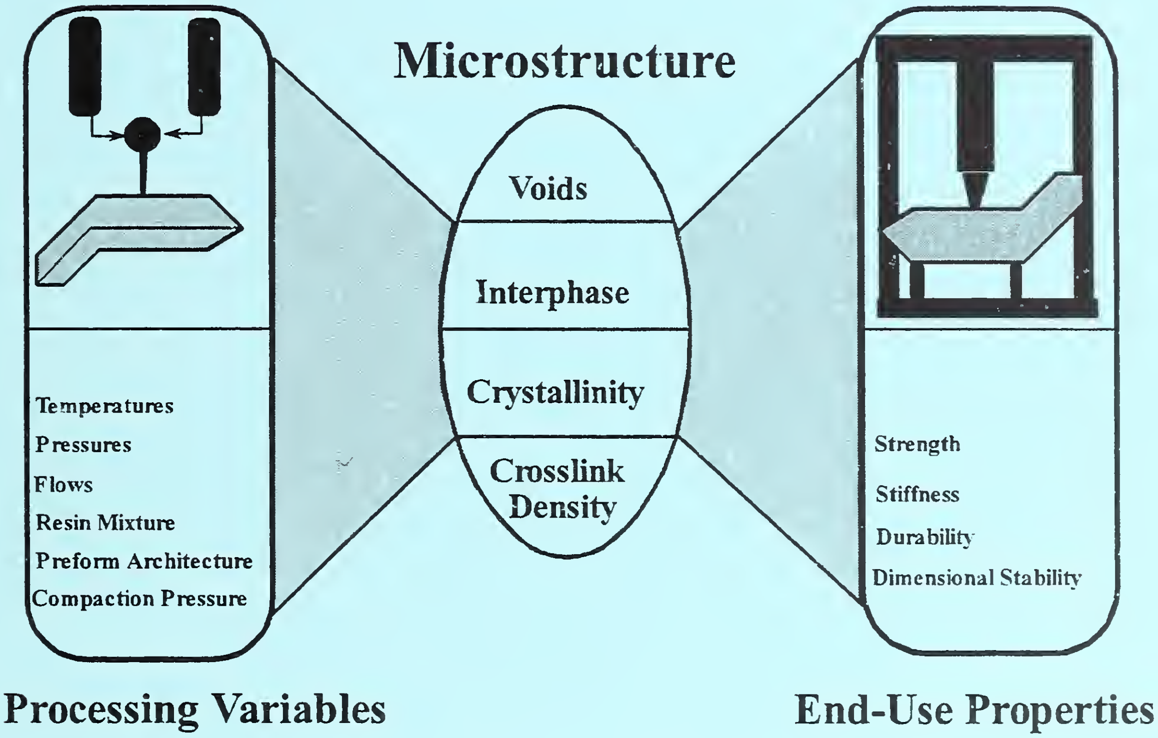
NISTIR 6044

Report on the

Industry Workshop for On-line Composite Process Monitoring April 3 & 4, 1996



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NIST

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December 1997

EXECUTIVE SUMMARY

The Industry Workshop for Online Composite Process Monitoring was organized by NIST to stimulate inter-industry discussion and to guide the internal research program in the Polymers Division on sensors and control in composite fabrication. To facilitate the discussion a diverse group of 15 people, including 11 from the automotive, aerospace, electronics, and construction industries, were invited and attended the meeting. The meeting was purposefully restricted to a carefully chosen very small group because of the extremely diverse nature of the topic and the concurrent desire to keep the discussion focused tightly enough to provide maximum guidance to the internal research effort.

The most important conclusion of the workshop is that industry wants, foremost, technology capable of monitoring and controlling both the resin cure state and the residual porosity because these microstructural properties are difficult to control in practice, yet strongly affect a broad range of end-use-properties. The aerospace and automotive industries, however, emphasized resin cure and porosity differently due to their differing requirements and manufacturing processes. For example, the rapid cycle time and lower performance requirements of the automotive industry led to a higher emphasis on void content than on resin cure state. Concurrently, the automotive industry also requires more robust and rapid response sensors than the aerospace industry to make the required measurements.

Factors that were considered most important in selecting a sensor for manufacturing composites were accuracy and cost, with durability also considered important. A number of sensors were discussed in the workshop, with conventional pressure transducers and temperature sensors ranked highest (tied), and the relatively new fiber optic sensors ranked second. The commercially available ultrasonic and dielectric sensors were ranked substantially lower. Although many interpretations of this result are possible, it may be reasonable to conclude that industry demand exists for less expensive, more versatile sensor technologies. During the workshop discussions, the potential for fiber optic sensors to provide fundamental measurements in an unintrusive manner clearly excited the participants with the possibility that such sensors could meet the accuracy, cost, and durability goals simultaneously.

Once the broad topics were introduced and the preliminary discussions occurred, important follow up discussions focused on the expectations of the industry participants for sensor and control technology. Briefly, the responses were almost evenly divided between the necessity to reduce part defects and to optimize processing, i.e. minimize cycle time. These two responses are indicative of the differing business environments of the performance driven aerospace industry and rate driven automotive industry. Thus, the "best" sensor and control structures may be substantially different in different industries that use and manufacture composite parts.

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OBJECTIVES

The Polymer Composite Group at NIST organized this focused workshop, held on April 3-4, 1996, to bring together a small group of experts and interested researchers to discuss the role of sensors and process control in composite fabrication. The workshop addressed the applicability of recently developed sensors and process control methods in fabricating high quality composite parts. In addition, the meeting discussed the role of classic non-destructive evaluation (NDE) techniques in meeting current processing needs. Although the technology in the areas of sensors and process control has been advancing rapidly, this has often occurred without a clear picture of the opportunities and needs in industries utilizing composites in structural applications. To discuss these issues the workshop considered the automotive and aerospace industries as contrasting examples. Automotive applications typically require high-speed, low-cost processing with the production of preforms in rapid cycle time. In contrast, the overriding concerns in aerospace applications are often high performance structural requirements. Therefore, stringent control of microstructure is critical. The workshop used these industries as a baseline to discuss the broad spectrum of composite applications.

The objectives in the meeting were to determine the role of sensors and process control in improved fabrication of structural composite parts and to identify the technical hurdles restricting the widespread use of these technologies. To accomplish this, the workshop sought to determine the essential end-use properties that are not effectively controlled with existing technologies, relate these end-use properties to critical microstructural properties, develop a clear understanding of the industrial environmental conditions in which in-line sensors must function, and determine the effect manufacturing speed has on sensor, NDE and process control technologies. The results of this workshop will also guide the development of a NIST research program in this effort. In addition, it is hoped that participants would gain insight into this area for their own companies and also explore collaboration opportunities with the NIST research effort.

BACKGROUND

In 1988 and 1990, NIST organized two industry workshops [1,2] to identify the most important technical and scientific barriers to the implementation of composite materials in commercial applications. The participants concluded that cost-effective processing was the most important problem. Liquid Composite Molding (LCM) was identified as the processing method with the most potential to address the fabrication issue for structural parts. The second most cited issue was uncertainty about long term performance (durability). In response to these challenges, NIST organized a major in-house research program. The initial focus was processing science for LCM, but an effort on durability was subsequently added. To update and redefine critical issues relating to specific aspects of processing science, NIST has subsequently organized or co-sponsored three additional workshops. These meetings included not only industry researchers but also government and academic scientists. The workshops [3] have discussed reinforcement/resin interactions during flow, preform architecture and permeability, and heating and rheokinetic effects during flow. In addition to flow related issues, high speed processing and the production of high quality preforms in rapid cycle times emerged as critical issues in the automotive industry.

An important thrust in NIST's in-house program is the development of flow models. In recent years, the NIST modeling program has developed a simple model, for uni-directional composites made by LCM, that describes the generation of voids and porosity during mold filling. More sophisticated models, employing the Lattice Boltzmann method,[4] are currently being formulated. During the last 3 years, the composite processing program has focused on linking composite processing with the mechanics and durability of the final composite part. The key to this link is a knowledge of the microstructure that is generated during processing. The relevant microstructural features are believed to be, but not limited to, voids, residual porosity, the resin/fiber interface, the state of the resin chemistry, and the degree of crystallinity in those resin systems that crystallize. The previously mentioned durability program, using primarily the single fiber fragmentation test and the microdrop test, was implemented to address issues relating to the resin fiber interface. This program focuses on adhesion at the resin/fiber interface, the durability of the interface to water and common automotive solvents, and the relationship of single fiber fragmentation results to full composite durability research.

Another important research area in the NIST program is process monitoring sensors. The NIST focus is on the development of a versatile optical fiber sensor for measuring resin cure, and other microstructural properties. This research program is an important key to developing the link between composite processing and the mechanics and durability of the final composite part. The sensor aspect of the NIST composites program has now developed to the point where it is appropriate to seek input and direction from industry. This is a major goal in this workshop.

INFORMATION SOUGHT

To achieve the objectives on page 1, the workshop format was formulated to address the following questions:

(1) Which end-use properties are both desirable and difficult to control?

(2) Which microstructural properties are critical to end-use performance?

(3) What are the industrial environments in-line sensors must tolerate?

(4) What are the effects of manufacturing speed on the requirements for sensors, NDE, and controls (i.e. what is the role of this technology in industries like automotive where speed is critical)?

These questions evolved from informal industry contacts who suggested that there was a critical need for fast methods to assess voids, porosity and interface properties. It was also proposed by these informal contacts that the measurement methods for on-line monitoring, control, and optimization of composite fabrication by rapid processes, *e.g.* LCM, must be rugged and fast. Since fast and rugged methods often compromise the quality of the measurement, it was noted that the development of slower and more accurate techniques was also desirable for calibration of the rapid methods and for use with slower fabrication processes. Hence, the information sought in this workshop was structured to prioritize the important microstructure features, determine the environmental factors that may inhibit the successful implementation of sensors in rapid processes, and understand the impact of processing speed on sensor requirements.

COMPOSITION OF THE WORKSHOP

A small group of experts from industry and academia were assembled to address the above questions. To insure significant input from industry the selection process was targeted toward industrial representatives who were experts in the area of rapid composite processing, microstructural defects, and the implementation of sensors in the industrial environment. Hence, 11 industry representatives were chosen from automotive, aerospace, electronics, controls, and equipment manufacturing. To augment this group 4 representatives from academia and research organizations were chosen based on their accomplishments in pertinent areas. A full list of attendees is given on pages 7-8.

Several NIST personnel were selected to attend the workshop based on their affiliation with the topics to be discussed. In addition, these personnel were selected to insure the accurate recording of issues and solutions arising from from the workshop during the presentations and discussion sections.

WORKSHOP PROGRAM

The agenda of this workshop is given on page 9, and began with an introduction by Dr. Donald L. Hunston. The introduction was followed by presentations designed to evoke participation in the discussion sessions which followed each topic area. The topic areas were designed to answer one or more of the questions targeted in the information sought section of this report. The presentation and discussion synopses, which follows the summary, reflect the important aspects discussed in each topic area. Where appropriate, information has been added by the authors of this report to enhance or clarify understanding of some of the main issues. The slides used in each presentation are included in the appendix (page 25).

In addition to the presentations and discussion section, a questionnaire, designed to determine the views of the participants, was distributed. The results of the questionnaire are on pages 17 -19.

SUMMARY

The Workshop first recognized that sensor and process control needs vary not only from one industry to another but even for different parts within the same application. Nevertheless, the attendees felt that they could identify general trends that run through the majority of applications within a given industry. In the area of high performance structural applications that typically occur in aerospace, the workshop concluded that the cure state of the resin and void/porosity content are often the most important microstructural features. The discussion mentioned delamination resistance and dimensional tolerance as important properties affected by these features. It was stated that void/porosity formation is difficult to control. Factors which have been shown to affect void/porosity formation are (1) presence of moisture-humidity, (2) solvent content, (3) air entrapment, (4) incomplete fiber wetting, and (5) poor tool design. In practice, void/porosity formation is minimized during processing by controlling humidity, pre-preg tack, the pre-preg film process, and autoclave pressure. Porosity has been shown to affect interlaminar shear strength and compression strength of composites (see Figures 19-21, on pages 46-48). In addition, voids/porosity affect micro buckling and longitudinal compression, since these properties are dependent on the stiffness of the matrix (see pages 50-51).

In manufacturing processes employing rapid composite processing techniques, *e.g.*, automotive, voids were considered the single most important microstructural feature that must be controlled. Although, the manufacturing of structural parts in the automotive and aerospace industries is driven by strength or stiffness factors, aerospace generally gives a higher priority to weight savings. This additional requirement necessitates the optimization of a structural composite to a higher level than is required in the automotive industry. Therefore the resin cure state in automotive composite manufacturing processes is not as critical as in aerospace applications. In the automotive industry cost per composite part is a primary driving factor in determining the feasibility of utilizing a composite part. Hence, rapid cycle times are critical to the manufacture of cost effective composites. As pointed out in the presentation on "Critical Composite Properties", the required liquid composite molding cycle time is in the range of 1-3 minutes.

With respect to microstructural properties and related features, the workshop rated residual cure stresses, rate of cure ,and moisture content equivalent in importance and ranked third behind void/porosity content and degree of cure. In addition to the above features, the dielectric properties of the resin, the presence of foreign materials, consolidation, fiber wetting, and percent reinforcement and orientation were also mentioned as important composite properties.

There was no clear preference with respect to off-line characterization techniques. Of the seven techniques ranked by the participants, the ASTM void content procedure, spectroscopic characterization techniques of raw materials and ultrasonic techniques were slightly favored over the characterization of raw material processing characteristics by rheological measurements, x-ray, and thermomechanical techniques. With respect to on-line

sensors, temperature and fiber optic, dielectric, and ultrasonic sensors were all considered useful.

Ultrasonic sensors fall in the broad class of techniques used for non-destructive evaluation (NDE), i.e. post processing and in-service inspection for flaws and defects. Other methods included in this class are acoustic emission and various thermal, optical, and X-ray measurements. NDE technology has been developed over many years and can contribute to the process monitoring field in two ways. First, NDE experience can provide insight into important microstructural features. Process monitoring often seeks to detect the same features (i.e. flaws, defects, etc.) that are the focus in NDE. The objective in process control, however, is to identify these features as they are formed during fabrication so the processing cycle can be adjusted to minimize or eliminate them. The second area for input from NDE is the measurement techniques themselves. Since NDE methods often measure the same features of interest in process control, there is the potential to adapt NDE sensors for use as process monitoring tools. For example, the presentation entitled "A Manufacturing View of Adaptive Process Control" reported the implementation of an ultrasonic sensor in a commercial fabrication facility. An adaptive process control system was used with the sensor, and the resulting system significantly reduced the costs of producing compression molded composite parts.

In the presentation on the "Impact of Preforms on Sensors" and subsequent discussions, it was concluded that sensors which could determine the type of fibers, the fiber orientation, and the fiber volume fraction at specific locations within a part would be extremely useful for the production of preforms and composite parts. This is true across a wide range of industries. In aerospace, the high performance requirements can only be achieved if the fiber content and orientation is tightly controlled. In automotive applications, on the other hand, the allowable variations are significantly greater, but these limits must be achieved at very high fabrication rates. For example, the present goal in the manufacture of complex automotive parts like a structural cross-member is to reduce the fabrication time from 6 hours to 6 minutes.

The factors considered most important in selecting a sensor were accuracy, precision and cost. Second tier factors were response time and sensitivity. Several participants indicated that durability was also an important factor in the selection of a sensor. Of those participants who ranked this factor, it ranked number one ahead of accuracy & precision and cost. Most participants viewed the role of sensors in a manufacturing process as being two fold. The responses were equally divided between reducing defects and optimizing the process. Consistent with this result, it was stated in the presentation on "High Speed Processing of Composites" that the role of sensors in the manufacturing regime is to (1) improve process performance, (2) expand automation, (3) assure component quality, (4) minimize value added scrap, (5) reduce costs, and (6) provide documentation. It was also noted that for sensors to be successfully implemented in the manufacturing process they must (1) survive the manufacturing environment, (2) have response times of < 1 minute, (3) require low maintenance, and (4) be simple to operate.

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Agenda
for
Industry Workshop for On-line Composite Process Monitoring

April 3, 1996

8:00am	- 8:30am	Registration
8:30am	- 8:45am	Introduction
		Don Hunston
		NIST, Polymer Composites Group
8:45am	- 9:00am	Survey
9:00am	- 9:30am	Topic: Critical Composite Properties
		Ken Kendall
		Ford Motor Company
9:30am	- 10:00am	Topic: Microstructure
		Thomas M. Donnellan
		Northrop-Grumman Corporate Research
10:00am	- 10:30am	Coffee Break
10:30am	- 12:00noon	Discussion - John Maguire
		Southwest Research Institute
12:00noon	- 1:00pm	Lunch
1:00pm	- 1:30pm	Topic: The Industrial Manufacturing Environment
		Foster Lamm
		United Technologies Research Center
1:30pm	- 2:30pm	Discussion - John Fildes
		Basic Industry Research Laboratory
2:30pm	- 3:00pm	Coffee Break
3:00pm	- 3:30pm	Topic: Role of NDE
		Boro Djordjevic
		The Johns Hopkins University
3:30pm	- 4:30pm	Discussion - Robert E. Green
		The Johns Hopkins University
4:30pm	- 5:30pm	NIST Lab Tour
6:30pm	-	Dinner Banquet, Courtyard Marriott

April 4, 1996

8:00am	- 9:00am	Poster Session
9:00am	- 9:30am	Topic: High Speed Processing
		Bruce Greve
		Budd Company
9:30am	- 10:00am	Topic: Impact of Preforms on Sensors
		Daniel T. Buckley
		American GFM Corporation
10:00am	- 10:30am	Coffee Break
10:30am	- 11:30am	Discussion - Richard Parnas, NIST
11:30am	- 12:00noon	Conclusion
12:00noon	- 1:00pm	Lunch

SYNOPSIS OF TOPIC PRESENTATIONS AND DISCUSSIONS

This section briefly summarizes what was said during the meeting. The agenda was organized around six topics that relate to the four questions mentioned earlier. For each topic, one or more presentations were given to stimulate thinking and then the meeting was open for discussion with everyone given the opportunity to contribute. The first topic, Critical Composite Properties and Microstructure, came from questions one and two while the second topic, The Manufacturing Environment, relates to question three. The topic, High Speed Processing of Composites, was taken from the fourth question. The final two topics, Role of NDE, and Impact of Preforms on Sensors, are related to question four but are broader than just high speed processing. The meeting concluded with a general discussion and a summary of the results from the questionnaire given to each participant. A highlight of the meeting was the description of a real success relevant to the topic of this meeting. It was included in the presentation by Foster Lamm. He described the development of a sensor based process control system and the transfer of this system to the manufacturing environment.

Critical Composite Properties & Microstructure

A particularly crucial issue for the workshop was the identification of properties most important for process control and the microstructural features that control these properties. This topic which relates to the first two questions in the list was discussed first.

(1) Which end-use properties are both desirable and difficult to control?

(2) Which microstructural properties are critical to end-use performance?

Presentations were offered by Ken Kendall of Ford (see Figures 1-11 on pages 26-37) and Tom Donnellan of Northrop-Grumman (see Figures 12-53 on pages 38-80) while John Maguire of Southwest Research Institute moderated the discussion. Because the presenters represented automotive and aerospace companies, the discussion was able to contrast the needs and priorities for the two industries. This is useful since these requirements generally bracket those for most other commercial applications of composites.

Automotive

With respect to composite manufacturing in the automotive industry, the importance of sensors is to help reduce cost. This is accomplished currently by reducing cycle time. In automotive applications, the materials requirements are stiffness driven. For structural parts produced by rapid processing, voids and the resin cure state are the primary microstructural properties that must be controlled to meet the stiffness requirements. Voids can have a detrimental effect on the stiffness and durability of a composite part. Existing technology indicates that void formation can be minimized by application of pressure at the appropriate time during the curing cycle. As a result, for complex parts where the pressure and temperature may change dramatically throughout the part and during curing, continuous monitoring of these variables would be very useful. In addition to thermocouples and pressure transducers, dielectric sensors have been used in composite processing to monitor the cure process. Because of the rapid cycle times, 1-3 minutes, in Liquid Composite Molding (LCM), process control algorithms adjust process variables on subsequent parts as opposed to making adjustments on the current curing part. Therefore, raw material stability and control of the processing environment are important. In high volume processes, such as LCM, there is a push to ensure product quality by guaranteeing the process. Advocates of this viewpoint suggest that a cure standard, hence the need for appropriate sensors, and not a time standard be adopted. Current methodologies, attempt to minimize the impact of cure on the final composite part by post curing out of the mold and altering the cure kinetics when possible.

The variation of temperature and pressure during LCM was demonstrated on an experimental plaque mold (see Figure 1, page 27) fitted with temperature, pressure, and dielectric sensors located at strategic positions in the mold. The importance of time constants, response time, and measurement accuracy of a sensor was underscored by a comparison of the temperature response curve from a "twisted wire" thermocouple and a "metal sheathed" thermocouple (see Figure 2, page 28. In this comparison the "metal sheathed thermocouple exhibited a much lower maximum temperature and different temperature profile than the "twisted wire" thermocouple. Other issues concerning sensor selection were mentioned briefly in the 1st LCM workshop report [3]. Also, the through-thickness temperature variations in the experimental plaque are significant (see Figure 3, page 29) and dependent on the location of the sensor within the mold. Hence, the cure state of the matrix and matrix sensitive composite properties may not be uniform throughout the composite part. In addition, the thermal and pressure histories measured in the plaques made by resin transfer molding (RTM, see Figure 6, page 32) or structural reaction injection molding (SRIM, see Figure 8, page 34) were found to depend on the location of the thermocouple within the plaque. During RTM the temperature rise due to the reaction of a polyurethane resin occurs at the plaque vent at least 15 seconds before the rise at the plaque gate (see Figure 5, page 31).

In RTM the mold pressure is also dependent on the location of the pressure transducer during the mold fill stage. However, during "pump-up" the pressure throughout the mold became more uniform and by the end of the injection the pressure distribution through the mold is uniform (see Figure 6, page 32). The pressure due to liquid resin expansion is highest near the inlet (see Figure 7, page 33). Since variations in pressure and temperature throughout the mold can affect void formation and the cure state of the resin, the discussion and presentation highlighted the need for having unobtrusive sensors in the manufacturing process to control the quality of the finished composite part.

