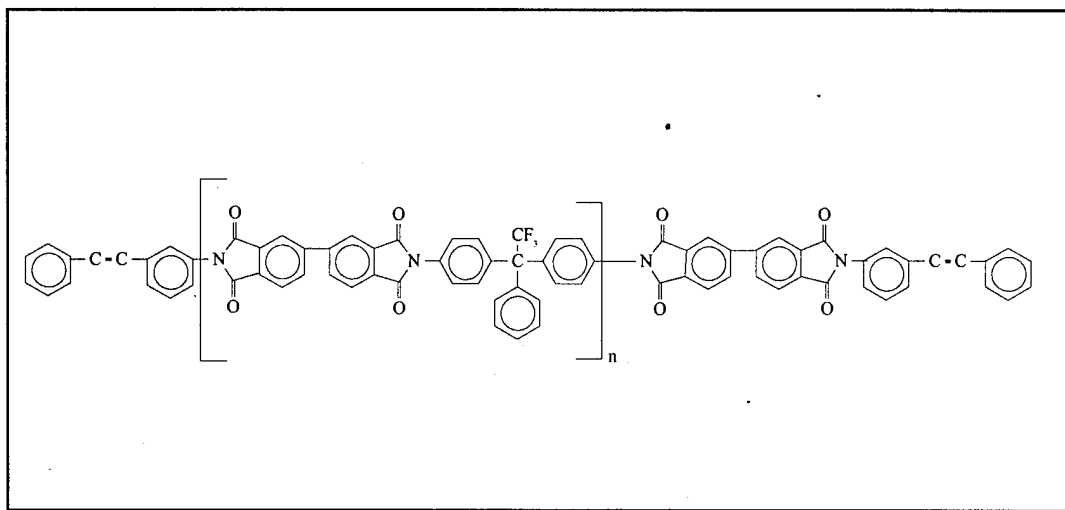
PA - Phthalic Anhydride Endcapped

GPC relative to polystyrene standard

Intrinsic viscosity measured at 30°C, 0.5g./ml in NMP

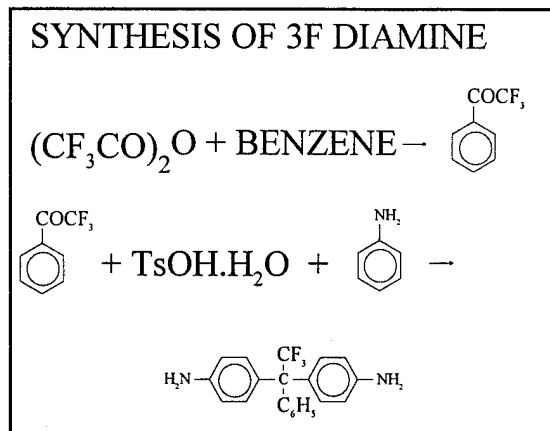
The melt/flow characteristics of the initial 3F polymer batches were not acceptable for composite processing. It was apparent that the acetylene endcapped polymers were undergoing polymerization (cure) prior to melting, and thus the ethynyl terminated 3F polyimides were not suitable for processing into composite laminates. The Program emphasis was shifted to SIPN blends of phenylethynyl terminated polyimides, and a SIPN blend of a phenylethynyl terminated 3F polyimide thermoset component IX with the previously prepared phthalic anhydride terminated 3F polyimide thermoplastic component VIII was selected. Both the thermoset and

thermoplastic components have the same 3FDA/BPDA backbone, but the thermoset component is endcapped with 3-(phenylethynyl)aniline. The synthetic procedure used for the preparation of 3-(phenylethynyl) aniline is shown in Figure 2. Small amounts of these phenylethynyl terminated (PET) polymers were prepared. These materials showed promise of more superior melt behaviour and a more favorable processing window due to their higher cure temperatures. Rheometrics and differential scanning calorimetry (DSC) of sample blends indicated good processability characteristics. Rheometrics of 1:1 and 3:1 blends of thermoset:thermoplastic components are shown in Figure 3, and the DSC of the phenylethynyl terminated 3F polyimide SIPN component is shown in Figure 4. Examination of the DSC and rheometrics data shows a reasonable processing window between the polyimide melt phase and the dissipation of the polymerization exotherm. A 1:1 blend of the two SIPN components was selected, and this blend was scaled up to a quantity of about 3.5 kilograms. Solvent prepregging of this blend on Hercules IM7 graphite fibers using cyclopentanone as solvent provided about 200 ft. of 12" prepreg tape having a resin content of 35+/-3%.