Aerospace

Aerospace composite applications are currently focused in the following applications: (1) Highly loaded, primary structures and (2) Large and/or contoured and/or integrated structures. The current process approach tends to be all experience based (trial and error).

Therefore, making a composite part with a new material and/or part shape requires the development of a new composite process. Unlike the automotive industry, composite technology in the aerospace industry is focused on high temperature materials (e.g. bismaleimides and polyimides (condensation)), tough materials (*e.g.*, multi-phase prepreg and materials which phase separate during the curing process). In addition, there is a driving force toward low cost materials which meet the above requirements. As a result, the manufacturing processes for these materials should be low cost (w.r.t. Fiber placement, RTM, etc.) and integrated.

The current fabrication induced composite defects that are of concern to the aerospace industry are: (1) porosity (voids), (2) delamination, (3) cure state, and (4) dimensional tolerance. Since high temperature resins with complex cure kinetics are normally used in aerospace structural composites the resin cure state may be more critical than the presence of voids. Undercuring the resin results in a reduction in hot, wet properties and overcuring the resin results in a decrease in toughness. The cure profile of the composite resin can be affected by the variability in chemistry and age of the starting material as well as by variations in tooling and autoclave loading. The cure profile of the composite resin is controlled by process design, system thermal profiles, and material quality control. An example of the effect of the cure rate on the gel temperature for a 16 ply 3501-6/T300 composite is shown in Figure 34, page 61. For this composite, reducing the heating rate from 1.8 °F/min. to 0.5 °F/min. resulted in a reduction of 30 degrees in the gel temperature of the resin. The effect of the change in the cure cycle on the compression after impact (CAI) strength of an aerospace composite is shown in Figure 39, page 66.

Void formation is a concern because it affects resin dominated and fiber dominated properties. Interlaminar shear strength, a resin dominated property, is adversely affected by the presence of voids (see Figure 19-20, page 46-47). In addition, laminate compressive strength, normally considered a fiber dominated property, is also adversely affected by the presence of voids (see Figure 21, page 48). Longitudinal compression and microbuckling, also considered to be fiber dominated properties, are tied to the dependence of the critical lengths for shear failure and microbuckling in the composite matrix (see Figure 22-24, page 49-51). Since the matrix modulus is sensitive to void content, fiber dominated properties are also affected by voids. Void formation is difficult to predict. The factors which contribute to void formation are (1) moisture-humidity, (2) solvents, (3) entrapped air, (4) degree of fiber wetting, and (5) tooling. Although voids are a problem, most of the composites are made by autoclave processes and the appropriate application of pressure can usually minimize the presence of voids. In addition, voids are also minimized by controlling humidity, pre-preg tack, and the pre-preg film process.

Delaminations are considered a material specific effect. Because of its relationship to buckling stability, delaminations have a large impact on compression dominated designs. Delamination is typically controlled by good quality control, good tooling concepts, and by controlling the process rates. The impact of single and multiple delaminations on compression failure strain is shown in Figure 28, page 55. For example a single delamination causes a larger reduction in compression failure strain than 2% porosity.

The Manufacturing Environment

The requirements placed on a sensor and control system by the need to operate in a real manufacturing environment were discussed in this topic which came directly from question three in the list (see page 2):

(3) What are the industrial environments in-line sensors must tolerate?

The discussion was initiated with a presentation by Foster Lamm of United Technologies Research Center (Figures 54-66 on pages 81-94) and moderated by John Fildes from Basic Industry Research Laboratory. A major conclusion from the session was summarized when Foster Lamm stated, "From a manufacturing view any new technology must impact the financial side of the business. It is not sufficient to be ***Good Technology***."

There are two types of sensor configuration utilized in on-line process monitoring (1) internal probes and (2) extrinsic (including non-contact) probes. The presentation in this section focused on an ultrasonic sensor that was external to the processing environment (see Figure 64 on page 92). This configuration resulted in the development of a reliable cost effective sensor design. The presentation centered on the successful implementation of a cost effective and supportable adaptive process control system to minimize the cost of producing compression molded composites. In the conventional compression molding operation the process requires a significant amount of process knowledge. In addition, the process is 'set point' controlled and rheology must be run on every lot to confirm the state of the process.

In the adaptive process control scheme, control of the process is based on the current condition of the curing resin. The condition of the curing resin is monitored using an ultrasonic sensor whose output is calibrated to viscosity changes in the curing resin. To effect adaptive process control, the information from the sensor is analyzed using a rules based approach. However, adaptive process control cannot make up for bad tooling and bad starting materials.

Dielectric sensors are used in the development of structural parts for aerospace applications. These sensors are also external to the process. The selection of the appropriate sensor will depend on what is to be measured, the chemistry of the resin system, the curing temperature, or the pressures used in fabrication the composite part. Once the appropriate sensor has been selected, making good connections between the information provided by the sensor and the properties of the part to be controlled is typically the major concern with all types of sensors.

High Speed Processing of Composites

For industries where production volumes are large, like automotive, the need for high speed fabrication is essential, and this has consequences for the use of sensors. This topic relates to question four in the list:

> (4) What are the effects of manufacturing speed on the requirements for sensors, NDE, and controls (i.e. what is the role of this technology in industries like automotive where speed is critical)?

Thinking in this area was stimulated by a presentation from Bruce Greve of the Budd Company (see Figures 86-111 on pages 115-141), and the discussion was moderated by Richard Parnas of NIST.

Currently SMC products, such as hood, trunk lids, etc., have the highest yearly volume. However, these parts tend to be of very low structural complexity. Liquid molding parts (*e.g*., passenger compartment body frames, pick up truck cabs, floor parts, and body side operatives) span the range of structural complexity, but have low yearly production volumes. The market is currently moving toward high structural complexity liquid molded composite parts with a significant increase in yearly volume.

The role of sensors in this manufacturing regime is to (1) improve process performance, (2) expand automation, (3) assure component quality, (4) minimize value added scrap, (5) reduce costs, and (6) provide documentation. For sensors to be successful, they must (1) survive the manufacturing environment, (2) have response times of 1 minute or less, (3) require low maintenance, and (4) be simple to operate. Sensors are typically used to monitor fabrication equipment and the component that is being fabricated. With respect to the fabrication equipment, sensors are commonly need to monitor pressure, vacuum, temperature, component ratios, and cure time. Component monitoring, which has been more widely discussed at this workshop, involves the measurement of the following parameters: (1) weight, (2) void content, (3) glass content, (4) degree of cure, (5) dimensional accuracy, and (6) assembly accuracy.

Although esthetic quality requirements are more stringent for appearance parts than for structural parts, there is a need for void detection sensors in foam core structures. In addition, there is a critical need for sensors that can inspect preforms and determine the fiber orientation and the amount of fiber present.

Role of NDE

The field of NDE is well established, and this experience has much to offer the area of on-line process monitoring. Consequently, this topic is appropriate for this meeting. It relates to the fourth question in the list but is considerably more general:

> (4) What are the effects of manufacturing speed on the requirements for sensors, NDE, and controls (i.e. what is the role of this technology in industries like automotive where speed is critical)?

The discussion began with remarks from Boro Djordjevic (see Figures 67-85 on pages 95-114), and the discussion was moderated by Robert Green, both from The Johns Hopkins University.

Classic NDE focuses on characterizing flaws and other defects in a part after fabrication and during its service life. In recent years, however, the distinction between this and on-line monitoring has begun to blur because the information sought and the measurement techniques used for the two applications strongly overlap. Historically, NDE has used a broad range of sensors including ultrasonics, acoustic emission, X-ray, and optical or thermal methods. More recently, studies have added laser ultrasonic, x-ray tomography, holography, etc. (see Figure 69 on page 98 for other NDE techniques). The NDE technologies are particularly adept in detecting defects such as delaminations, porosity, voids, misoriented fibers & plies, etc. (see Figure 68 on page 97 for other examples). Parameters and properties of organic matrices that are amenable to process control are shown in Figure 70, page 99. Devices that have been targeted for organic matrices are shown in Figure 71, page 100. One important consideration for any measurement technique is that the detection sensor should cause minimal interference in the fabrication process. A second critical issue in process monitoring is what features in the material are important and which process variables can be controlled.

A promising technique for process monitoring is embedded acoustic sensors. They fall into three classes (1) bulk wave , (2) surface wave, and (3) guided wave sensors. The latter is dependent on the material geometry. Another promising technology is fiber optics using evanescent wave absorption (see in Figures 72 & 73 , page 101 & 102.). Other emerging techniques that have the attractive feature of non-contact measurements are ultrasonics with laser generation and detection, gas coupled ultrasonics, and microwave sensors (see Figures 79-84. on pages 108-113). Recall that in the previous presentation the ultrasonics sensor utilized in that process was a non-contact ultrasonics sensor.

Impact of Preforms on Sensors

Preform manufacturing is a critical issue not only for high speed fabrication but for the entire range of applications with LCM, RTM, and structural reaction injection molding (SRIM). Since sensors could have an important role in this topic, it was discussed at the meeting. A presentation by Daniel Buckley of American GFM (slides not available) introduced the area, and the discussions were moderated by Richard Parnas of NIST.

The technology developed by the aerospace industry to meet stringent performance criteria in composites is being applied to the manufacture of sporting goods equipment. Current automotive technology in the making of structural cross-members requires 6 hours and 3 people. Because this industry is cost driven, the present goal is to make this part in 6 minutes.

Preforms tend to fall into three categories: (1) foam core, (2) shells - random fibers, and (3) woven fiber mats. A number of promising new techniques for preform manufacturing are under development. The conventional spray up method is labor intensive and does not provide good control of fiber orientation. An automated version sometimes called the directed fiber process is now being tested, and this should be a significant improvement. Another new method is the slurry process. In this approach, the reinforcement is suspended in the slurry and gets deposited on a screen when the slurry is forced through the mesh. Proper application of this method results in rapid production of a rigid preform with semi-random orientation. As with spray up techniques, the challenge is to obtain the proper density and orientation of the fibers in a preform with good dimensional control. If the final preforms must be trimmed, this adds cost. The automotive industry is pushing for net shape preforms.

Thermoforming is another fabrication method that is under study. In this technique, control of fiber location and orientation can be a problem if the shapes are complex. Much of the work to date has involved random orientation of the fibers, and this generally limits the preforms that are made to non-load bearing applications. A final example of a new fabrication method is called the “compform” process. It incorporates high speed ultrasonic cutting to generate pre-cut shapes that are placed into a compression tool. A binder that can be UV cured is partially reacted to produce rigid preforms. This process has been used with a variety of reinforcements, *i.e.,* glass, Kevlar, and carbon.

With any of these approaches, it is critical to assess and control the fiber type, density, and orientation at each location in the preform. A sensor and control technology which could do this would be a major advance in the field.

Results of the Questionnaire

To get a clear view of the attendee's opinions on critical issues, a questionnaire was distributed to each participant (excluding the NIST attendees) at the beginning of the meeting. These forms were completed during the course of the conference, and a summary of the results was presented in the discussion period. The tabulated results which are given on pages 18 and 19 show that the participants represent a variety of industries. Among the attendees, 65% indicated that they are currently using sensors in some form. With regard to microstructure, a wide range of features were viewed as important but void content and degree of cure ranked highest. Off-line characterization tools were also widely used. Although ultrasonic inspection and spectroscopic examination of raw materials were highly cited, a broad range of tools were considered important. Not surprisingly, the workshop listed temperature and pressure probes as the most widely used on-line sensors. This undoubtedly reflects the current availability of these technologies, and the fact that they measure the variables that can be controlled. Nevertheless, the results also show a strong interest in sensors that measure the "state" of the material and not just the processing environment.

When ask what was most important in a sensor, the response indicated that the sensor must be rugged and provide reliable data. Without this, other factors such as speed, cost, and sensitivity do not matter. If a sensor meets the rugged and reliable criterion, cost was ranked as the next most important consideration. Reasons for using a sensor varied widely which probably reflects the diversity of problems associated with the broad range of applications for composites. Finally, when ask to indicate what part of the process they would most like to control, the attendees listed all aspects as important, but ranked raw materials quality and cure as the highest priorities.

Results of Questionnaire for
Industry Workshop for On-line Composite Process Monitoring

(1) What Industry Segment do you represent or would like to respond for?

(1) Aerospace 38.4%
(2) Automotive 23.1%
(3) Electronics 7.7%
(4) Construction 7.7%
(5) Other 23.1% Manufacturing; Controls; Research

(2) Do you or your Company use sensors or would like to use sensors?

Yes We are Currently Using Sensors 75%
Yes We Would Like to 25%
No 0%

Rank Numerically the responses in each of the following questions with 1 as most important

Tabulated values represent the average rank based on participant responses.

(3) What microstructural properties of the composite do you think are most important in your company's application? ***(Please Rank)***

2.3 Degree of Cure
1.7 Void Content
3.4 Residual Cure Stresses
3.6 Rate of Cure
3.6 Moisture Content
4.7 Temperature Profile during Cure
6.0 Refractive Index
3.4 Other (Specify) Viscosity, % Reinforcement, Consolidation, Customer Specs; Foreign Materials

(4) What Off line Characterization Techniques do you consider important? ***(Please Rank)***

2.9 ASTM Void Content Procedure
2.3 Spectroscopic Characterization of Raw Materials
4.1 Electronic Speckle Pattern Interferometry (ESPI)
3.6 Thermal Techniques (e.g. SPATE & Thermal Conductivity)
____ Other (Specify) x-Ray, Thermomechanical Analysis, Mechanical Testing, FTIR/Optical Time Domain Reflectrometry, DSC, DMA
2.1 Ultrasonics
3.4 Digital Shearography
4.9 Dye Penetrant Techniques

(5) What type of on line sensors do you think are most useful to the manufacture of composites in your company's application? **(Please Rank)**

- 2.8 Dielectric Sensors
- 2.3 Fiber Optics Sensors
- 3.0 Ultrasonic Sensors
- 2.0 Temperature Sensors
- 2.0 Other (Specify) Pressure Transducers

(6) In a sensor what do you consider important? ***(Please Rank)***

- 3.6 Response Time
- 4.6 Sample Size
- 2.9 Cost
- 3.9 Sensitivity
- 2.1 Accuracy & Precision
- 4.8 Range
- 2.0 Other (Specify) Durability, Reliability; Survivability

(7) Why would you use a sensor in your manufacturing process? ***(Please Rank)***

- 1.6 Reduce defects
- 2.0 Optimize Processing
- 2.5 Reduce Scrap
- 3.3 Relax raw material specifications or overcome variability in raw materials
- 2.0 Other (Specify) Process Control, Rate

(8) What part of the production process do you consider most important to control? ***(Please Rank)***

- 2.2 Quality and physical properties of raw material feed
- 3.1 Controlling the production environment (humidity, temperature)
- 2.2 Controlling the cure process
- 3.8 Controlling the mold preparation step
- 3.3 Controlling the mold filling step
- 3.0 Other (Specify) Microstructure, Dimensional Tolerance, Control Entire Process

Summary Discussion Session

The closing discussion addressed three issues in some detail. The format involved offering a question which elicited a series of responses, comments, and sub-questions from attendees.

The first issue considered was Preforms.

Question: What do we want to measure?

~ Permeability. This cannot be measured directly with an on-line sensor, but we can measure the factors that control or influence permeability such as

~ Thickness of final preform

Comment: Control of preform thickness is a tooling problem

~ Preform deformations during injections

~ Difference in volume fraction and orientation around curve

~ Contour changes and shape changes (*i.e.*, sense geometry of preform)

~ Ply orientation. This affects permeability but also directly controls important properties in the final part

Issue: Do we have the right amount of material where we need it? Metal or tracer fibers in rovings can be used to follow the orientation.

Query: Is orientation part of the process and more importantly is there variability in orientation?

Response: Yes, but orientation is usually too complex to deal with so we often just try to over design the part and cross our fingers!

~ Preform integrity - are the fibers where we need them?

Comment: Determination of biaxial or triaxial, orientation is a very complex problem. It is often circumvented by over designing the part.

~ Mold closure operation can be an issue since it can change fiber position and orientation

Question: If we measure one thing on a preform what would it be?

~ For virtually all applications we want to know fiber volume fraction.

Comment: In processes such as RTM, the overall fiber volume fraction is dictated by the mold and preform, but can still vary from one location to another. We need to know the fiber content in critical regions not just the overall average.

~ In high performance composites, fiber content is not adequate, orientation of the fibers is also critical.

Comment: The aerospace industry buys preforms and hopes they conform to specs. Unfortunately, preforms can be quite variable.

Query: Would 3-D image microstructure be useful ?

Response: Yes

The second area discussed was the Molding Operation

Question: What end use properties of the composite are both desirable and difficult to control?

In Aerospace these properties are:

~ Compression strength. It depends on features like voids and porosity.

Comment: Post processing inspection for voids is well established. We can use C-scan, ultrasonics, and X-Ray tomography. On-line detection would be very useful.

Process variability can cause changes in porosity, and this is more difficult to detect. Advances here would be very desirable.

~ Fiber waviness in thick composite

Comment: Tracer fibers can be included and examined in post processing inspection, but fiber waviness cannot be detect if it is less that 2-3% in a 500 ply lay up!

Query: Is waviness a random event? Where is it critical? Where will it occur the most?

Response: Known sources include (1) corners where lots of plies come together, (2) areas with large flow gradients during processing, (3) poor manufacturing of a preform, and (4) deformation during mold closure.

~ Cure level

In Automotive these properties are:

~ Voids

~ Resin rich areas

~ Loss of architecture

Comment: The problems with aerospace and automotive are similar here.

Query: But what about processing speed?

Response: This increases the problem for applications like automotive but usually these applications also have less severe performance requirements.

~ Gel time control is critical because it controls when the mold can be opened and therefore cycle time.

~ Fiber wetting is particularly important in fast processes

Comment: Even in a slow process like vacuum infiltration molding, fiber wetting can be a concern.

~ Microstructure of interface

Comment: Drzal s work shows that fiber-polymer bonding is a function of many things: processing speed, sizings, etc.

~ Resin cure

~ Exotherm and temperature control is still a problem is thick composites.

The final issue discussed was the Industrial Environment

Question: What characteristics must a sensor have if it is to be used in an Industrial Environment?

~ A sensor must be transparent to the process.

~ Embedded sensors usually appear to be inclusions (Hence, thin sensors must be developed)

~ Sensors are needed that have a strong application to physical properties

REFERENCES

1 P. Beardmore and D. Hunston, "Polymer Composite Processing (An Industry Workshop)", NBSIR 87-3686, National Bureau of Standards, Gaithersburg, MD, February, 1988.

2 C. Johnson, S.S. Chang, and D. Hunston, "Polymer Composite Processing (2nd Industry Workshop)", NISTIR 4461, National Institute of Standards and Technology, Gaithersburg, MD, December 1990.

3 R.S. Parnas, A.J. Salem, K.N. Kendall, M.V. Bruschke, "Report on the Workshop on Manufacturing Polymer Composites by Liquid Molding", National Institute of Standards and Technology, Gaithersburg, MD, February 1994.

4 M. A. A. Spaid, F. R. Phelan, Jr., "Lattic Boltzmann Methods for Modeling Microscale Flow in Fibrous Porous Media", Submitted to Physics of Fluids.

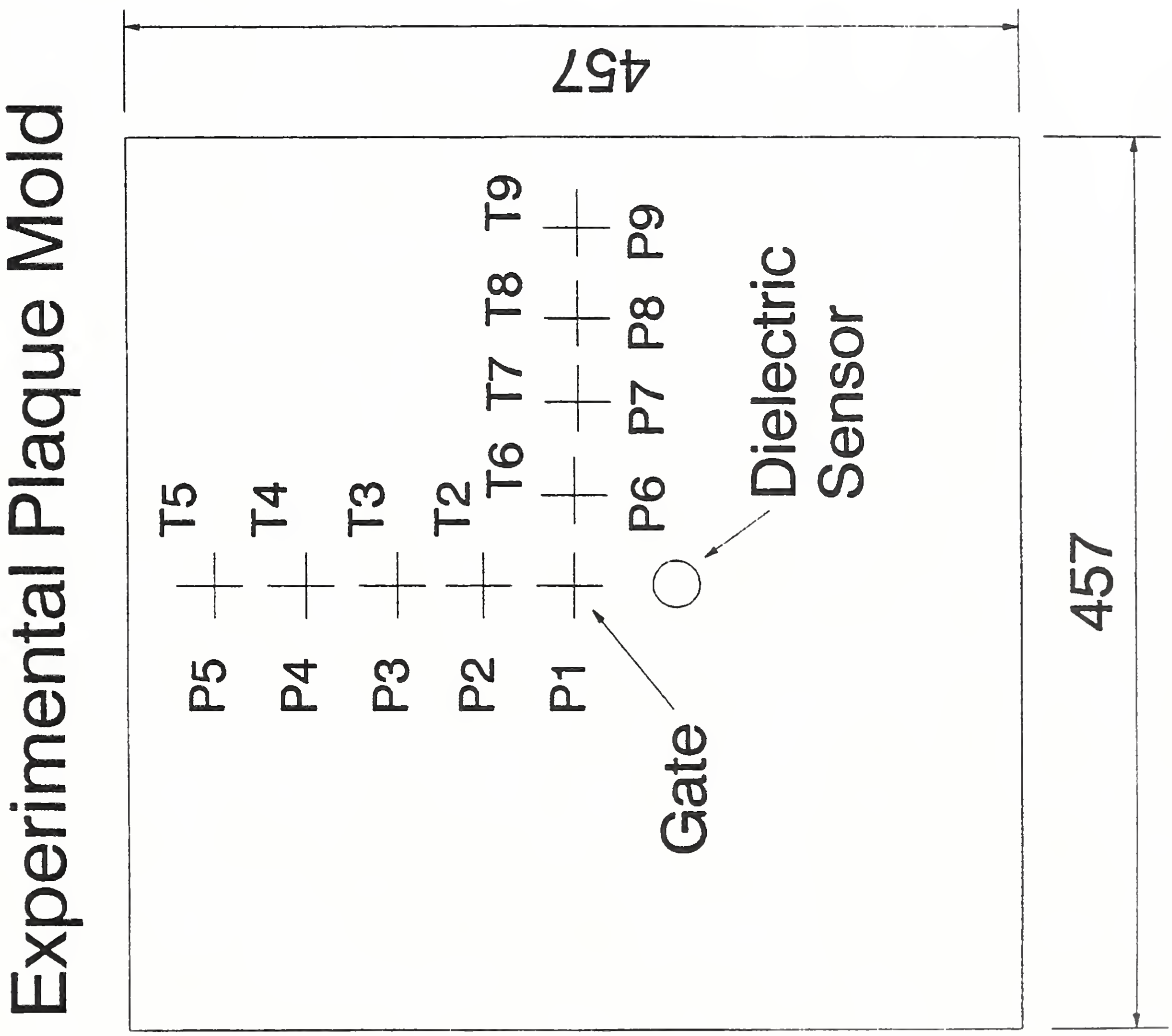
Presentations

Process Monitoring for Composites Manufacturing in the Automotive Industry

Kenneth N. Kendall

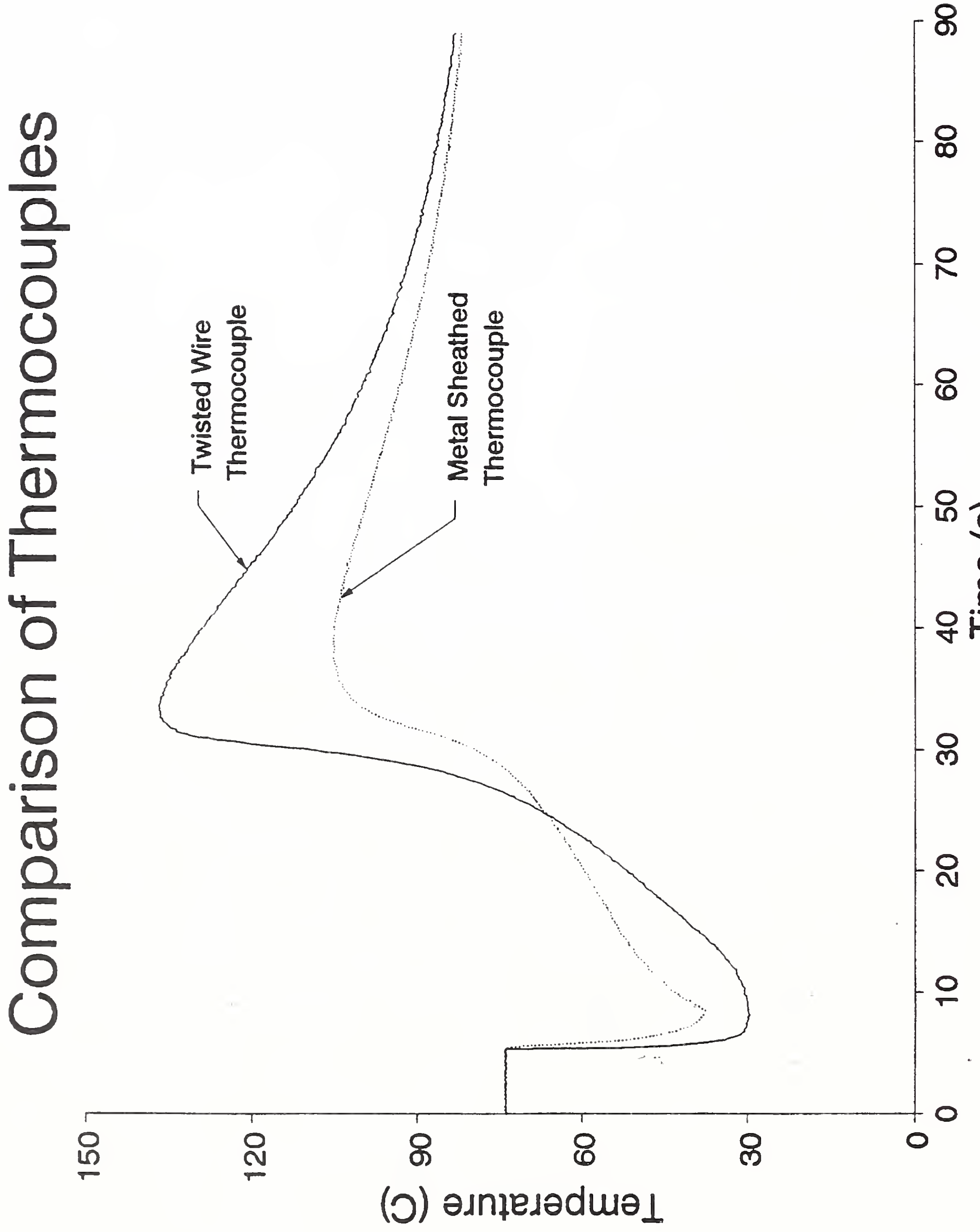
Ford Motor Company

Figure 1



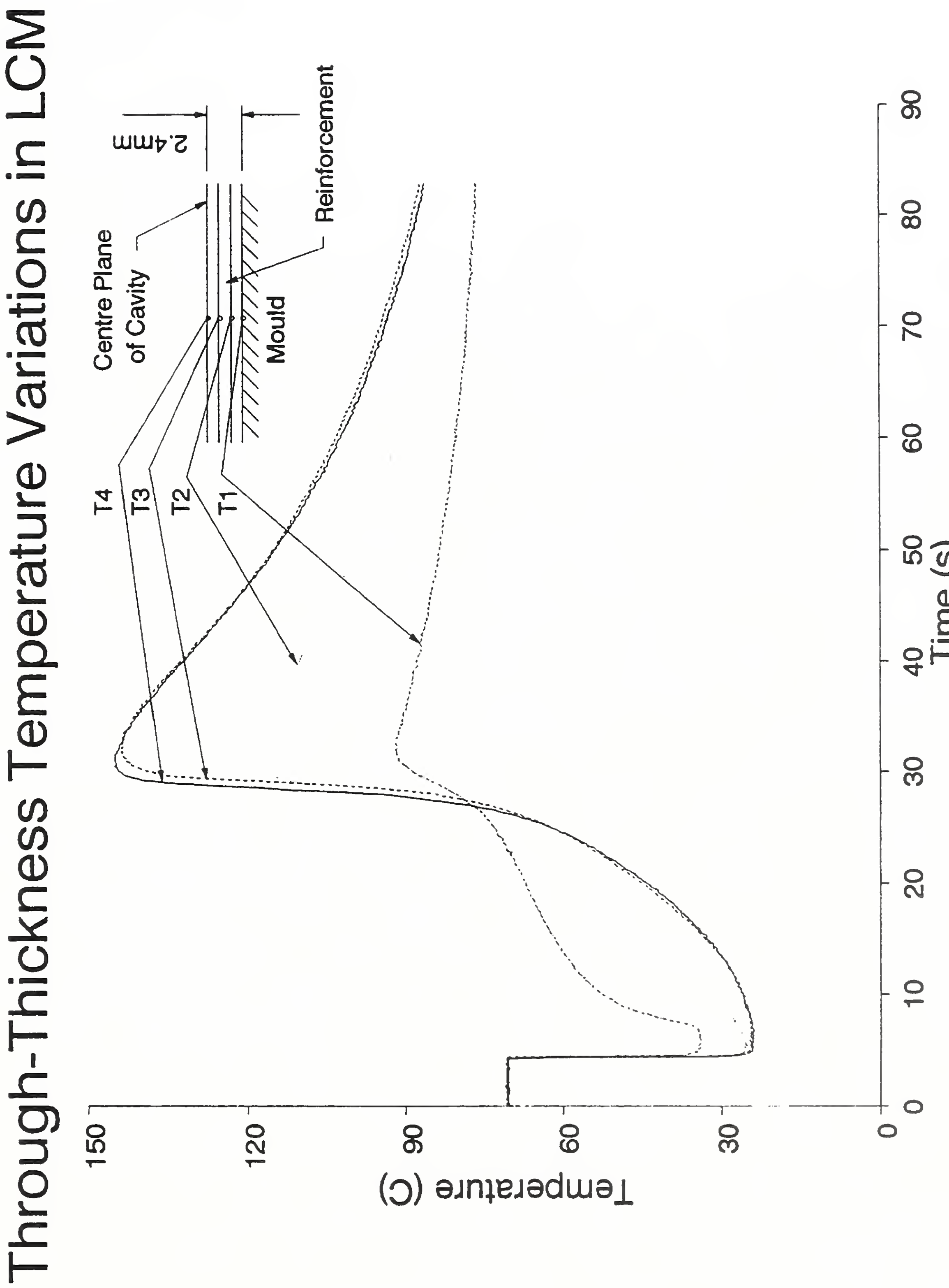
Experimental Plaque Mold
457
457
T5
T4
T3
T2
T6
T7
T8
T9
P5
P4
P3
P2
P1
P6
P7
P8
P9
Gate
Dielectric
Sensor

Figure 2



Comparison of Thermocouples
Twisted Wire Thermocouple
Metal Sheathed Thermocouple
Temperature (C)
Time (s)
0
30
60
90
120
150
0
10
20
30
40
50
60
70
80
90

Figure 3



Through-Thickness Temperature Variations in LCM
Temperature (C)
Time (s)
0
30
60
90
120
150
0
10
20
30
40
50
60
70
80
90
T4
T3
T2
T1
Centre Plane
of Cavity
Mould
Reinforcement
2.4mm

Figure 4

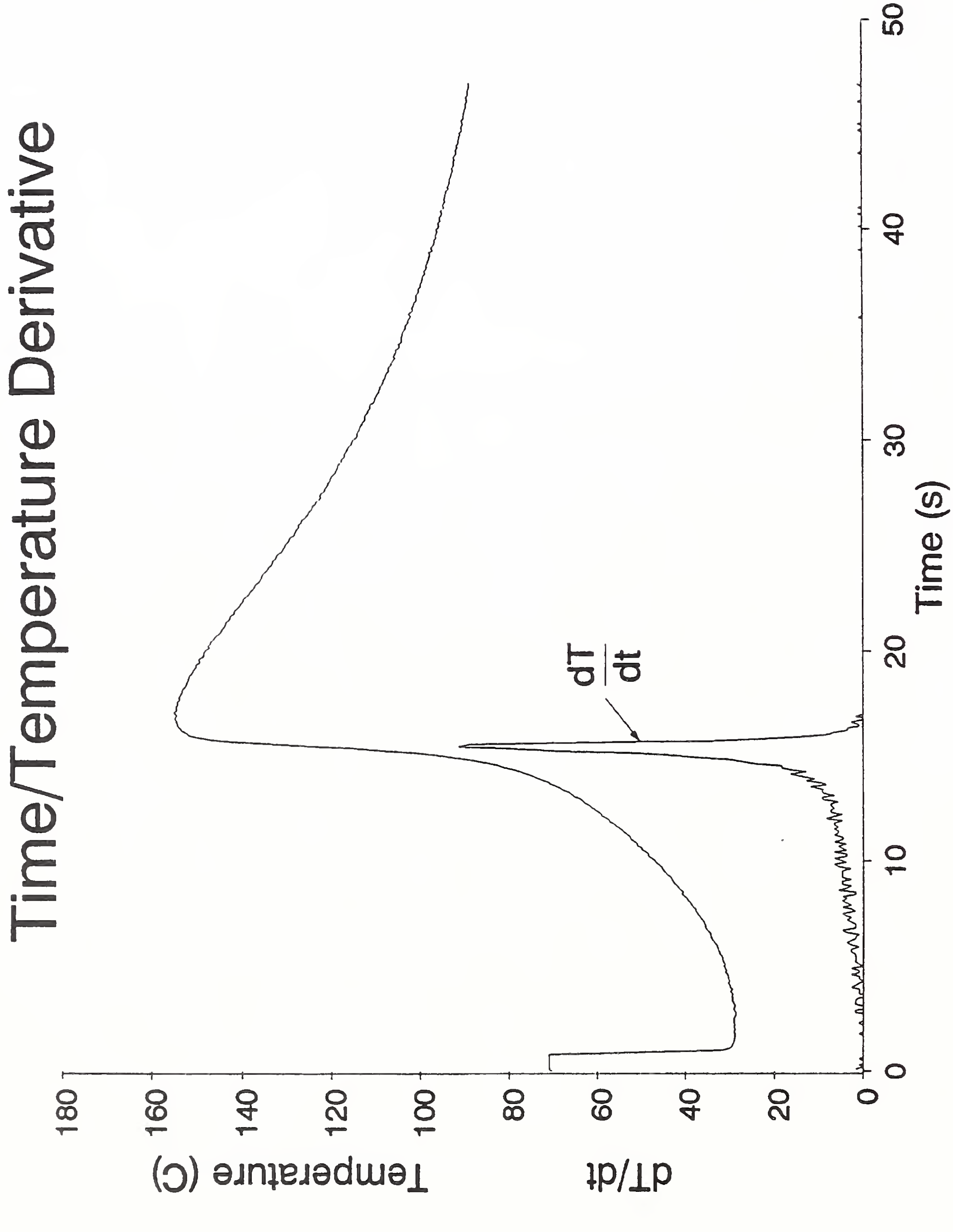
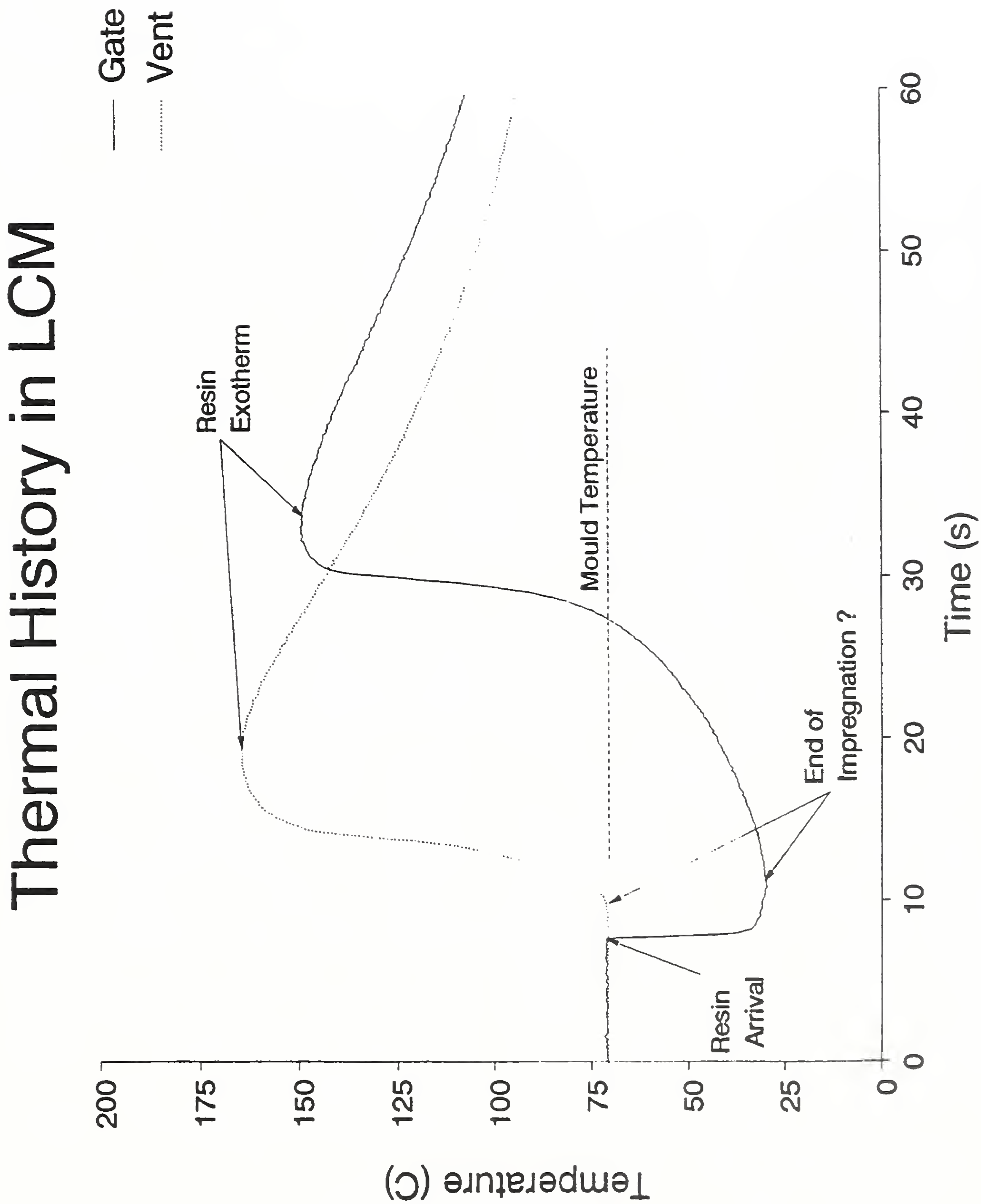
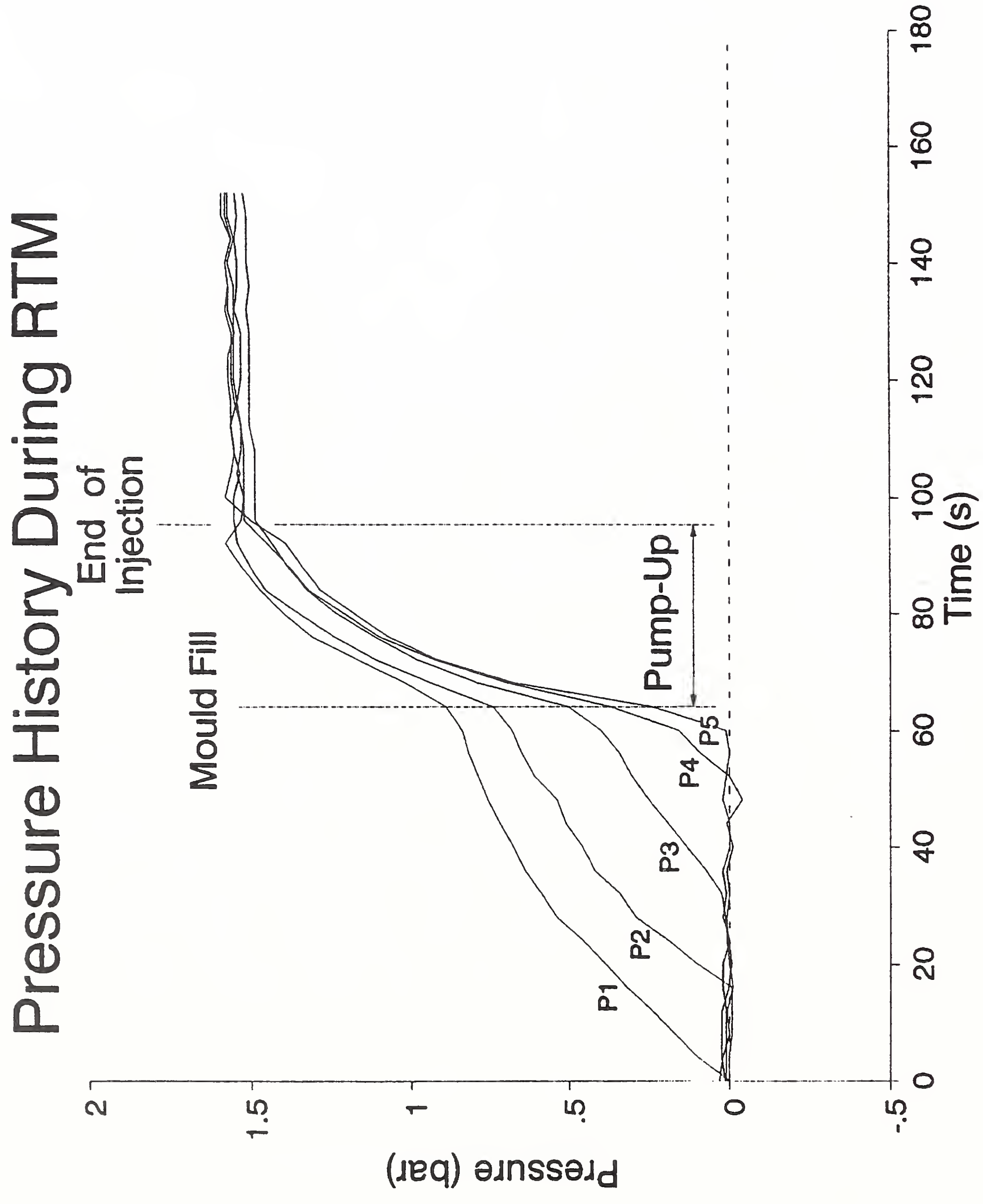

Time/Temperature Derivative
Temperature (C)
dT/dt
Time (s)
dT/dt
0
20
40
60
80
100
120
140
160
180
0
10
20
30
40
50

Figure 5



Thermal History in LCM
Temperature (C)
200
175
150
125
100
75
50
25
0
Time (s)
0
10
20
30
40
50
60
Gate
Vent
Resin Exotherm
Mould Temperature
End of Impregnation ?
Resin Arrival

Figure 6



Pressure History During RTM
End of Injection
Mould Fill
Pump-Up
P1
P2
P3
P4
P5
Pressure (bar)
Time (s)
2
1.5
1
.5
0
-.5
0
20
40
60
80
100
120
140
160
180