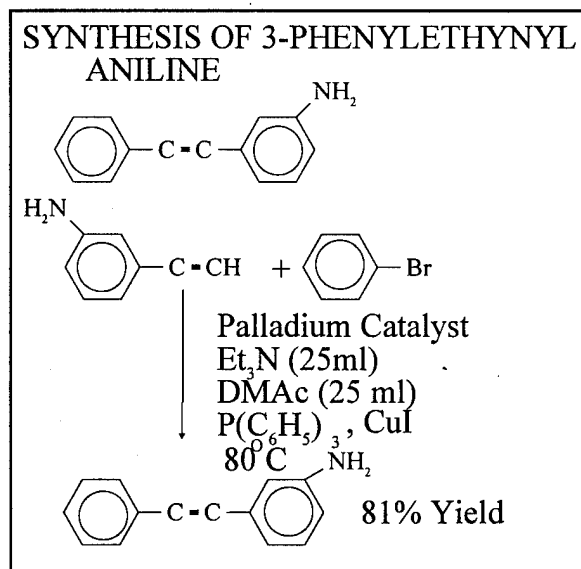


## IX. PHENYLETHYNYL TERMINATED 3F OLIGOMER

Making use of dielectric cure monitoring techniques, a number of laminates were laid up and cured to fabricated flat panels. The size, ply thickness and ply orientation of these panels are shown in Table 1. The use of dielectric cure monitoring provided a "window" by which key events in the cure cycle could be followed in real time. A typical dielectric monitoring trace is shown in Figure 5. By use of appropriate sensors for resistance and capacitance monitoring, events such as solvent egress, viscosity changes, minimum viscosity, cure exotherm, gelation, and crosslinking, with suitable interpretation, can be followed during the cure.



**Figure 1. SYNTHESIS OF 3F DIAMINE**



**Figure 2. SYNTHESIS OF PHENYLETHYNYLANILINE**

## DISCUSSION OF EXPERIMENTAL RESULTS

A semi-interpenetrating polymer network, (SIPN) containing a 1:1 blend of a thermoplastic phthalic anhydride endcapped 3F polyimide oligomer VIII and a thermosetting 3F polyimide oligomer IX has been synthesized, scaled up, impregnated on graphite tape, and fabricated into composite panels. Program activities on this SIPN system have included (1) Monomer and Oligomer Synthesis; (2) Resin Scaleup; (3) Differential Scanning Calorimetry (DSC) and Rheometrics; (4) Blending to SIPN; (5) Solution Impregnation on IM7 6K Tow to Yield 12" Wide Prepreg Tape; (6) Fabrication of 8-Ply, 16-Ply and 24-Ply Unidirectional Laminates, and 12-Ply, +/- 45° Laminates, with Application of Dielectric and Resistance Cure Monitoring; (7) Ultrasonic C-Scan and Tag-end Tests on Panels.

### OBSERVATIONS AND RESULTS

Considerable care was necessary during the cure cycle in order to dissipate the large cure exotherm. (See Figure 4, Differential Scanning Calorimetry) Some of the earlier attempts at panel fabrication resulted in burned panels. After development of a suitable cure cycle by dielectric monitoring, fabricated panels up to 24 plies thickness appeared visually to be well consolidated, however ultrasonic C-scan, microscopic analyses, and quantitative void content by acid digestion revealed that the level of porosity was of the order of 2-3%, compared to an acceptable level of porosity of <2%. Resin starved areas on some panels indicated that improved resin dispersion would have alleviated the porosity problem. With minimum resin viscosity prior to cure of about 2000 poise, resin flow may not be adequate prior to onset of the cure exotherm.