Figure 7

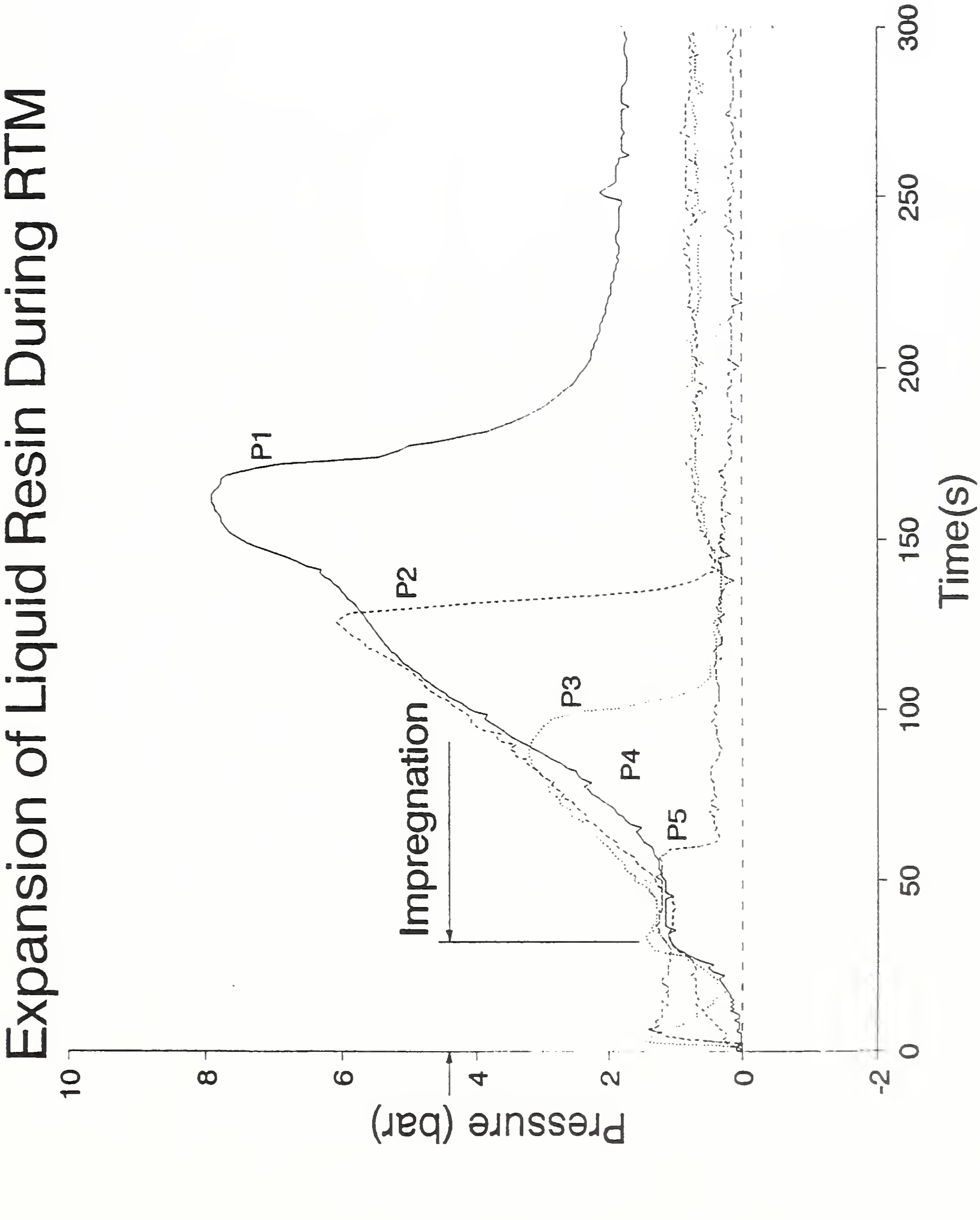

Expansion of Liquid Resin During RTM
Pressure (bar)
Time(s)
10
8
6
4
2
0
-2
0
50
100
150
200
250
300
P1
P2
P3
P4
P5
Impregnation

Figure 8

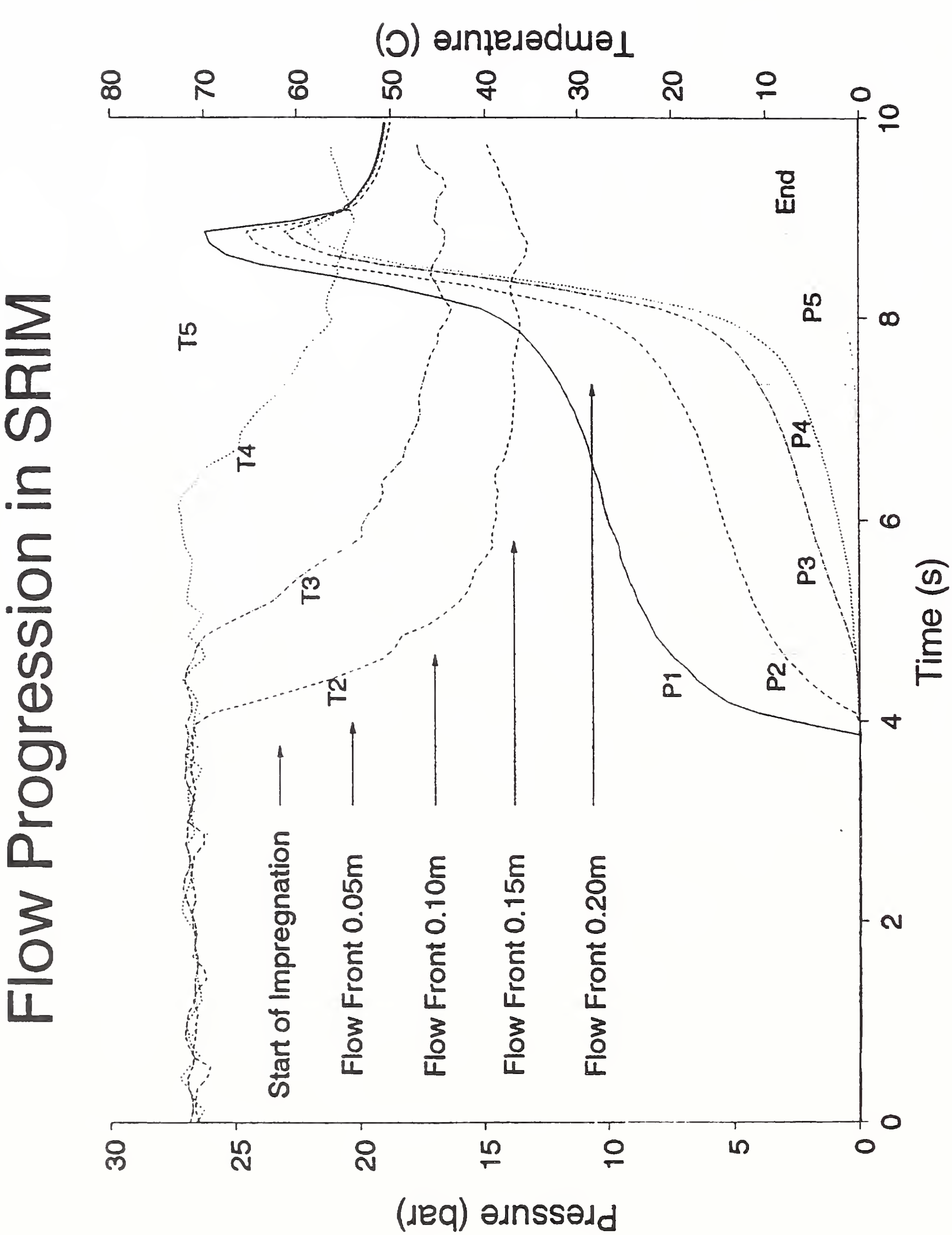
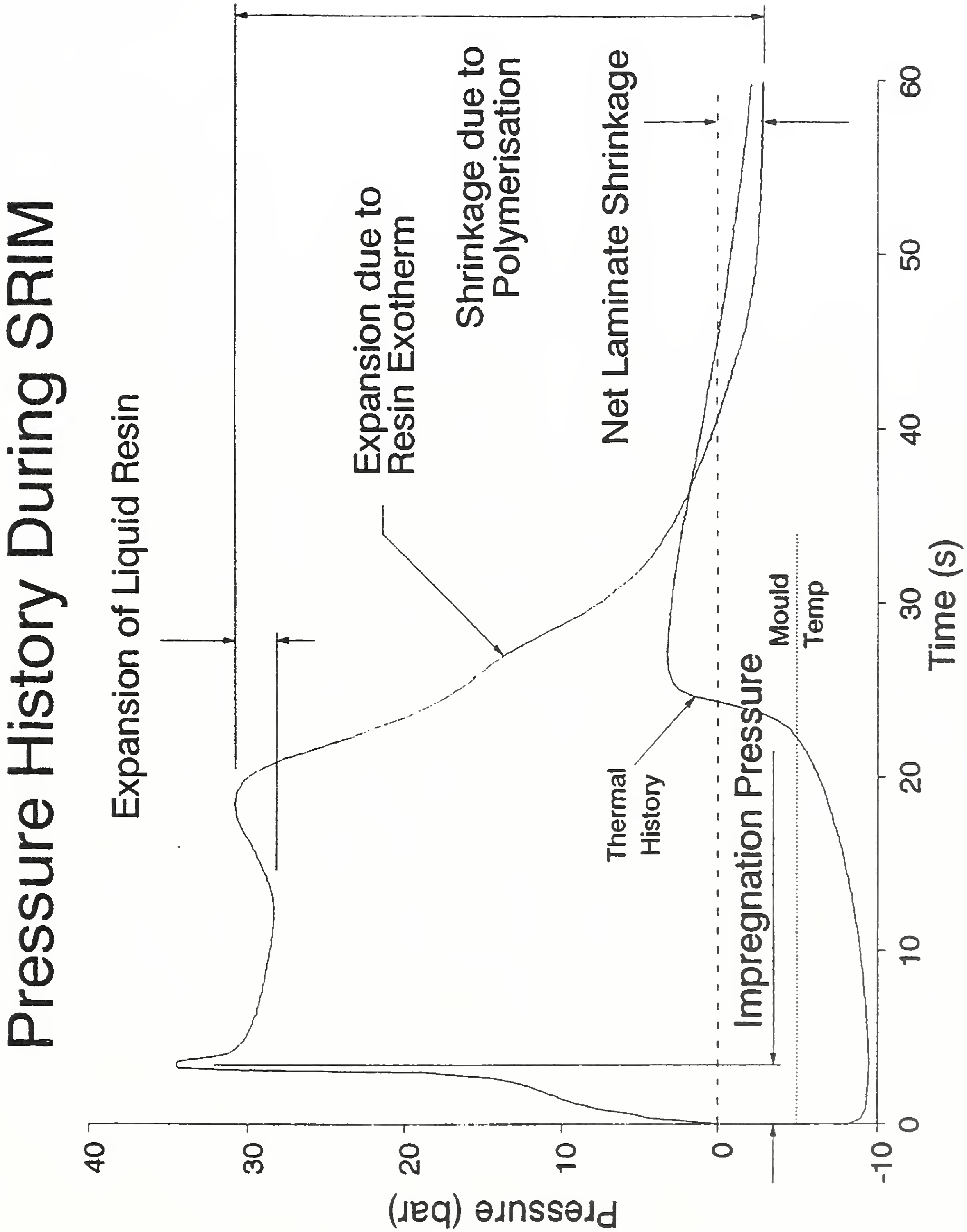
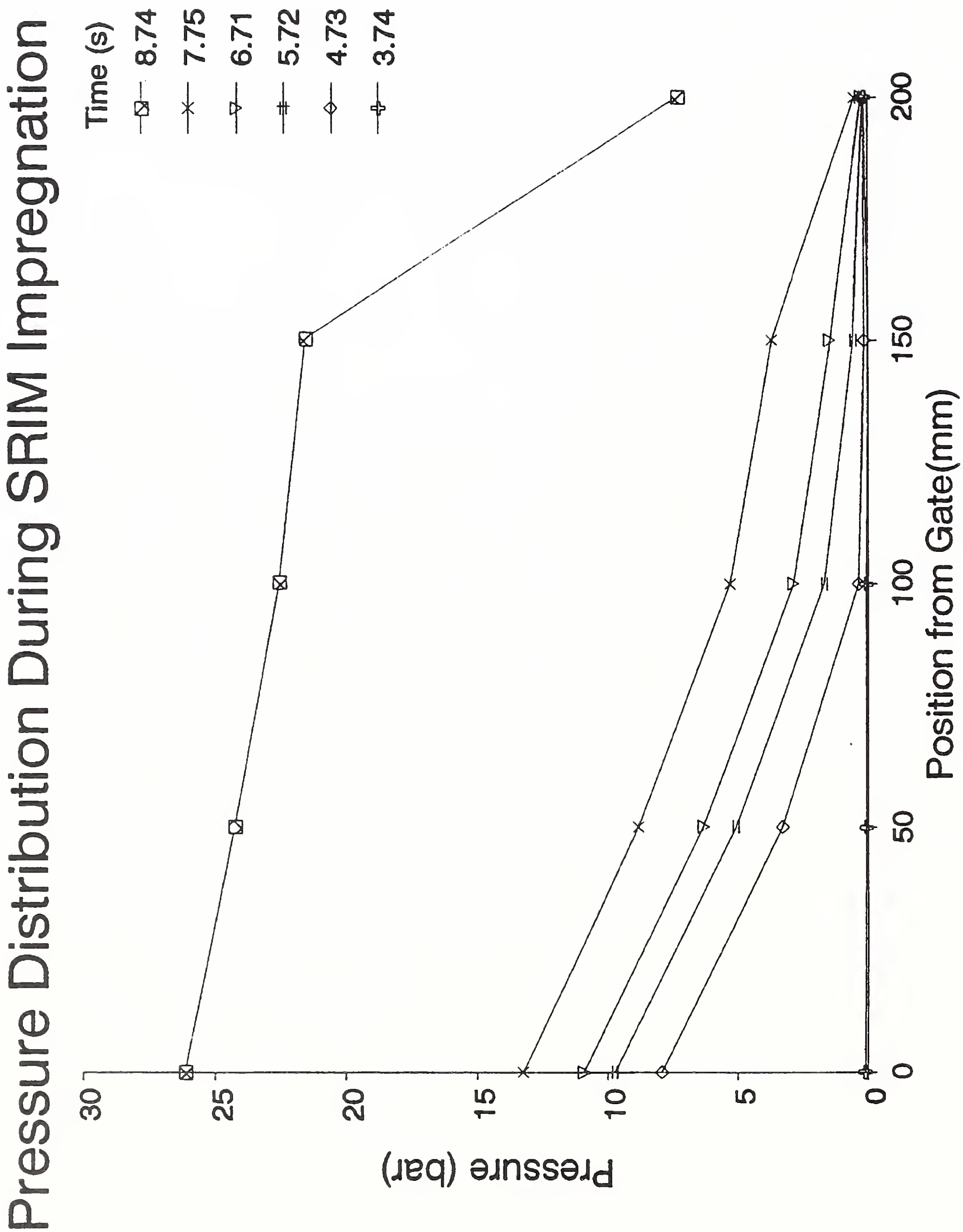

Flow Progression in SRIM
Pressure (bar)
Temperature (C)
Time (s)
Start of Impregnation
Flow Front 0.05m
Flow Front 0.10m
Flow Front 0.15m
Flow Front 0.20m
End
P1
P2
P3
P4
P5
T2
T3
T4
T5
0
5
10
15
20
25
30
0
10
20
30
40
50
60
70
80
0
2
4
6
8
10

Figure 9



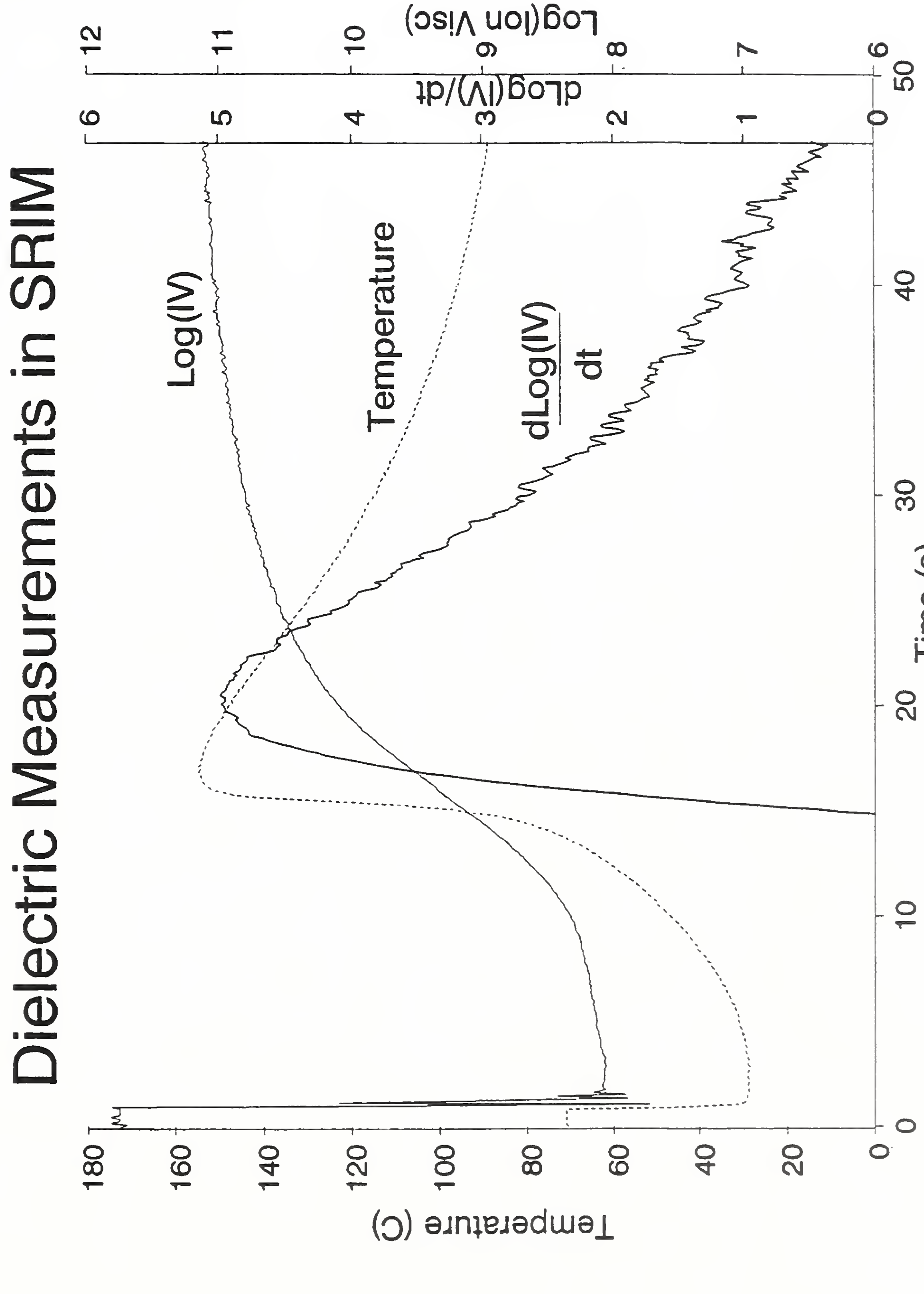
Pressure History During SRIM
Expansion of Liquid Resin
Expansion due to
Resin Exotherm
Shrinkage due to
Polymerisation
Net Laminate Shrinkage
Thermal
History
Impregnation Pressure
Mould
Temp
Pressure (bar)
Time (s)
40
30
20
10
0
-10
0
10
20
30
40
50
60

Figure 10



Pressure Distribution During SRIM Impregnation
Time (s)
8.74
7.75
6.71
5.72
4.73
3.74
Pressure (bar)
30
25
20
15
10
5
0
0
50
100
150
200
Position from Gate(mm)

Figure 11



Dielectric Measurements in SRIM
Log(IV)
Temperature
dLog(IV) / dt
Temperature (C)
Time (s)
dLog(IV)/dt
Log(Ion Visc)
0
20
40
60
80
100
120
140
160
180
0
10
20
30
40
50
0
1
2
3
4
5
6
6
7
8
9
10
11
12

FABRICATION DEFECTS IN COMPOSITES

T. M. DONNELLAN

INDUSTRY WORKSHOP FOR ON-LINE
COMPOSITES PROCESS MONITORING

APRIL 3 - 4, 1996

ATDC

NORTHROP GRUMMAN

Figure 12

OUTLINE

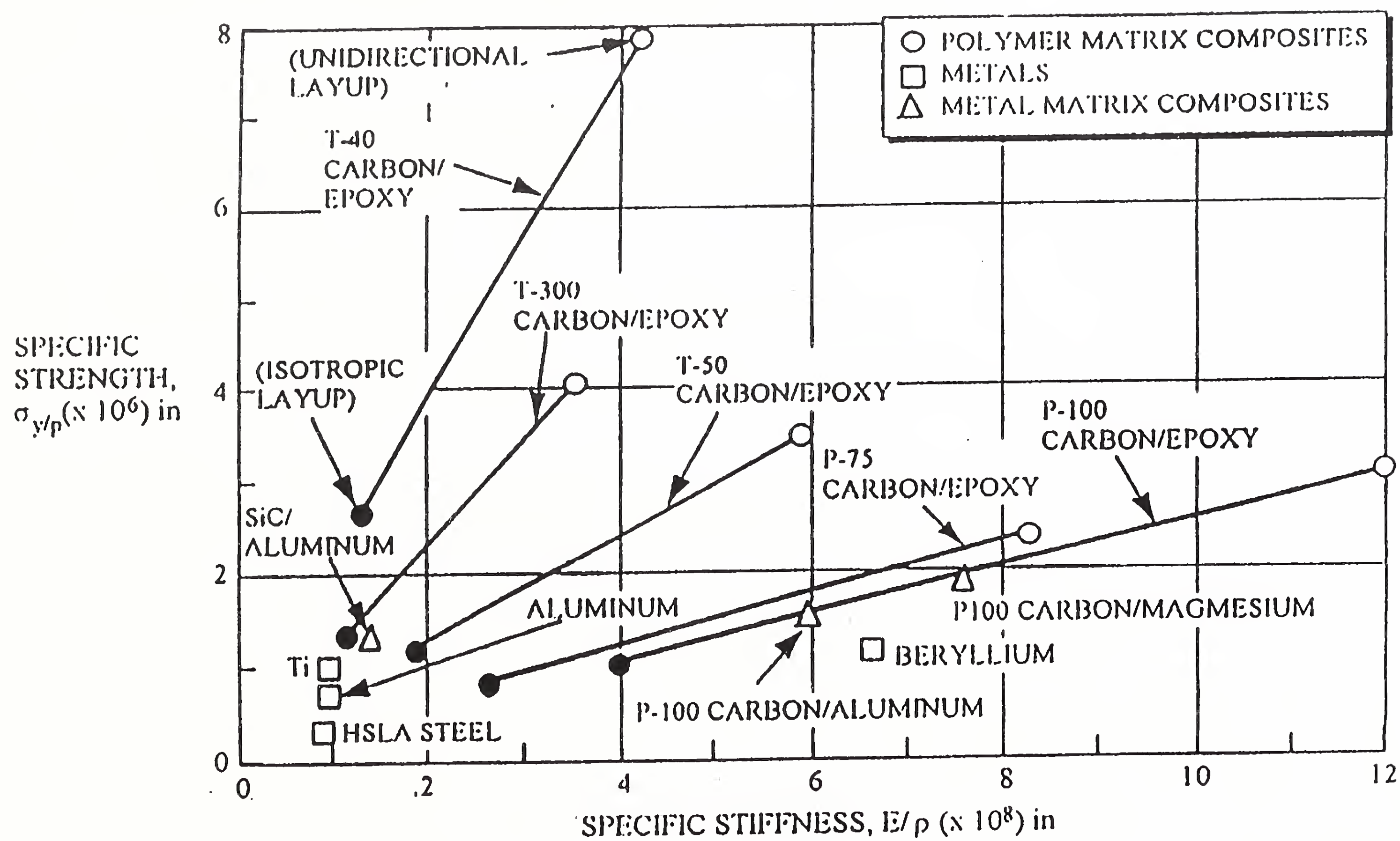
- COMPOSITES IN AEROSPACE APPLICATIONS
  - EFFECTS OF DEFECTS STUDIES
- PAST SENSOR TECHNOLOGY WORK
- SENSOR TECHNOLOGY NEEDS

ATDC

NORTHROP GRUMMAN

Figure 13

COMPOSITE PROPERTY COMPARISONS



W.E. DAVIS "EMERGING TRENDS IN COMPOSITE MATERIALS APPLICABLE TO SPACECRAFT STRUCTURE"
DESIGN OF COMPOSITE SPACECRAFT STRUCTURES VIDEO CONFERENCE WORKSHOP

Figure 14

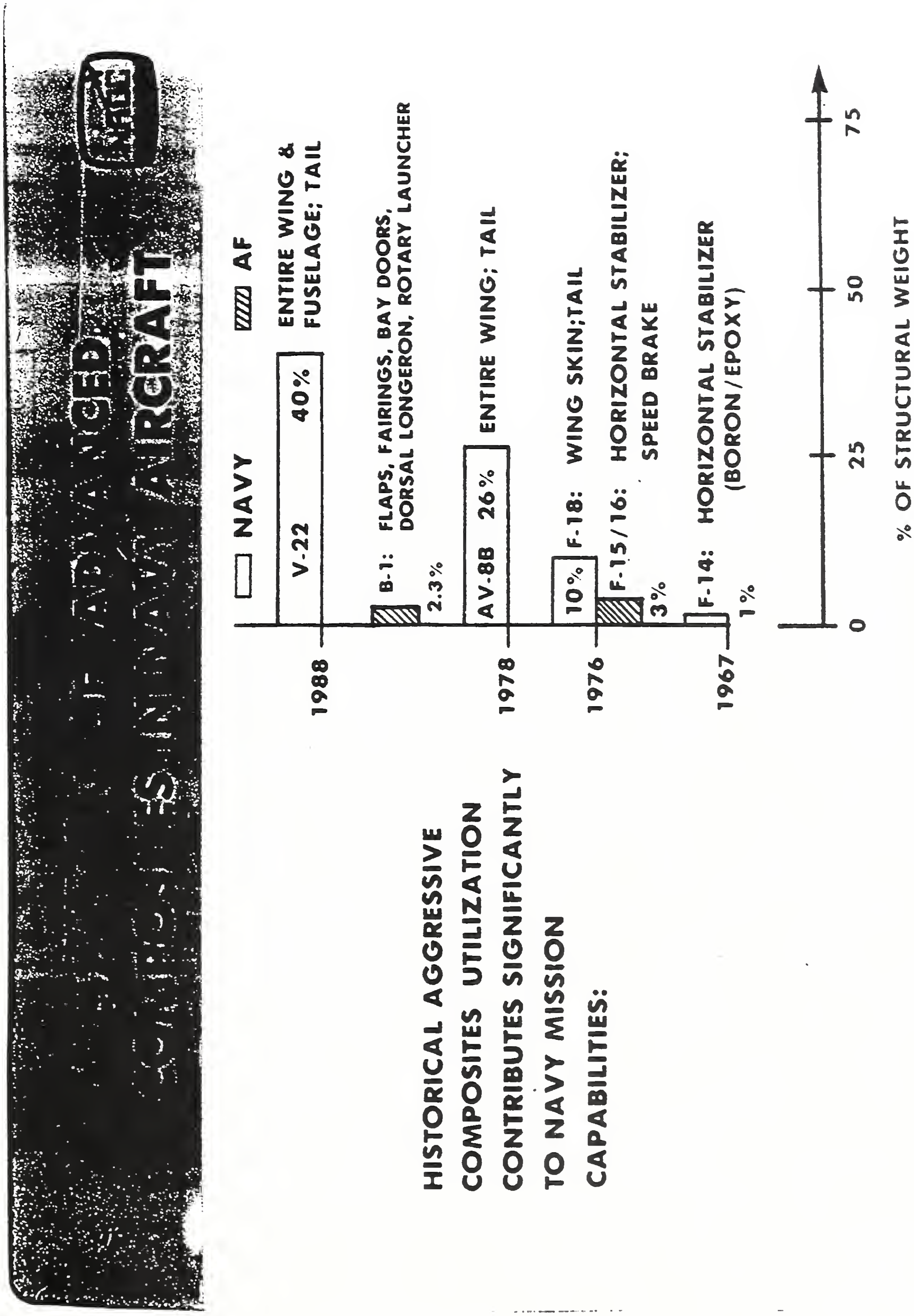

AIRCRAFT
HISTORICAL AGGRESSIVE COMPOSITES UTILIZATION CONTRIBUTES SIGNIFICANTLY TO NAVY MISSION CAPABILITIES:
NAVY
AF
1988
V-22 40%
ENTIRE WING & FUSELAGE; TAIL
B-1: FLAPS, FAIRINGS, BAY DOORS, DORSAL LONGERON, ROTARY LAUNCHER
2.3%
1978
AV-8B 26%
ENTIRE WING; TAIL
1976
10%
F-18: WING SKIN;TAIL
F-15/16: HORIZONTAL STABILIZER; SPEED BRAKE
3%
1967
F-14: HORIZONTAL STABILIZER (BORON/EPOXY)
1%
0
25
50
75
% OF STRUCTURAL WEIGHT
N1809-OA-88-00020

Figure 15

AEROSPACE COMPOSITES TECHNOLOGY

- HIGHLY LOADED, PRIMARY STRUCTURE
- LARGE AND/OR CONTOURED AND/OR INTEGRATED STRUCTURES
- TRIAL AND ERROR PROCESS SPACE DEFINITION REQUIRED (TOOL CONCEPTS, PROCESS PARAMETERS, MATERIALS AND PROCESS SPECS)

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Figure 16

AEROSPACE COMPOSITES TECHNOLOGY

TECHNOLOGY THRUSTS

- MATERIALS
  - HIGH TEMPERATURE (BMI, PT, PI (CONDENSATION))
  - TOUGHNESS (MULTI-PHASE PRE PREG, PHASE SEPARATION ON CURE)
  - LOW COST
- PROCESSES
  - INTEGRATED
  - LOW COST (FIBER PLACEMENT, RTM, ...)

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Figure 17

FABRICATION INDUCED COMPOSITE DEFECTS

- POROSITY (MOISTURE-HUMIDITY, SOLVENTS, AIR, DEGREE OF WETTING, TOOLING)
- DELAMINATION (FOREIGN FILMS, TOOLING, AIR)
- CURE STATE (TOOLING, LOCATION IN AUTOCLAVE, PART COMPLEXITY)
- DIMENSIONAL TOLERANCE (TOOLING, DESIGN, MATERIAL VARIANCE, PROCESS CONDITIONS)

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NORTHROP GRUMMAN

Figure 18

POROSITY

- ACCEPTABLE LEVELS BASED ON DESIGN, EFFECTS OF DEFECTS STUDIES
- TYPICAL ALLOWABLE LEVEL 1/2 IN. X 1/2 IN. AREA WITH 6 IN. SEPARATION BETWEEN AREAS
- AFFECTS RESIN DOMINANT AND FIBER DOMINANT PROPERTIES
- MINIMIZE BY CONTROL OF HUMIDITY, PRE-PREG TACK, PRE-PREG FILM PROCESS, AUTOCLAVE PRESSURE
- FORMATION CAN BE DIFFICULT TO PREDICT

EXAMPLES: YAV-8B WING
F-14 OVERWING FAIRING
F/A-18 STABILIZERS

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Figure 19

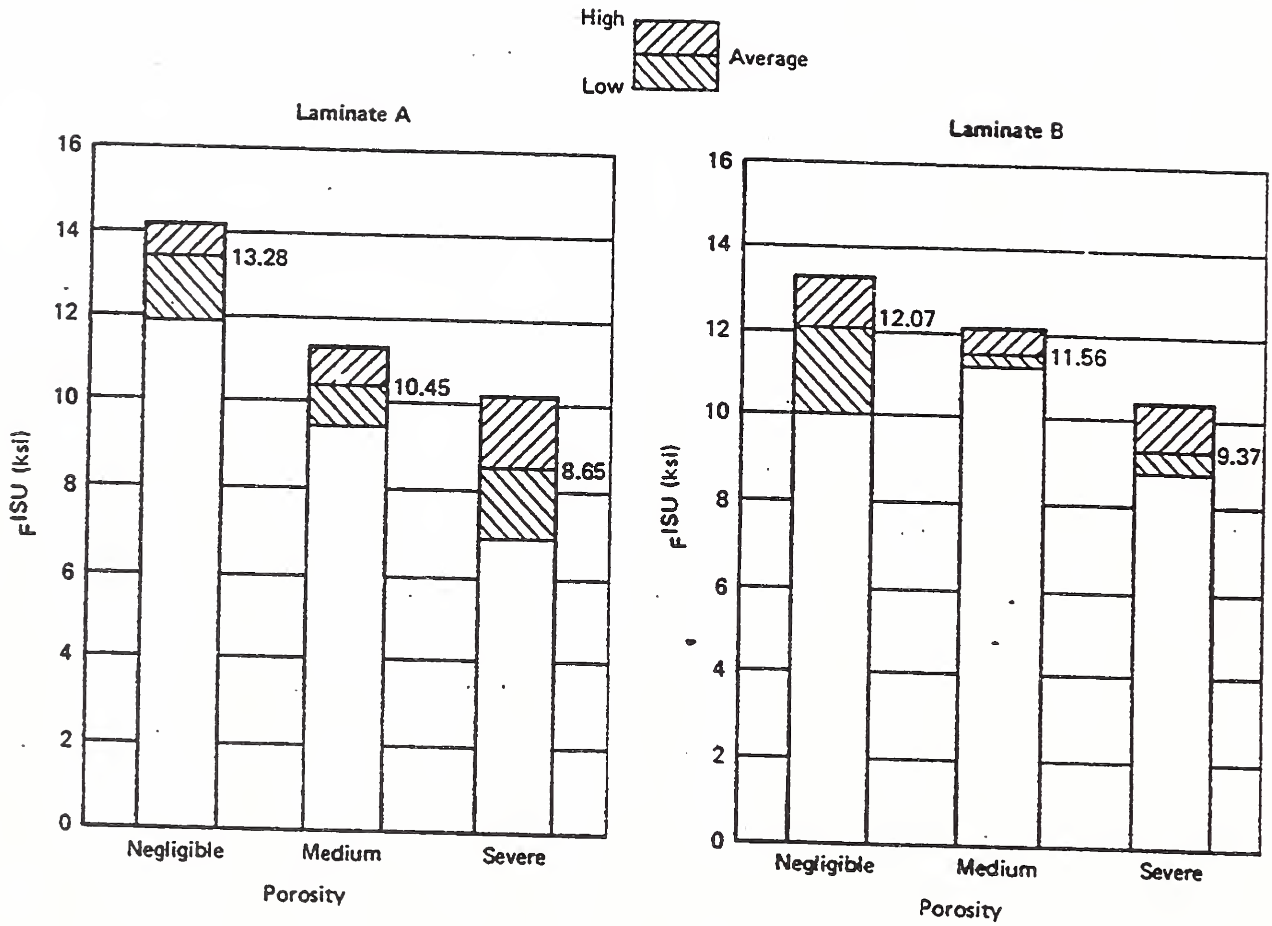
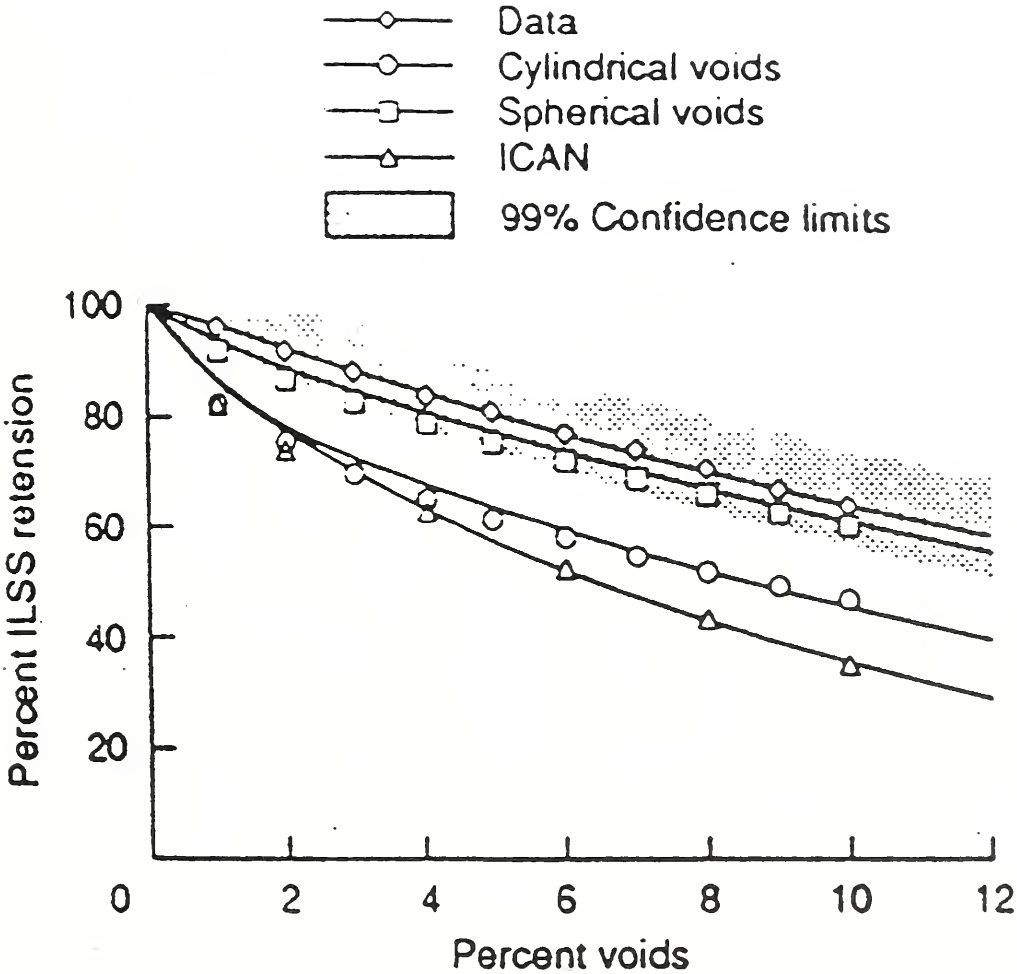


FIGURE 5-20
EFFECTIVE OF POROSITY ON LAMINATE A AND B STATIC
INTERLAMINAR SHEAR STRENGTH
R.T./Dry

RE BOHLMANN, G D RENIERI, J J KOZAREWICZ
DEVELOPMENT OF ACCEPTANCE CRITERIA FOR GRAPHITE/EPOXY
STRUCTURES

MARCH 1982

Figure 20



ILSS as a function of void content for 60 v/o AS/PMR-15 unidirectional com-

KJ BOWLES & S. FRIMPONG
VOID EFFECTS ON THE INTERLAMINAR SHEAR
STRENGTH OF UNIDIRECTIONAL GRAPHITE FIBER
REINFORCED COMPOSITES

J. COMP. MATLS 26, 10, 1992
1487-1509

Figure 21

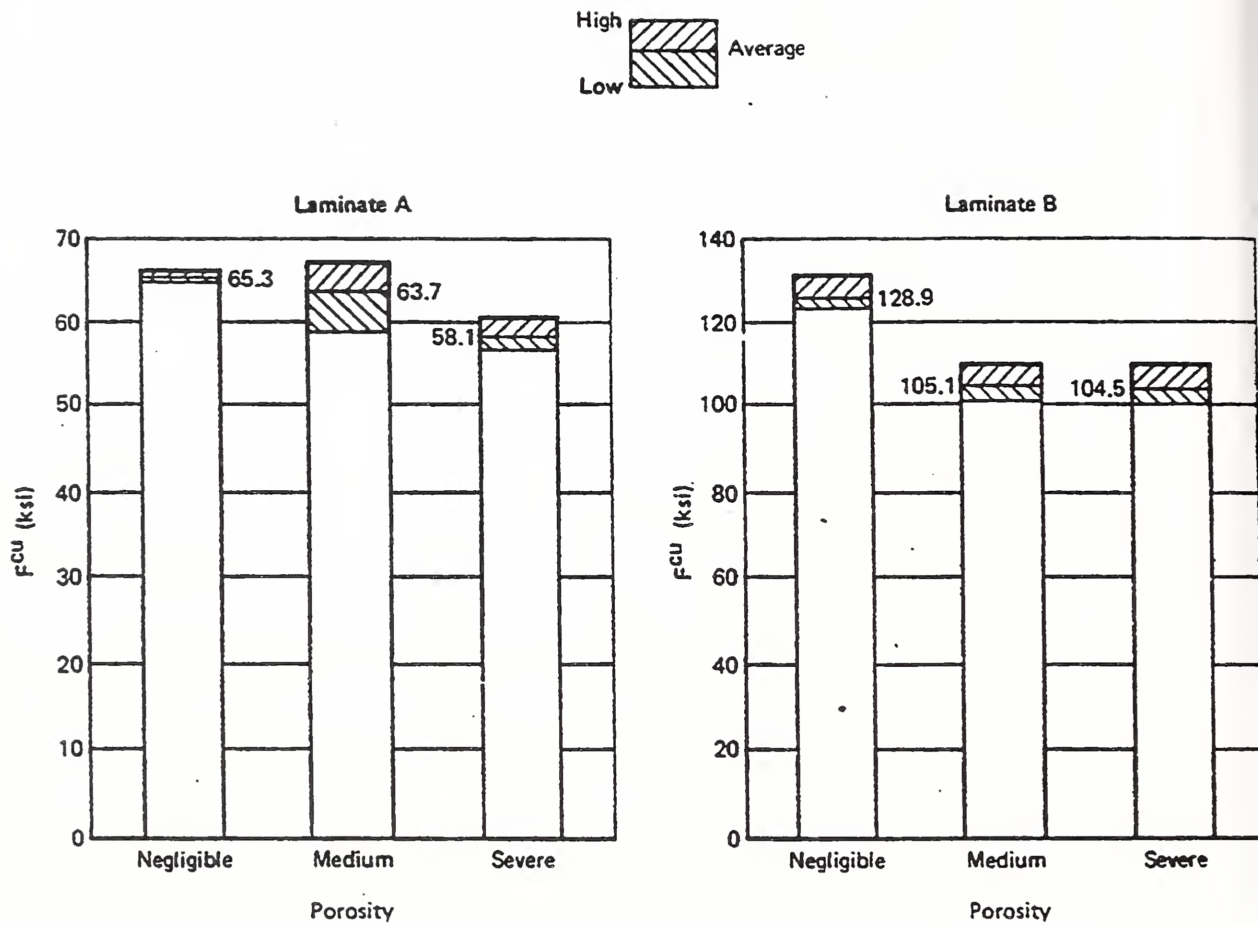


FIGURE 5-18
EFFECT OF POROSITY ON LAMINATE A AND B STATIC COMPRESSIVE STRENGTH
R.T./Dry

Bowman, Renieri, Kozarewicz
Development of Acceptance Criteria for Graphite/Epoxy Structures

Figure 22

COMPRESSION FAILURE MODES

LONGITUDINAL COMPRESSION

- FILAMENT MICROBUCKLING
- MATRIX YIELD FOLLOWED BY FILAMENT MICROBUCKLING
- FIBER / MATRIX DEBOND FOLLOWED BY FILAMENT MICROBUCKLING
- PANEL MICROBUCKLING
- SHEAR FAILURE
- DELAMINATION

TRANSVERSE COMPRESSION

- MATRIX COMPRESSIVE FAILURE
- MATRIX SHEAR FAILURE
- FIBER / MATRIX DEBOND
- FIBER CRUSHING

J. M. WHITNEY, C.E. BROWNING
COMPRESSION OF COMPOSITE MATERIALS
ADVANCED COMPOSITES SC 50

Figure 23

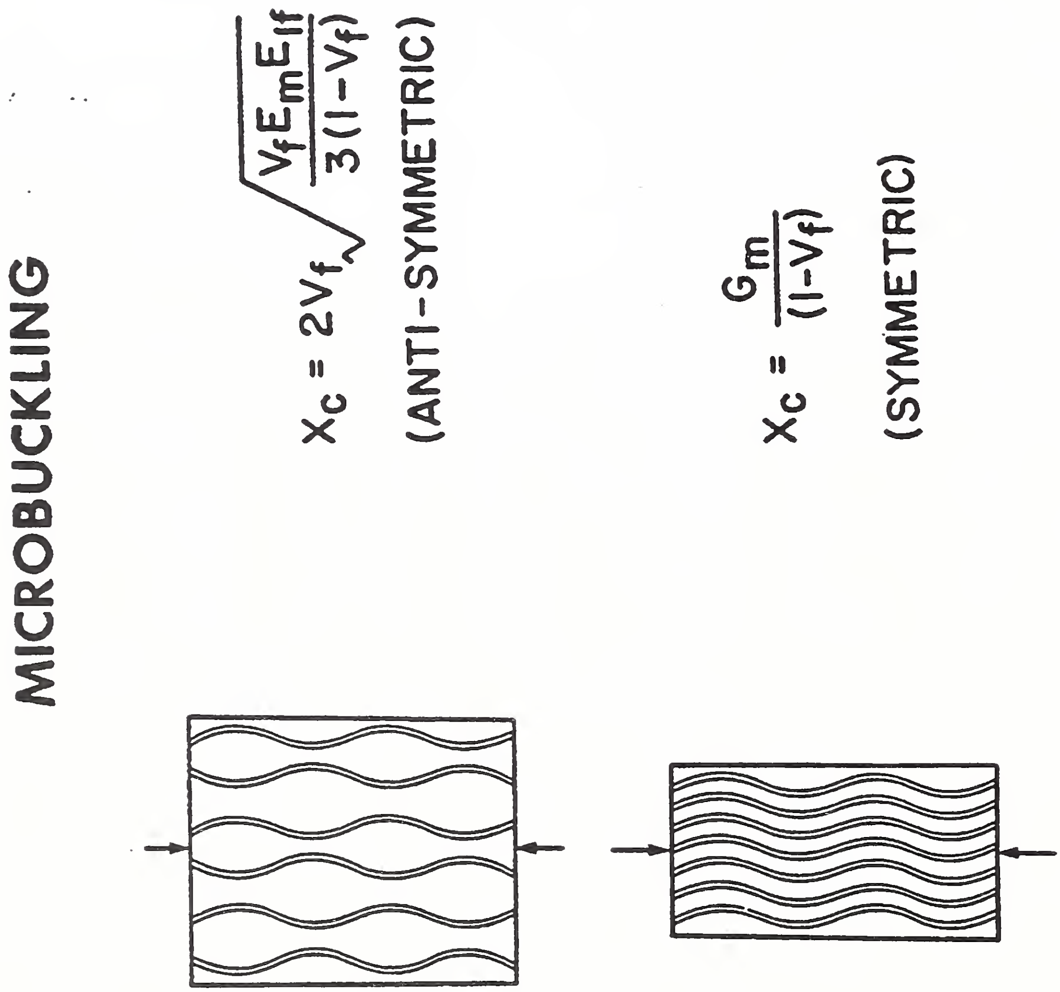

MICROBUCKLING
$X_c = 2V_f\sqrt{\frac{V_f E_m E_{lf}}{3(1-V_f)}}$
(ANTI-SYMMETRIC)
$X_c = \frac{G_m}{(1-V_f)}$
(SYMMETRIC)