### PROPOSED SOLUTION AND PROGRAM MODIFICATION

Approximately 1 kilogram of SIPN resin powder is remaining after solution prepregging. It is recommended that powder prepreg be fabricated from this resin powder, followed by fabrication of towpreg into tape, and layup and cure of additional laminates. During powder impregnation, dispersion of resin throughout the fiber bundles is considerably more extensive, thus reducing the sensitivity of laminate quality to resin flow.

### ADDITIONAL RECOMMENDED PROGRAM TASKS

While the principal objectives of the Program, including conception, synthesis development, scaleup, prepregging, and composite panel fabrication and assessment, have all been fulfilled, there are certain recommended tasks directed toward the improved quality of laminates. These tasks apply to composite panel fabrication from 3F SIPN polyimide blends, in any continuation of the work on this program, or to other polymeric blends in future programs directed toward elevated temperature

composite polyimide applications. These tasks incorporate powder prepreg technology. Impregnation of reinforcing fibers with powdered prepolymer has been shown to allow for better dispersion of the prepolymer within the fiber bundles, thus permitting consolidation at higher process viscosities. In addition, impregnation of fiber tow bundles via a water slurry process or a dry powder fluidized bed substantially minimizes the presence of organic solvents in the fiber/resin prepreg, thus greatly reducing or eliminating voids due to solvent entrapment.

**Task 1.** Fabrication of powder prepreg tape. This includes drying and micronizing the SIPN blend, powder impregnation and sintering of graphite tow, and consolidation of impregnated graphite tow into tape.

**Task 2.** Fabrication of test panels from powder towpreg tape. Prepreg tape would be used to fabricate test panels. Small panels (6-8 plies) would be fabricated using dielectric cure monitoring procedures to optimize the process cycles, followed by fabrication of larger panels. The size, thickness and number of test panels will be dependent upon the quantity of prepreg tape produced.

**Task 3.** Quality assurance of fabricated panels. The quality of the panels from powder prepreg tape is assessed by use of ultrasonic C-scan, microscopic analyses, resin content by chemical degradation, and grinddown to determine ply integrity.

**Task 4.** Mechanical testing of fabricated panels. Panels are tested in tension, compression and shear, depending upon the number, size and thickness of panels available from fabrication.

#### TASK PERFORMANCE

Virginia Polytechnic Institute and State University (Virginia Tech) has the capability and personnel to perform the above tasks. Virginia Tech (Professors James McGrath and Judy Riffle) submitted a proposal to Lockheed Aeronautical Systems Company covering the performance of the above tasks, however these tasks were not performed on the current Program due to the termination of the technical portion of the Thermally Stable Organic Polymers (TSOP) Program at the end of June, 1994. Other academic organizations capable of performing these tasks include Michigan State University (Professor Larry Drzal) and Georgia Institute of Technology (Professor John Muzzy).

#### TECHNICAL PRESENTATION

"Preparation, Scaleup and Evaluation of 3F Polyimide Matrix Composites", Presented at High Temple Workshop XIV, Cocoa Beach, Florida, February 2, 1994.

TABLE 1. LAMINATES FROM 3F SIPN POLYIMIDE BLEND

LAMINATE #	LAMINATE SIZE	NUMBER OF PLYS	PANEL ORIENTATION
1	18"x18"	8	0°/90°
2	12"x14"	8	unidirectional
3	12"x14"	16	unidirectional
4	12"x14"	24	unidirectional
5	2"x2"	4	unidirectional
6	2"x2"	4	unidirectional
7	12"x14"	16	unidirectional
8	12"x14"	16	unidirectional
9	12"x14"	16	unidirectional