Figure 24

LONGITUDINAL COMPRESSION

SHEAR FAILURE MODE

$$X_c = 2X_{6f}\left[V_f + (1 - V_f)\frac{E_m}{E_{1f}}\right]$$

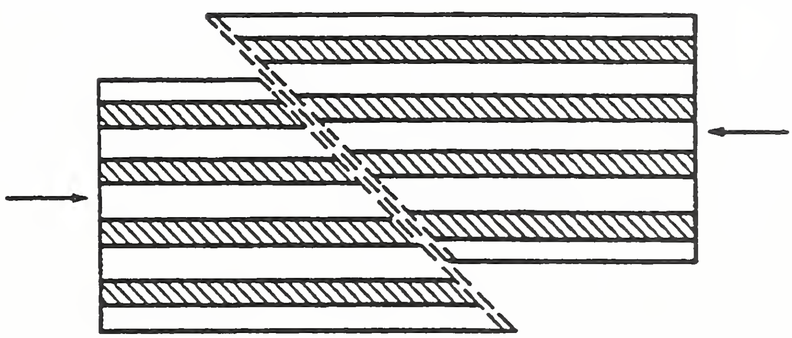
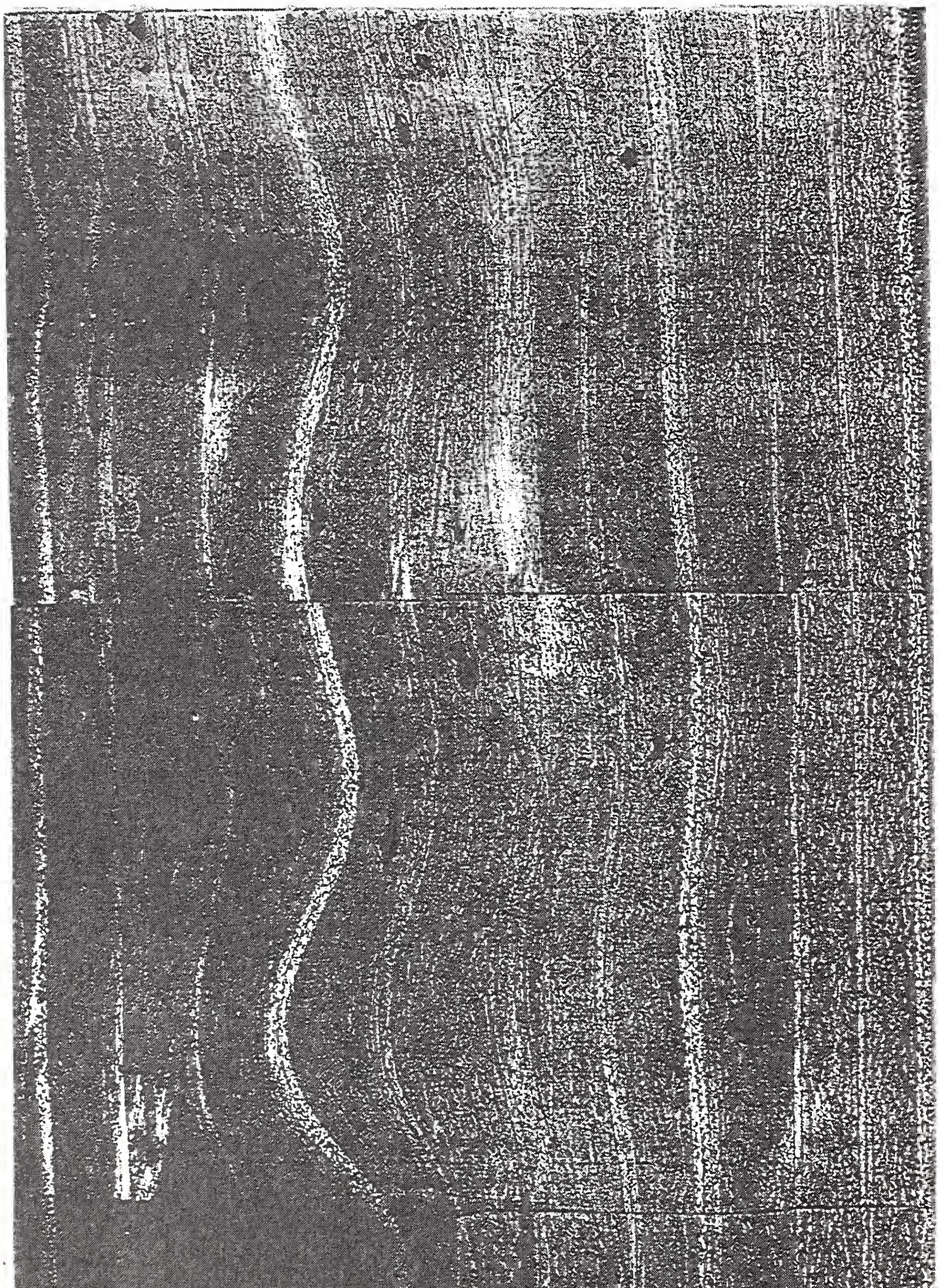
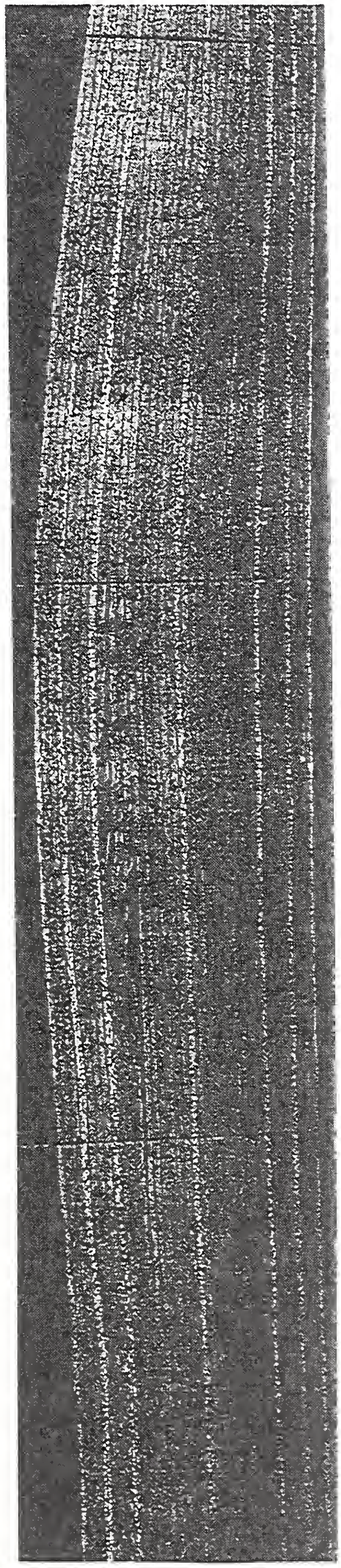


Figure 25



F-14 Over-Wing Fairing (Porosity)

Figure 26



F-18 Vertical Stabilizer (Porosity)

Figure 27

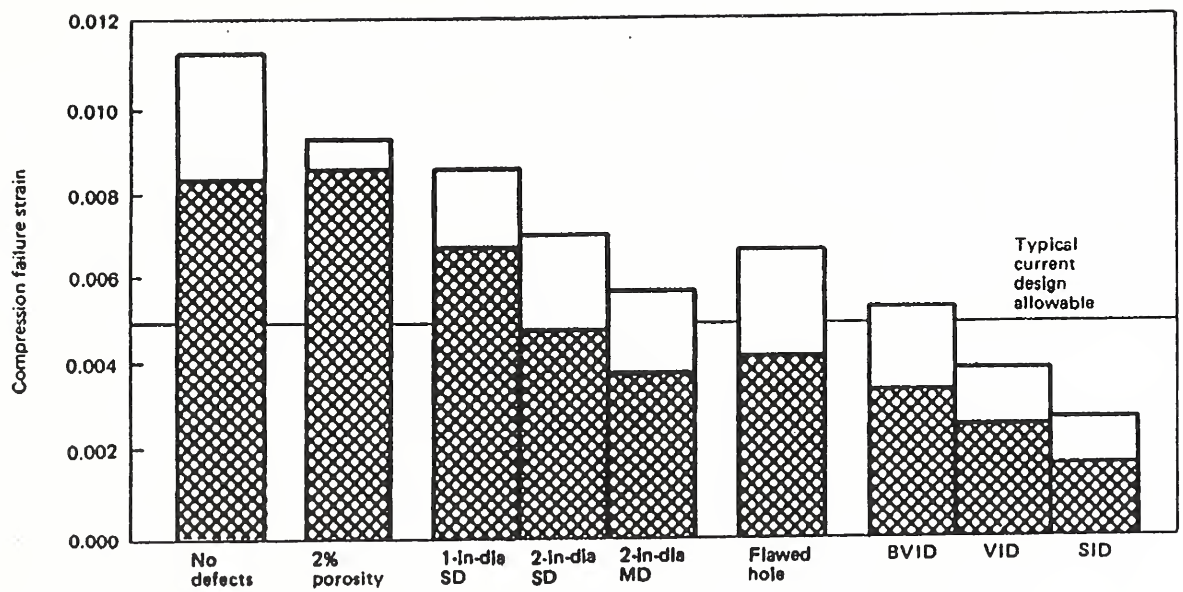
DELAMINATION

- MATERIAL SPECIFIC EFFECT
- TYPICAL ALLOWABLE LEVELS 1/2 IN. X 1/2 IN.
- LARGER IMPACT ON COMPRESSION DOMINATED DESIGNS; RELATED TO BUCKLING STABILITY
- CONTROL BY TOOLING CONCEPT, PROCESS RATES, QC

  EXAMPLE: F-14 OVERWING FAIRING
  SUBMARINE DRY DECK SHELTER

ATBC NORTHROP GRUMMAN

Figure 28



Legend:
- Static strength
- 10^6 fatigue threshold (R = 10.0)

Abbreviations:
- BVID barely visible impact damage
- MD multiple delamination
- SD single delamination
- SID severe impact damage
- VID easily visible impact damage

Condition:
- Room temperature, dry

Figure 4-5. Defect/Damage Severity Comparison for Compression Loading

RE NORTON, R S WHITEHEAD

DAMAGE TOLERANCE OF COMPOSITES
VOL I DEVELOPMENT OF REQUIREMENTS
AND COMPLIANCE DEMONSTRATION

JUNE 1988

Figure 29

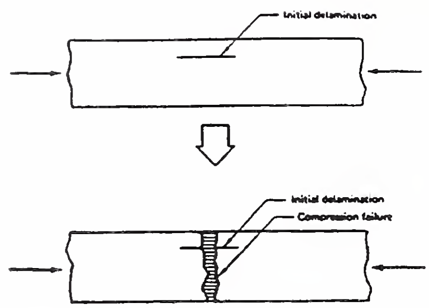


Figure 3-6. Gross Compression Failure (Failure Mode 1)

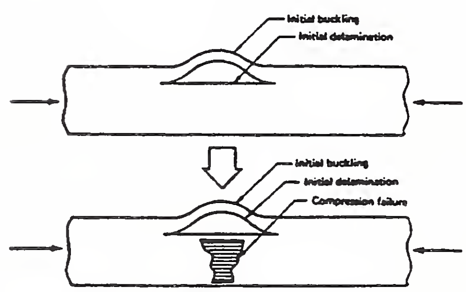


Figure 3-7. Initial Buckling of the Delamination Followed by Compression Failure (Failure Mode 2)

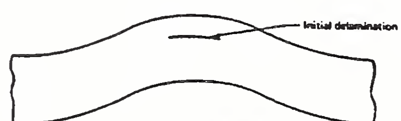


Figure 3-8. Global Buckling (Failure Mode 3)

Figure 3-9. Initial Buckling of the Delamination Followed by Global Buckling (Failure Mode 4)

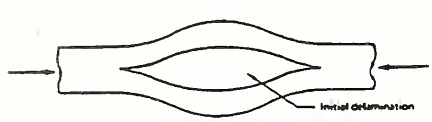


Figure 3-10. Local Buckling (Failure Mode 5)

Figure 30

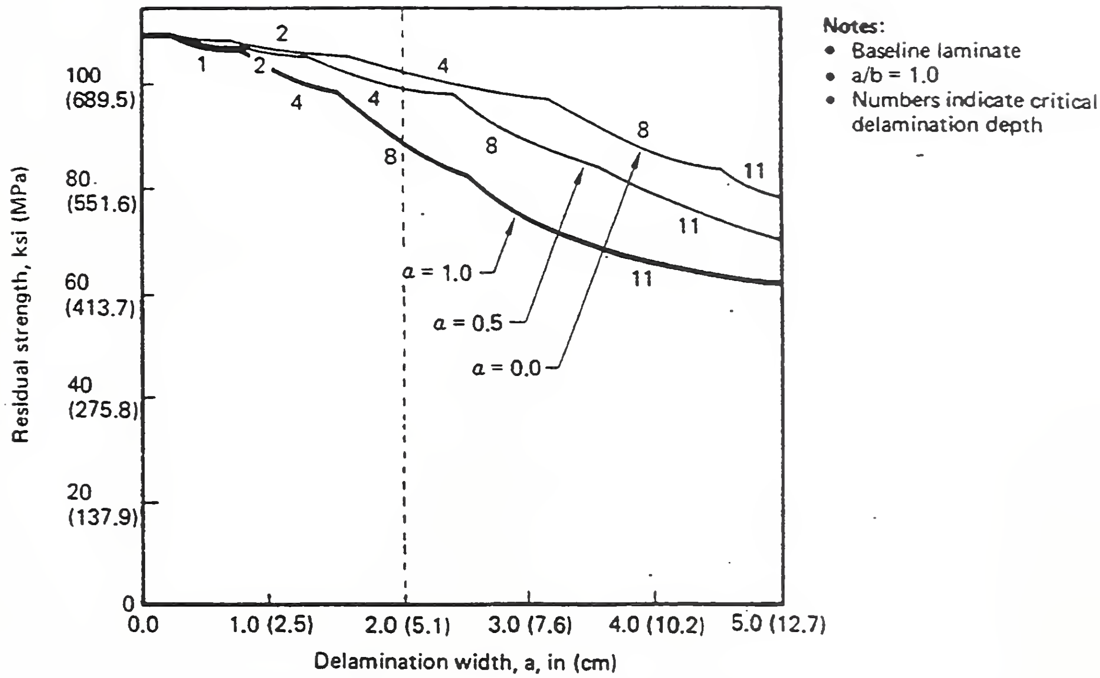
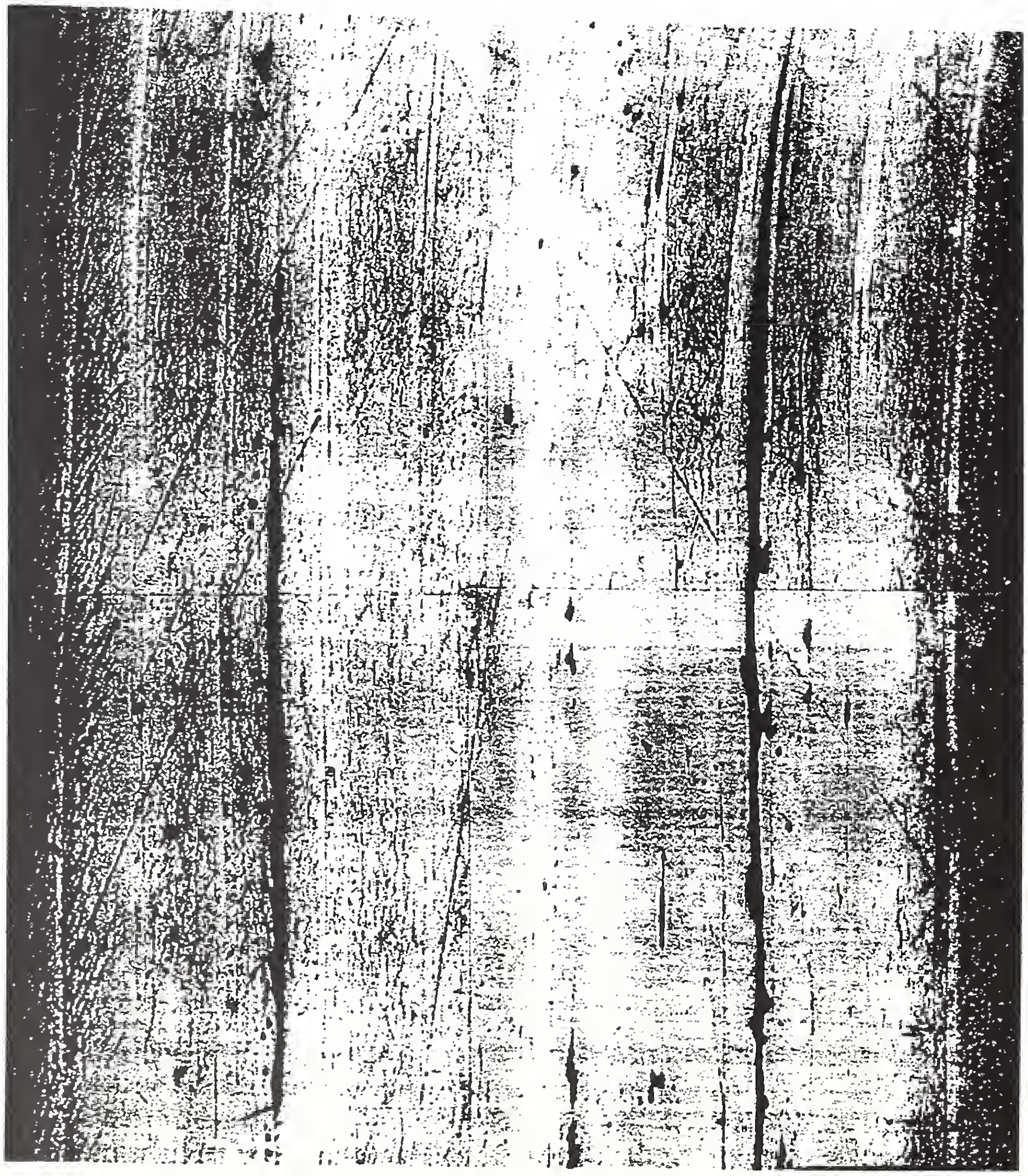


Figure 3-24. Influence of Boundary Fixity on Laminate Static Strength

Figure 31



F-14 Over-Wing Fairing (Delamination)

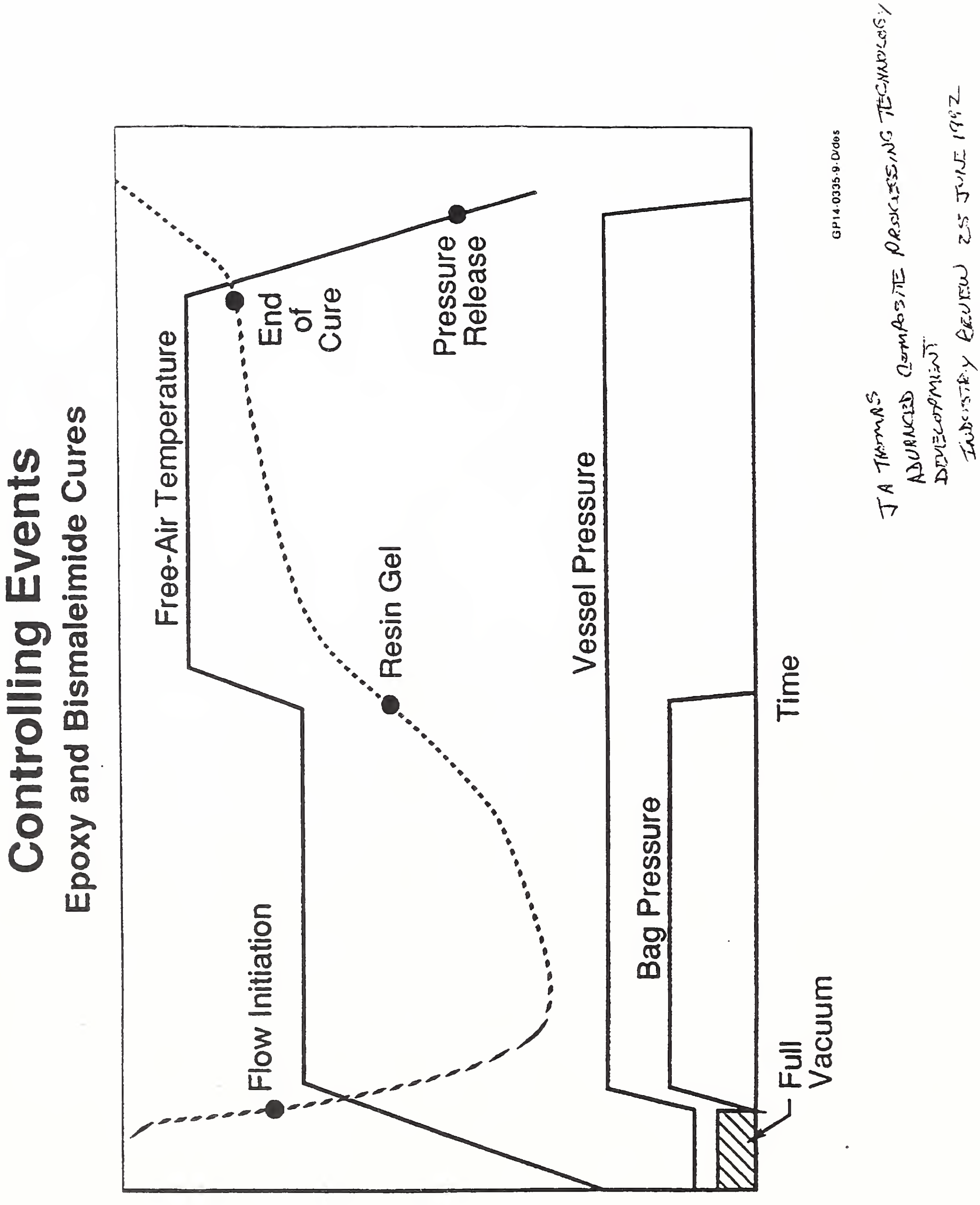
Figure 32

CURE STATE

- CHEMICAL STATE CHANGES RELATED TO VISCOSITY, VOLATILE REMOVAL, EXOTHERM, THERMAL AND MECHANICAL PROPERTIES
  - AGE OF STARTING MATERIAL CAN BE A VARIABLE
  - TOOLING AND AUTOCLAVE LOADING CAUSE DEVIATIONS FROM PROCESS SPECIFICATION
- UNDERCURE REDUCTION IN HOT, WET PROPERTIES; OVERCURE REDUCTION IN TOUGHNESS
- CONTROL BY PROCESS DESIGN, SYSTEM THERMAL PROFILES, MATERIAL QC

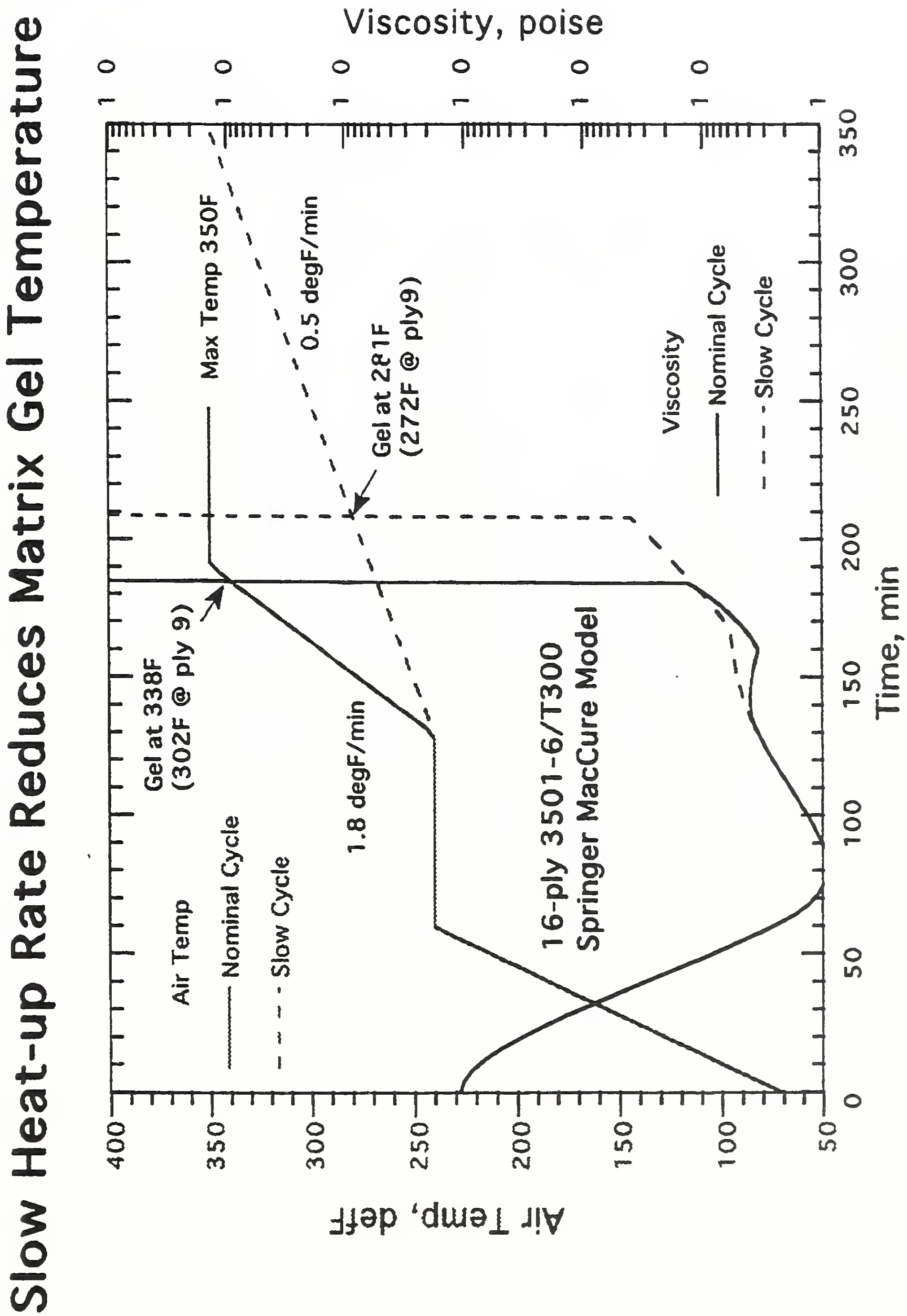
ATDC NORTHROP GRUMMAN

Figure 33



Controlling Events
Epoxy and Bismaleimide Cures
Free-Air Temperature
Flow Initiation
Resin Gel
End of Cure
Pressure Release
Vessel Pressure
Bag Pressure
Full Vacuum
Time
GP14-0335-9-D/des
J A Thomas
Advanced Composite Processing Technology
Development
Industry Review 25 June 1992

Figure 34



Slow Heat-up Rate Reduces Matrix Gel Temperature
Viscosity, poise
Air Temp, degF
Time, min
Gel at 338F
(302F @ ply 9)
Max Temp 350F
0.5 degF/min
Gel at 281F
(272F @ ply9)
1.8 degF/min
16-ply 3501-6/T300
Springer MacCure Model
Air Temp
Nominal Cycle
Slow Cycle
Viscosity
Nominal Cycle
Slow Cycle

Figure 35

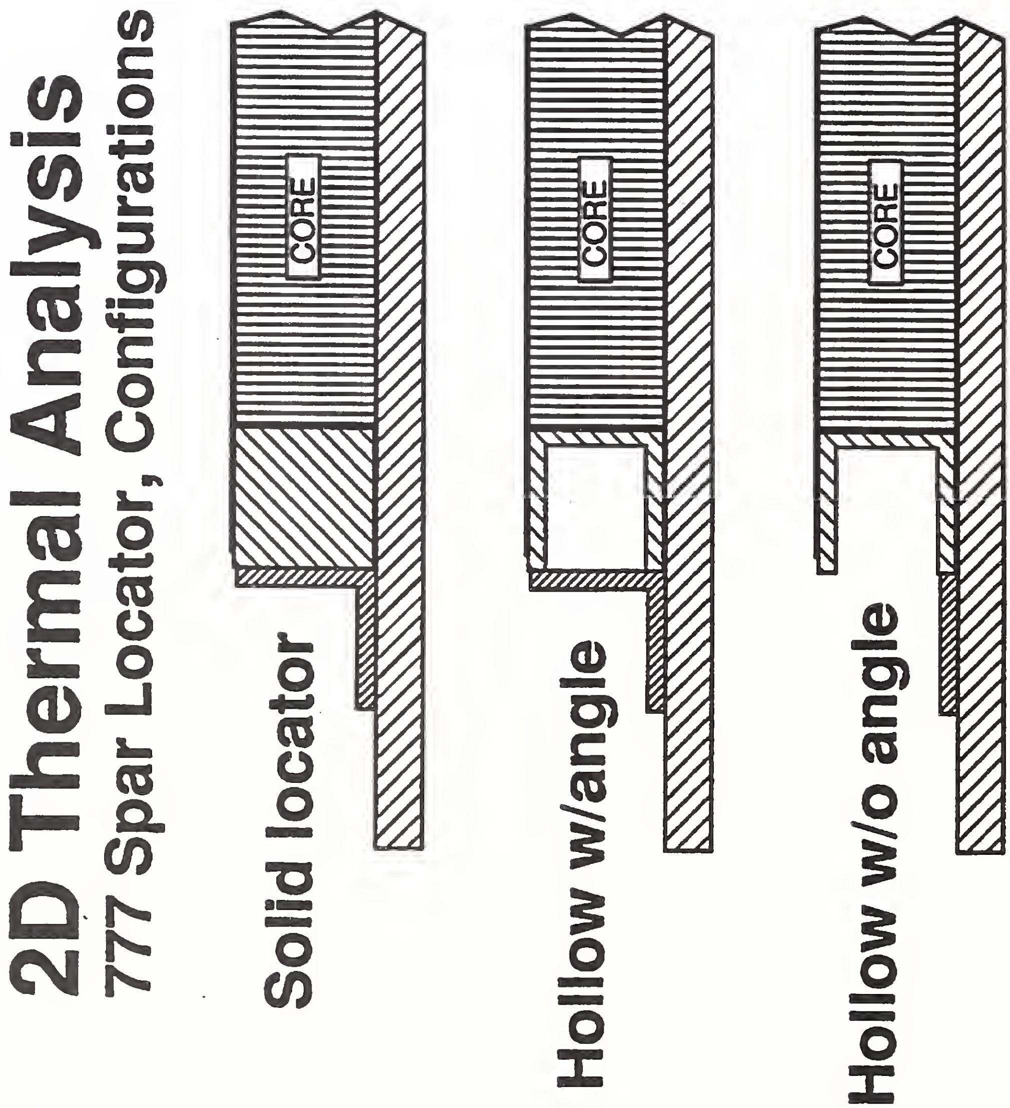

2D Thermal Analysis
777 Spar Locator, Configurations
Solid locator
Hollow w/angle
Hollow w/o angle
CORE
CORE
CORE

Figure 36

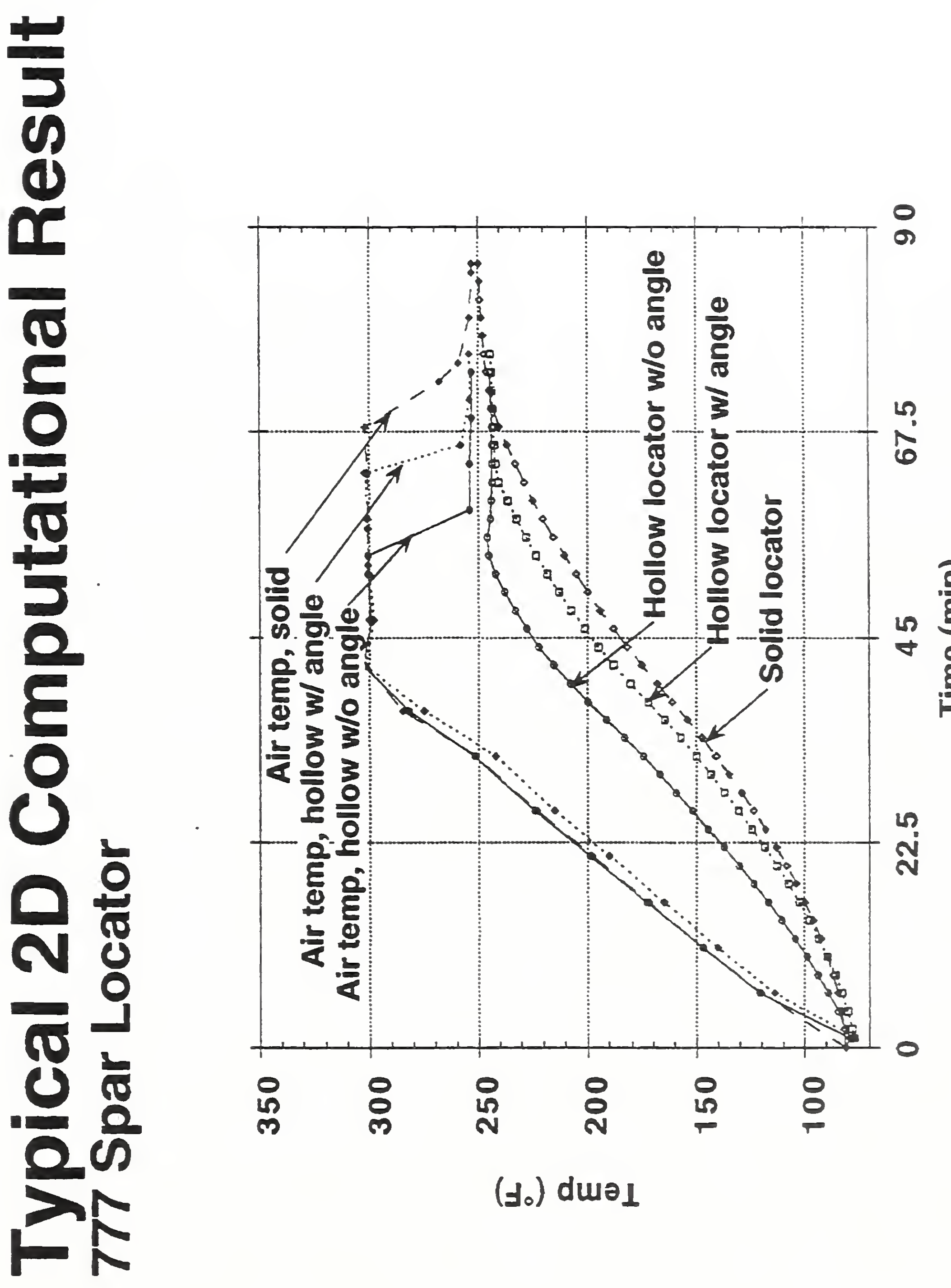
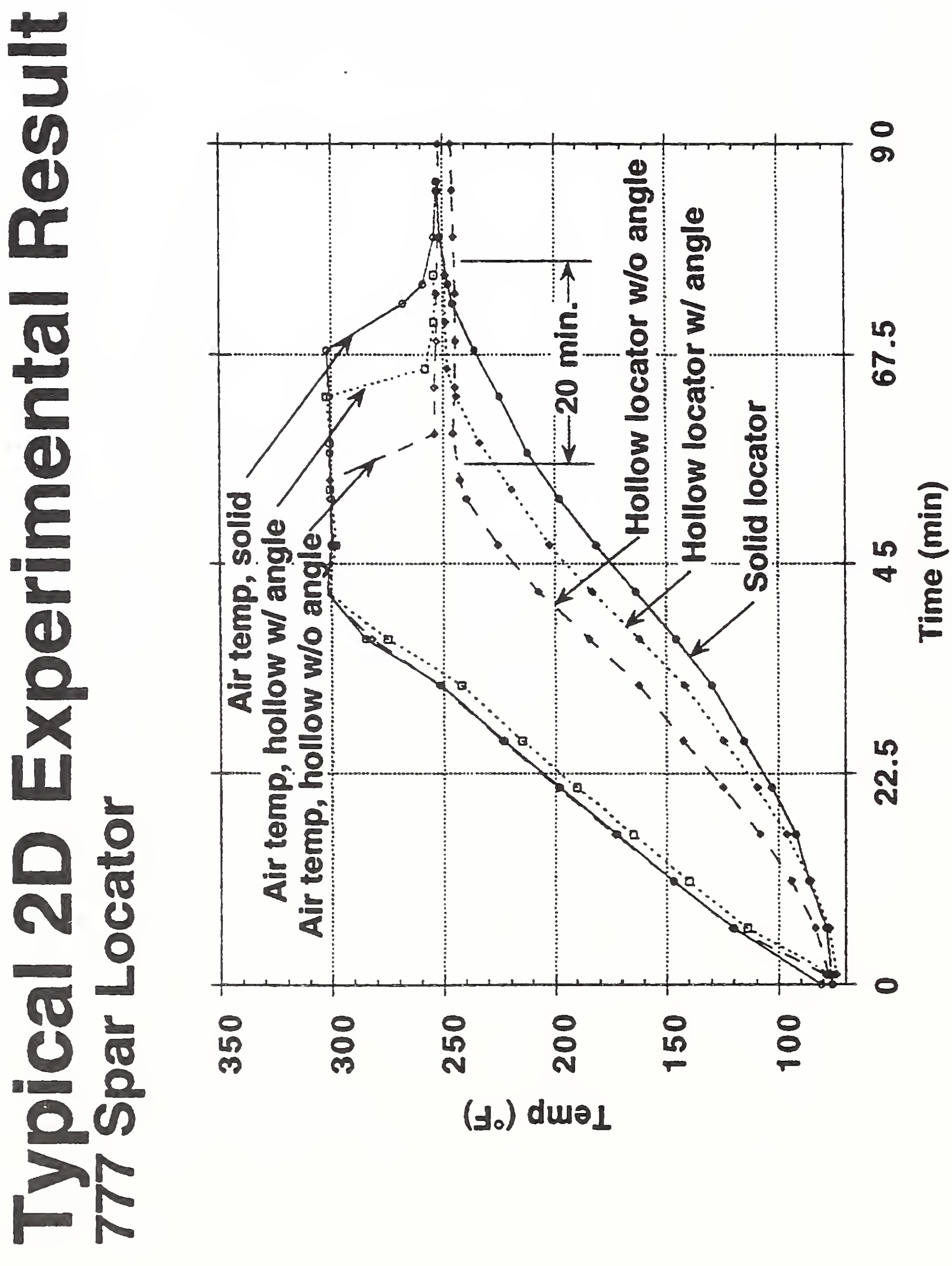

Typical 2D Computational Result
777 Spar Locator
Temp (°F)
350
300
250
200
150
100
0
22.5
45
67.5
90
Time (min)
Air temp, solid
Air temp, hollow w/ angle
Air temp, hollow w/o angle
Hollow locator w/o angle
Hollow locator w/ angle
Solid locator

Figure 37



Typical 2D Experimental Result
777 Spar Locator
Temp (°F)
Time (min)
Air temp, solid
Air temp, hollow w/ angle
Air temp, hollow w/o angle
Hollow locator w/o angle
Hollow locator w/ angle
Solid locator
20 min.
350
300
250
200
150
100
0
22.5
45
67.5
90

Figure 38

977-3/IM7 LAMINATE Tg DATA

Cure	2 Hrs./180°C	6 Hrs./180°C	2 Hrs./180°C + 2 Hrs./200°C
Dry Flex Tg, °C	NA	215	215
Dry DMA Tg, °C			
G'	164	186	180
G"	180	185, 231	193, 240
Tan Delta	177, 203	186, 239	195, 242
Wet DMA Tg, °C			
G'	141	165	145
G"	154, 177	185, 190	160, 198
Tan Delta	157, 188	186, 202	166, 198

Note:

Wet = 48 hr. water boil

ICI FIBERITE

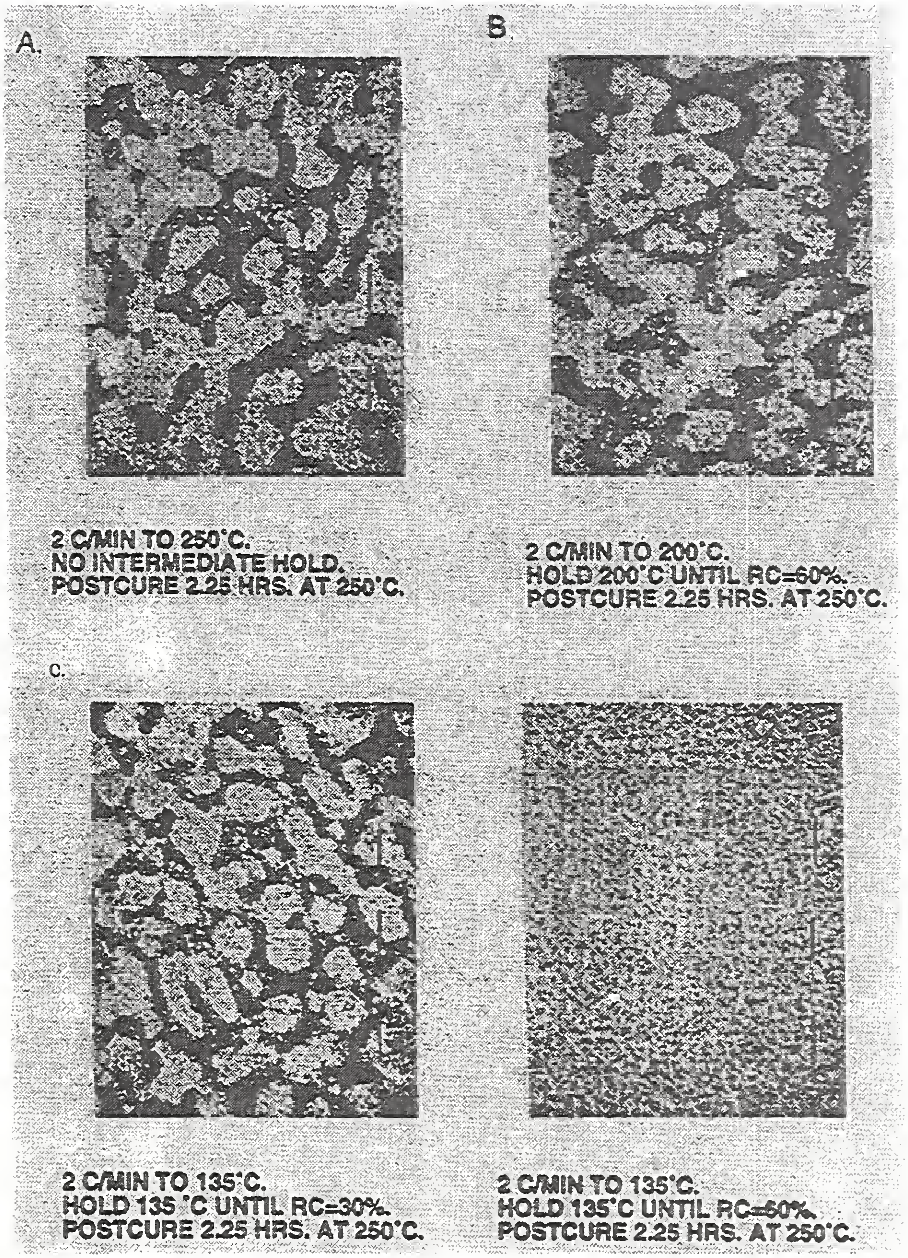
Figure 39

Cure Cycle Evaluation Summary of ICI FIBERITE's Hy-E 5377-3A (977-3/IM7 UDT) per F-22 Document CMD/91-033 and E-HH-012-92

	As Cured Tg[1]		CAI Strength[2] ksi		EDS Onset Strength[3] ksi	
Cure Cycle #1 Minimal Heat History	Average	239.2	Average	34.8	Average	37.9
Ramp Rate of 5.0-5.5°F/Minute	St Dev	2.49	St Dev	0.8	St Dev	0.9
Hold at 340-345°F for 330-340 minutes	Cov	1.0	CoV	2.4	CoV	2.3
Cure Cycle #2 Nominal Heat History	Average	240.8	Average	29.4	Average	36.4
Ramp Rate of 2.5-3.5°F/Minute	St Dev	1.64	St Dev	1.1	St Dev	1.3
Hold at 353-357°F for 355-365 minutes	Cov	0.7	CoV	3.9	CoV	3.6
Cure Cycle #3 Elevated Heat History	Average	239.0	Average	26.9	Average	36.4
Ramp Rate of 0.5-1.5°F/Minute	St Dev	1.44	St Dev	0.9	St Dev	1.2
Hold at 365-370°F for 380-390 minutes	Cov	0.6	CoV	3.2	CoV	3.3

1) As tested per 5PTPTT01 Method 2.6 (TMA Penetration)
2) As tested per 5PTPTT01 Method 4.30 with the following exceptions from F-22 document E-HH-077-92
Panel Orientation [+45,90,-45,0]4s; Impact energy of 1500 in.-lb/in., based on nominal per-ply thickness; Impact Tup 0.5 inch diameter and Specimen Dimensions: Figure 3, prior to remachining after impact, and figure 4 (4.0 x 10.0 in.) remachined for compression testing.
3) As tested per 5PTPTT01 Method 4.27.
4) Five specimens were used for each data set.