Figure 3

## RHEOMETRICS

MELT VISCOSITY PROFILE OF SOLUTION BLENDED  
3F POLYIMIDES VIII AND IX

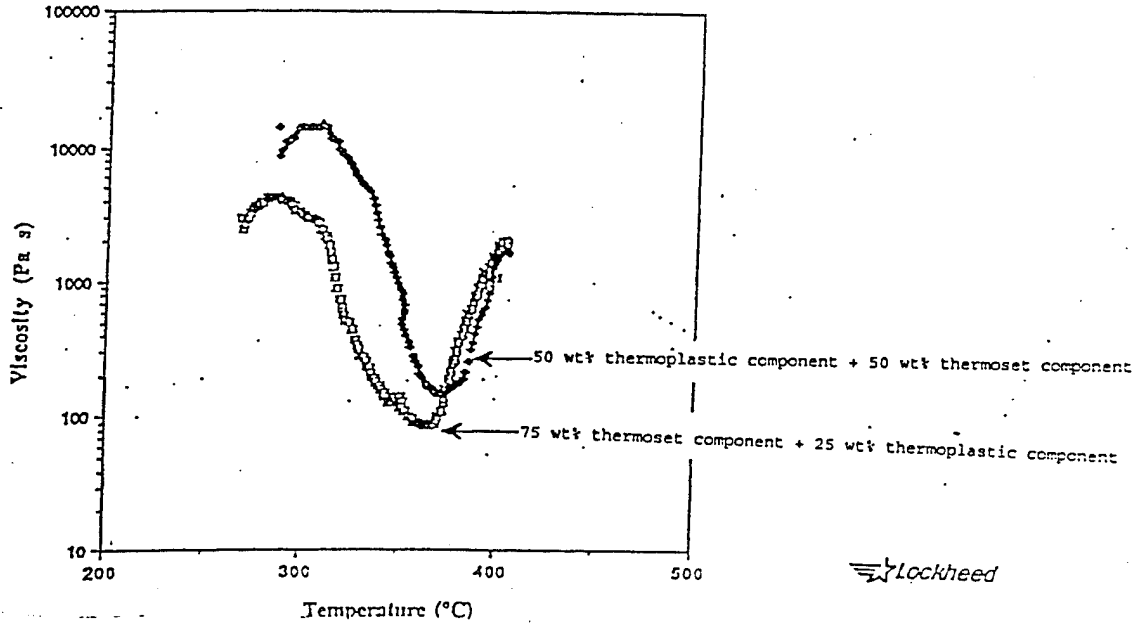


Figure 4.

## DIFFERENTIAL SCANNING CALORIMETRY

3F THERMOSETTING POLYIMIDE X

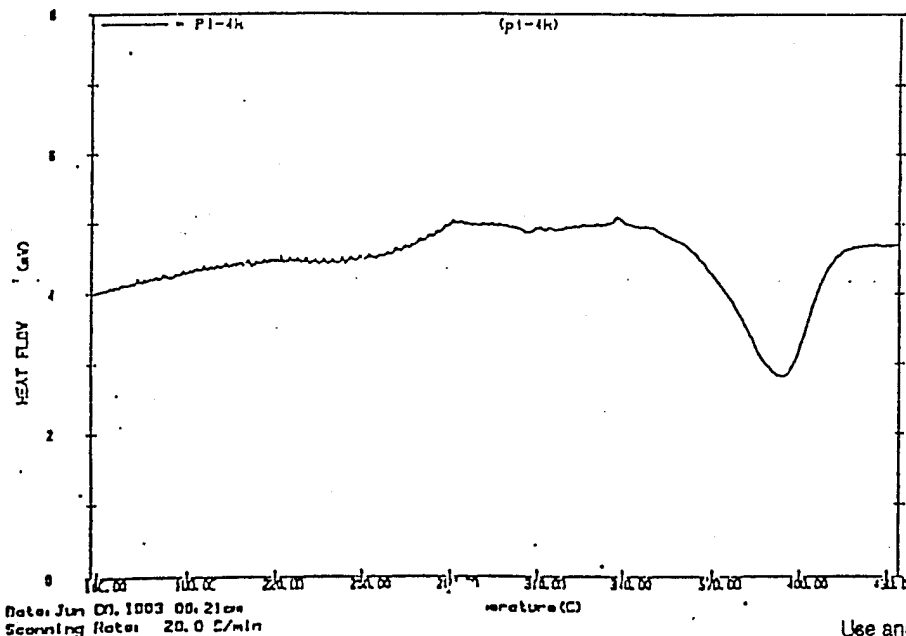
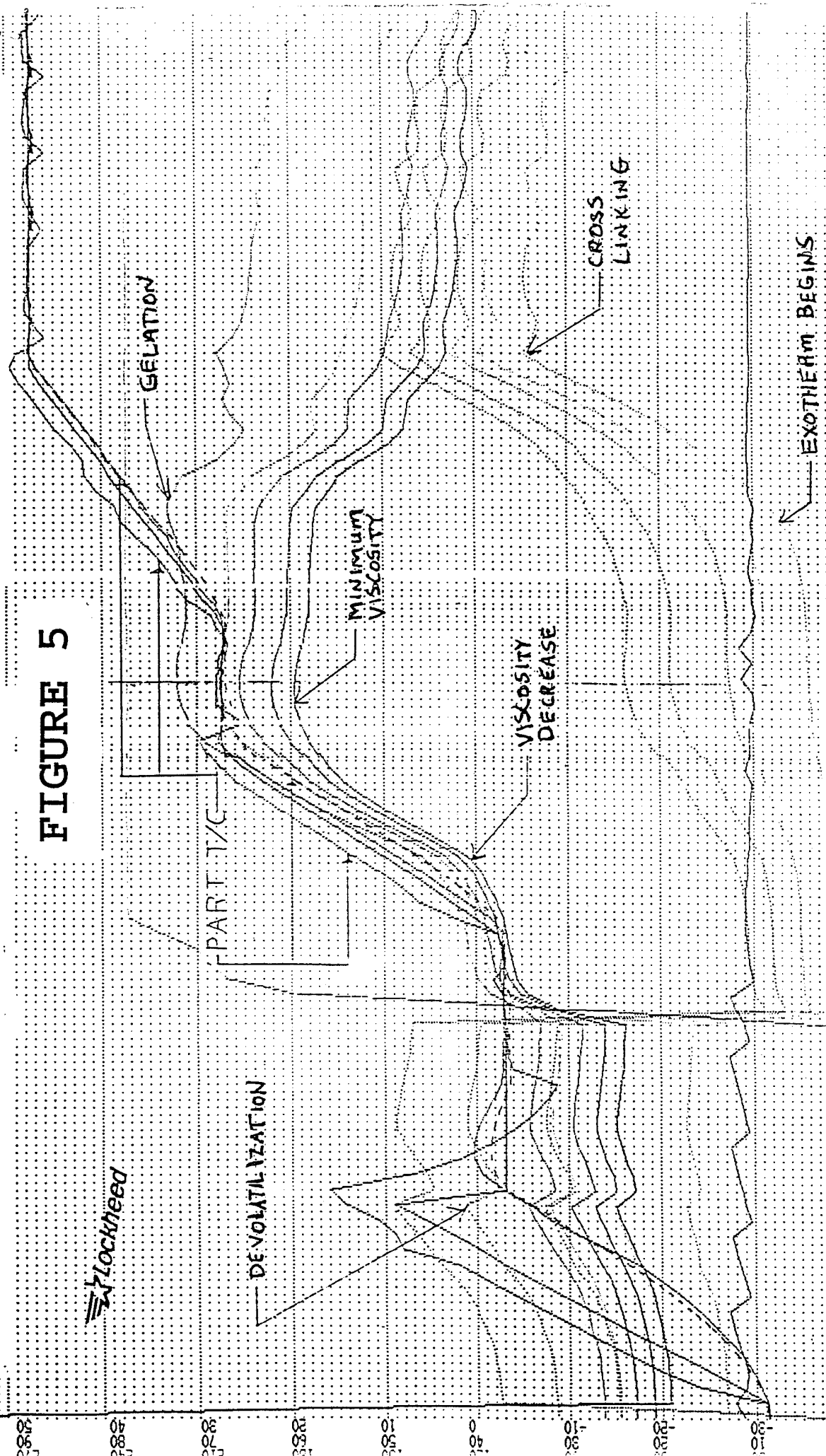


FIGURE 5



EXOTHERM BEGINS

380  
 360  
 340  
 320  
 300  
 280  
 260  
 240  
 220  
 200  
 180  
 160  
 140  
 120  
 100  
 80  
 60  
 40  
 20  
 0  
 -20  
 -40  
 -60  
 -80  
 -100  
 -120  
 -140  
 -160  
 -180  
 -200  
 -220  
 -240  
 -260  
 -280  
 -300  
 -320  
 -340  
 -360  
 -380

APPENDIX I

SUMMARY OF MONOMER SYNTHESSES

Trifluoroacetophenone

Original Procedure

$\text{PCl}_5$   
 $\text{CF}_3\text{COOH} \text{ -----} \rightarrow \text{CF}_3\text{COCl} + \text{Benzene} \text{ -----} \rightarrow \text{Trifluoroacetophenone}$

1.  $\text{CF}_3\text{COOH}/\text{PCl}_5/\text{dichloroethane}/4 \text{ hr.}$
2. Collect and distill trifluoroacetyl chloride
3. Add  $\text{CF}_3\text{COCl}$  to  $\text{AlCl}_3/\text{benzene}/\text{carbon disulfide} -50^\circ\text{C}$
4. Stir 6 hr at  $-40^\circ\text{C}$
5. Add 36% aqueous HCl and ice
6. Separate organic layer and extract aq. layer with ether/benzene
7. Combine organic solutions and wash with bicarbonate
8. Dry
9. Distill to give trifluoroacetophenone in 65% yield

Maxdem Modified Procedure

$(\text{CF}_3\text{CO})_2\text{O} + \text{Benzene} \text{ -----} \rightarrow \text{Trifluoroacetophenone}$

1. Add  $\text{AlCl}_3$  to trifluoroacetic anhydride/benzene at RT under  $\text{N}_2$
2. Stir 4 hours
3. Add ice water slowly and separate organic layer
4. Dry and distill to give trifluoroacetophenone in 60-73% yield

3F Diamine

Original Procedure

1. Mix aniline/aniline hydrochloride/trifluoroacetophenone
2. Stir 24 hr. at  $160^\circ\text{C}$
3. Cool to  $100^\circ$  and add aqueous bicarbonate. (HPLC yield 65%)
4. Steam distill and filter solid crude product
5. Wash with water and dry thoroughly to give dark purple crude.
6. Dissolve in ethanol (35 ml/g)
7. Acidify with 17% HCl to pH2
8. Add charcoal (4g. charcoal to 10g crude)
9. Reflux and filter
10. Repeat last two steps twice.
11. Add 50% NaOH to pH8
12. Add toluene (30ml/g)
13. Extract aqueous layer three times with toluene
14. Dry and remove toluene extract under reduced pressure to leave tan solid residue.
15. Suspend solid in water and filter.
16. Wash with water to pH7
17. Dry for 24 hr. at  $100^\circ\text{C}$  to give 3F diamine in 50% yield.

APPENDIX I (CONT.)

Maxdem Procedure

1. Mix toluenesulfonic acid and aniline and distill water out.
2. Add trifluoroacetophenone
3. Stir 24 hr. at 150°C
4. Add aqueous sodium hydroxide to pH12
5. Cool to RT and add methylene chloride (HPLC yield 85-90%)
6. Separate organic layer and dry with MgSO<sub>4</sub>
7. Precipitate product by adding hexane.
8. Filter to give pink crude product.
9. Dissolve in toluene (30 ml/g)
10. Filter through silica gel (0.5g silica gel per gram crude)
11. Add charcoal (0.5g charcoal/gram crude)
12. Filter and concentrate toluene solution.
13. Filter the crystals to give purified 3F diamine in 60-70% yield.

## APPENDIX II

### SCALE-UP SURVEY

To evaluate new oligomeric and polymeric polymer matrices, scale-up from chemical laboratory scale to quantities required for prepregging, test panel fabrication and mechanical and environmental testing is necessary. Initial quantities of prepolymers required for evaluation usually range from about 20 lbs. to about 200 lbs., depending upon the prognosis of the matrix polymers as determined during the initial evaluation. Scale-up at this level is too small for major chemical companies such as Dow, duPont, and Cytec to commit their facilities. There are, however, a number of pilot plant operations around the country with scale-up facilities adequately suited to conversion from laboratory to pilot plant. Facilities in these pilot plant organizations generally include small to medium glass lined reactors with facilities for distillation, filtration, and washing, and analytical instrumentation for the necessary quality control. For inclusion in this final report on the TSOPS Program, a survey of some of these organizations was conducted.

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CONTACTS: DR. CHARLES STONE, LAB MANAGER; DR. ALFRED STECK,  
PRESIDENT/CEO, (604) 986-9367.**

Ballard Advanced Materials is a wholly owned subsidiary of Ballard Power Systems, Inc. Ballard Power Systems is devoted to the manufacture of fuel cells for power sources. Ballard's \$100 million annual sales provide revenue for research, development and manufacture of fuel cells. As part of this effort, Ballard Advanced Materials develops and produces high performance polymeric materials for fuel cells. Their facilities include a fully equipped chemistry lab, pilot plant equipment featuring two 25 gallon and a 100 gallon glass-lined reactor, and analytical instrumentation including spectrometers, chromatographs, and a scanning electron microscope. Thus Ballard is well equipped to provide pilot plant level scaleup of matrix resin prepolymers and polymers. Ballard was recommended by Professor Frank Harris of the University of Akron.

**MERLIN TECHNOLOGIES INC., 910 AMERICAN STREET, SAN CARLOS,  
CALIFORNIA 94070. CONTACT: WALT WILSON, PRESIDENT, (415) 591-  
2229.**

Merlin has scale up facilities which include a 20 gallon glass-lined Pfaudler Reactor, and analytical instrumentation including Perkin-Elmer and Nicolet IR, Perkin-Elmer DSC, and a Hitachi Scanning Electron Microscope. Productin processing equipment includes autoclaves, ovens, a furnace, platen presses, RTM and filament winding equipment. In addition, Merlin is equipped with machine shop equipment, a cutting table, spray deposition and vacuum sputter coating.

**YLA, INCORPORATED, 2970 C BAY VISTA COURT, BENICIA, CALIFORNIA**

94510. CONTACT: GARY PAPST OR SUSAN ROBITAILLE, (707) 747-2750.

YLA fills the need in the aerospace industry for a materials supplier willing and able to prepreg small to intermediate batches of specialty resins and reinforcements. YLA has performed prepregging tasks for the major aerospace companies and a number of large chemical companies. Prepreg capabilities at YLA include 12" unidirectional tape, 50" wide fabric, prepreg tow, and fiber sizing.

**MAXDEM, INC., 140 EAST ARROW HIGHWAY, SAN DIMAS, CALIFORNIA 91773. CONTACT: DR. ROBERT GAGNE, PRESIDENT, OR DR. MATTHEW MARROCCO, VICE PRESIDENT, (909) 394-0644.**

Maxdem has a state of the art 15000 square foot chemical R&D laboratory, wquipped for monomer and polymer synthesis in small to moderate quantities, with scale up facilities up to 50 liter operating capacity. Instrumentation includes a Waters HPLC/GPC, a Shimadzu UV/Vis Spectrophotometer, a Shimadzu capillary GC, and tube furnaces with controllers.

**CYTEC ENGINEERED MATERIALS, INC., 1440 N. KRAEMER BLVD. ANAHEIM, CALIFORNIA 92806. CONTACT: TIM HARTNESS, (714) 666-4362**

CYTEC is part of a large chemical corporation with annual sales of about \$1 billion/year. CYTEC performs a unique service within the chemical industry in providing custom prepregging of small, medium and large quantities of matrix resins. Especially attractive is the powder prepregging operation, which CYTEC achieves with a proprietary water slurry impregnation operation. Fiber towpreg can be fabricated in this fashion, and the towpreg can subsequently be used for tow or tape placement operations, or can be consolidated into unifabric up to 6" wide. In addition, CYTEC can perform solution coating of tow or of fabric broadgoods.