Figure 40



J. Brown et al.
Production of Controlled Networks and Morphologies in Toughened Thermosetting Resin using Real Time In-Situ Cure Monitoring

41st Sagamore Conference Proceedings
US Army Research Lab
August 1994

Figure 41

DIMENSIONAL TOLERANCE

- STARTING MATERIAL VARIANCES, TOOLING CONCEPTS, PART DESIGN PRODUCE COMPONENTS THAT HAVE POOR CORRELATION TO DESIGN
  - RADIUS PROBLEMS - MALE TOOL - THINNING
    - FEMALE TOOL - THICKENING
  - THICKNESS CONTROL - ASSEMBLY INDUCED DELAMINATIONS
  - GEOMETRY CONTROL - SPRING IN/OUT - RESIDUAL STRESS
- CONTROL BY TOOL DESIGN, COMPONENT DESIGN, PROCESS

ATDC NORTHROP GRUMMAN

Figure 42

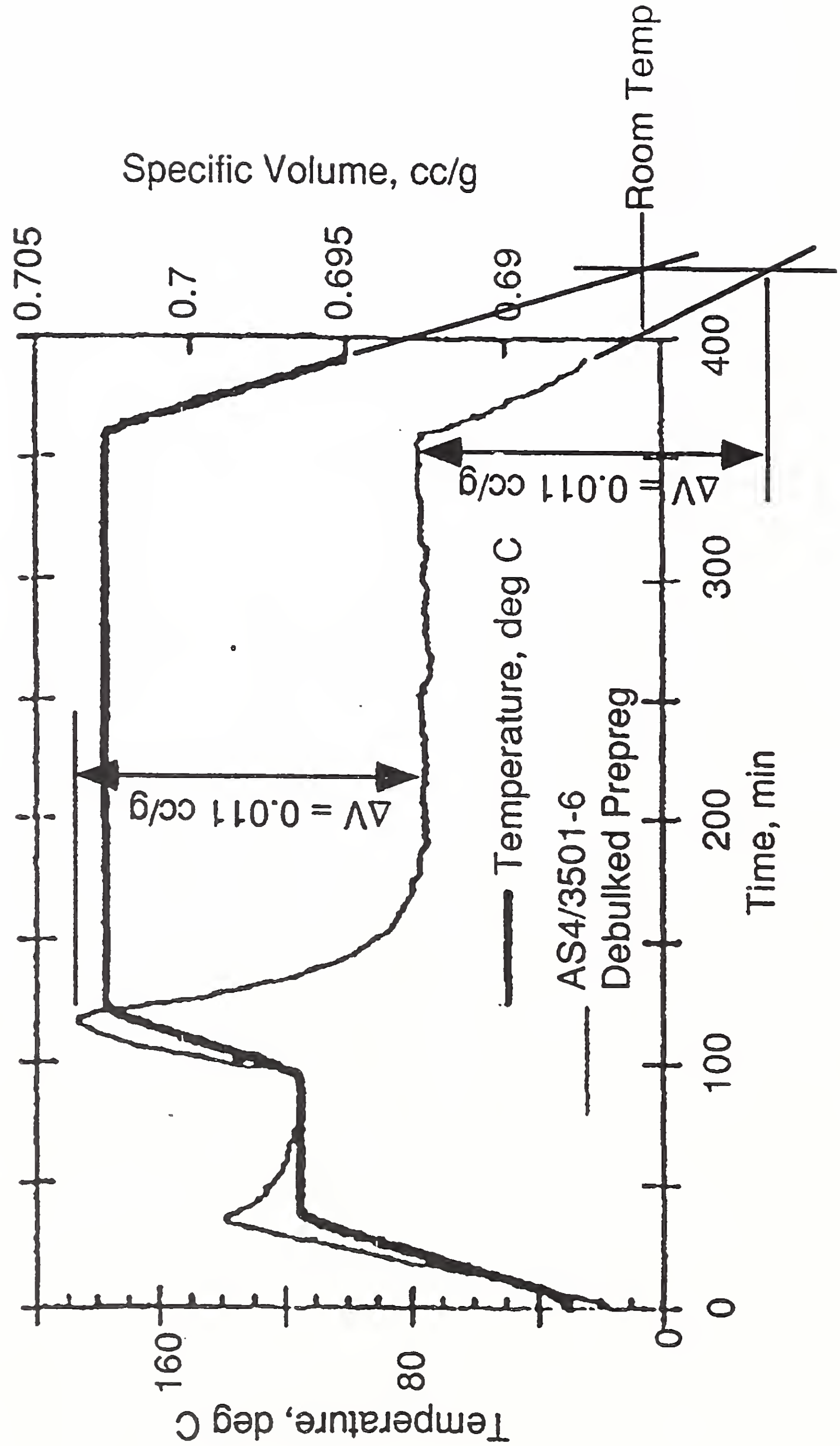
Factors Contributing to Spring-In

- **Anisotropic thermal shrinkage during cool down**
  - composite lay-up
  - number of plies
  - radius of curvature
  - initial angle

- **Process-induced residual stresses**
  - cure cycle dependent
  - chemical shrinkage during cure
  - time history of volume change vs. viscosity change
  - fiber volume fraction gradient through the thickness

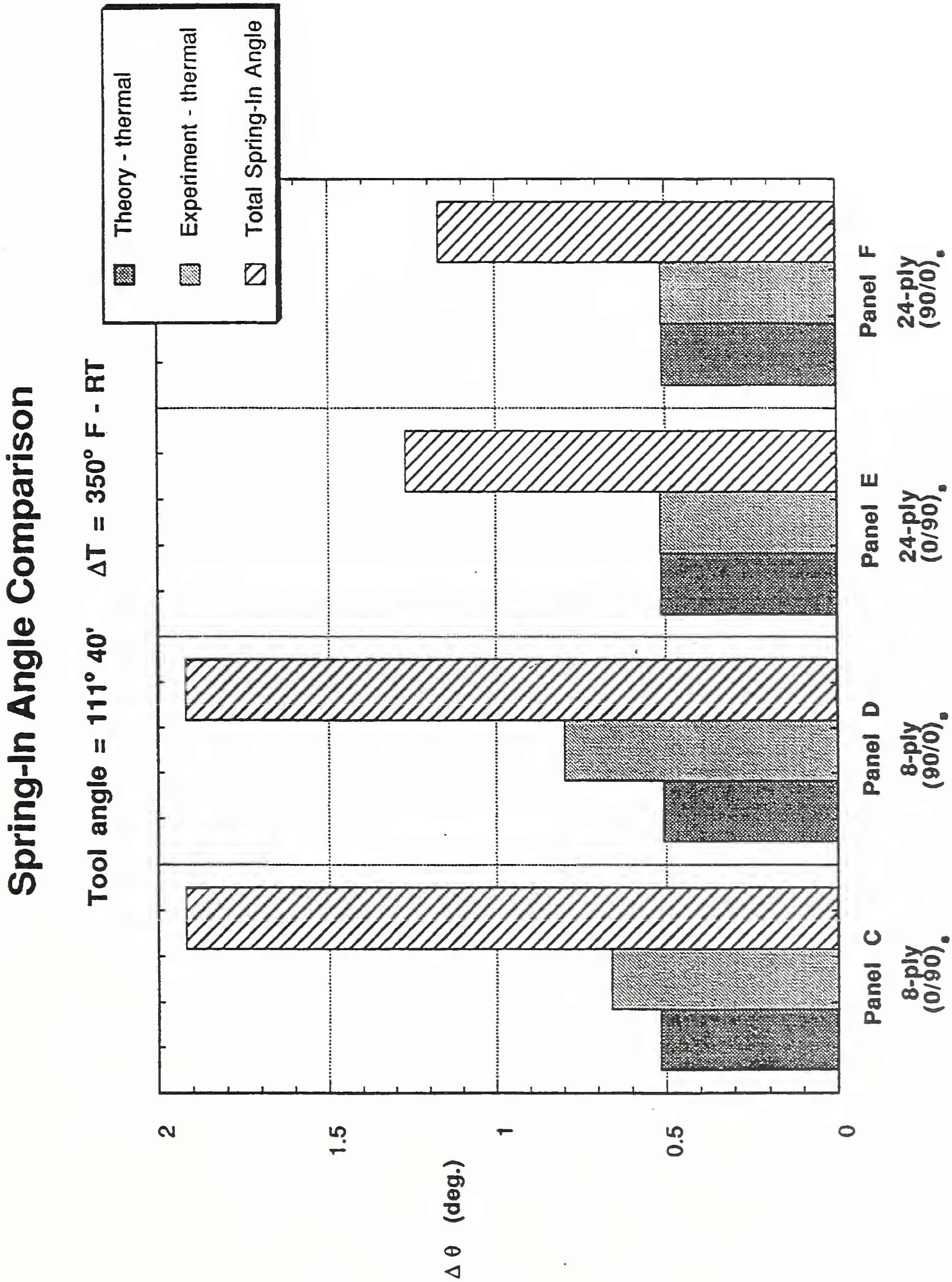
Figure 43

Effect of Cure Cycle on the Volume Changes in Debulked AS4/3501-6 Prepreg



J. D. Russell, 1993, *SAMPE Quarterly*, 24-2, 28-33

Figure 44



Spring-In Angle Comparison
Tool angle = 111° 40'
ΔT = 350° F - RT
Theory - thermal
Experiment - thermal
Total Spring-In Angle
Δ θ (deg.)
2
1.5
1
0.5
0
Panel C
8-ply
(0/90)s
Panel D
8-ply
(90/0)s
Panel E
24-ply
(0/90)s
Panel F
24-ply
(90/0)s

Figure 45

TYPICAL SKIN DELAMINATION

Outboard Wing

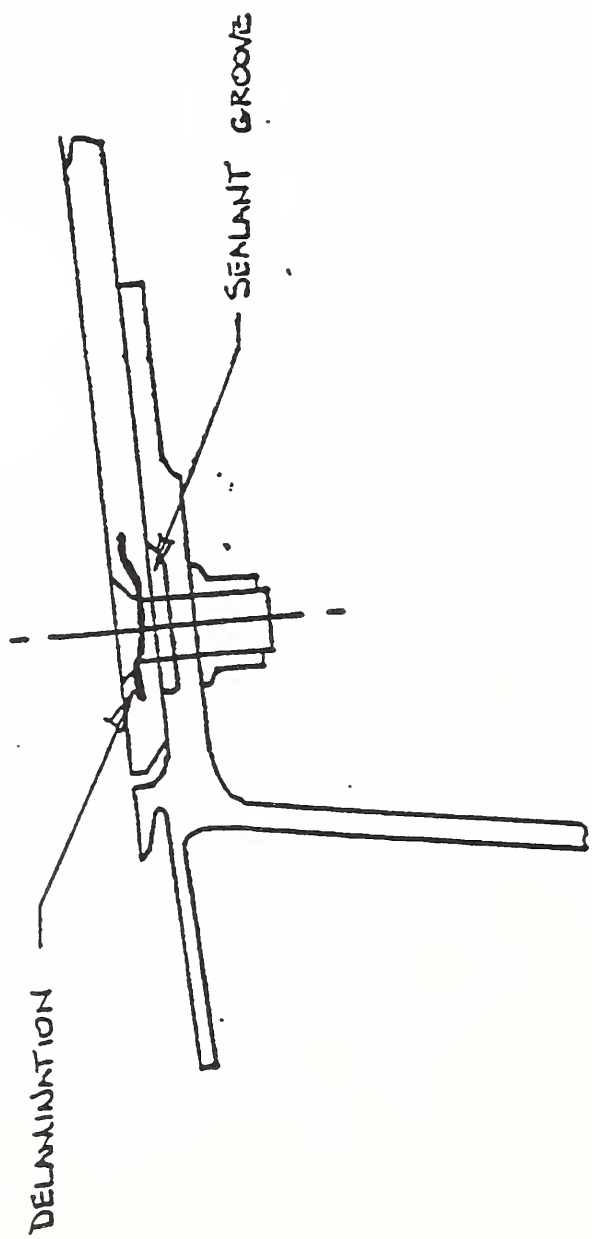


Figure 46

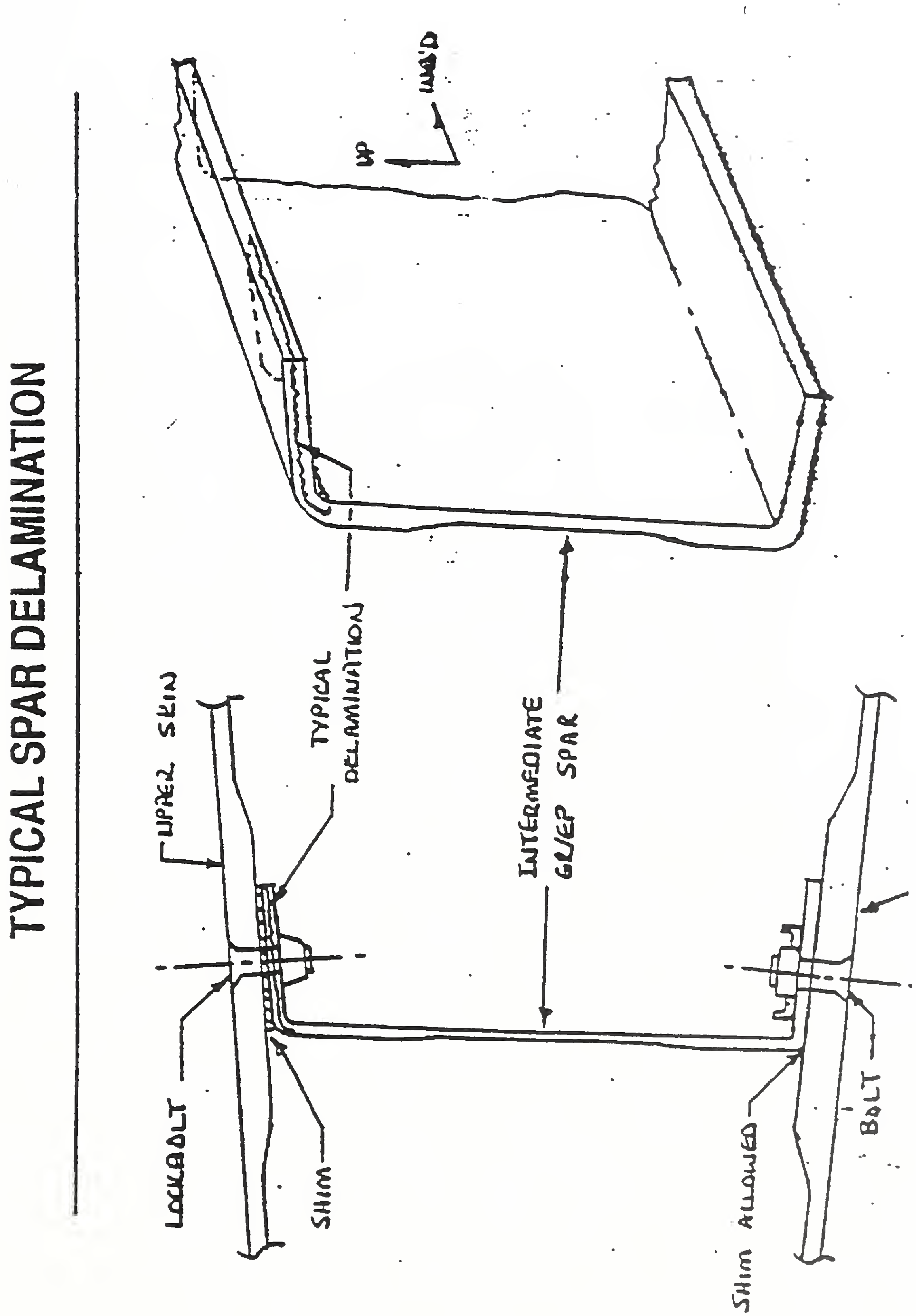
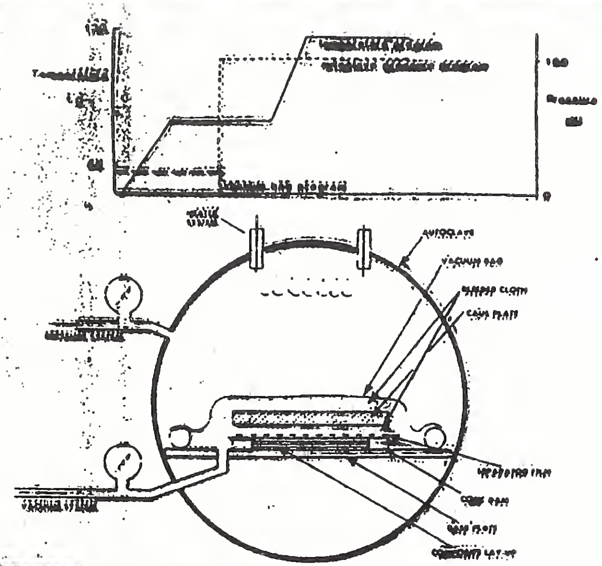

TYPICAL SPAR DELAMINATION
UP
INB'D
UPPER SKIN
LOCKBOLT
SHIM
TYPICAL DELAMINATION
INTERMEDIATE GR/EP SPAR
SHIM ALLOWED
BOLT

Figure 47



APPROACH:

- PROCESSING MODEL DEVELOPED INTO CURE OPTIMIZATION PROGRAM INSTALLED ON PRESS
- A THICKNESS GAUGE FOR USE IN AUTOCLAVE DEVELOPED

OBJECTIVE:

- MODEL RHEOLOGY OF RESIN FLOW DURING COMPOSITE PROCESSING
- PREDICT CONDITIONS FOR VOID FORMATION
- CONTROL CURE CYCLE TO PREVENT VOID FORMATION

TRANSITIONS:

- AIRFRAME MANUFACTURERS (F/A-18, AV-8B, V-22)
- MODEL USED FOR CURE CYCLE DEVELOPMENT FOR 6.2 PROGRAM ON RESIN CHARACTERIZATION
- MODEL USED FOR ANALYSIS OF CUMULATIVE EFFECTS OF PROCESS VARIABLES IN V-22 PROGRAM

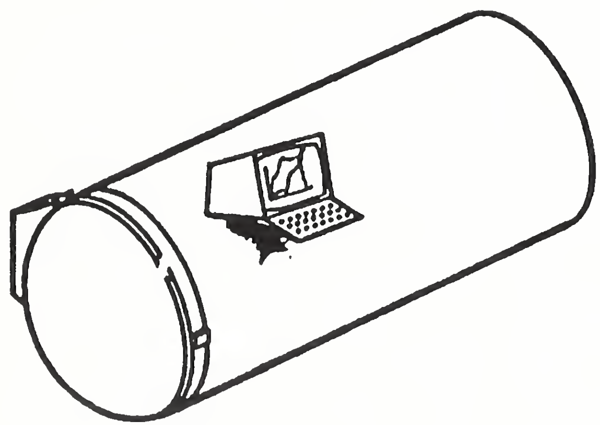
PERFORMERS:

- DR. JOHN WILLIAMS, NAVAIRDEVCEN

N1808-OA-88-02079

Figure 48

Background



"Advanced Composite Processing Technology Development"

Program Manager: J.E.Kurz, MCAIR
Principle Investigator: F.R. Muncaster, MCAIR
Program Monitor: J. Russell, WRDC/MLBC

"Qualitative Process Automation for Autoclave Curing of Composites"

S.R. LeClair, WRDC/MLTC

"Computer-Aided Curing of Composites"

F. Abrams, WRDC/MLBC

J A Thomas
"Advanced Composite Processing Technology Development"
Industry Review 25 June 1992

GP03-0258-2-D

Figure 49

Preliminary Sensor Systems

Sensor System	Critical Composite Property	Sensor Expert	Company
Dielectric	Resin State	Dr. David Day	Micromet Instruments
Eddy Current	Thickness	Dr. Masood Zaidi	Douglas Aircraft
Fluorescence Optrode	Resin State	Dr. Ram Levy	McDonnell Douglas Research Labs
Fiber Optics	Voids Resin State	Alan Markus	Douglas Aircraft
Ultrasonics	Thickness Voids	Mark Reighard	McDonnell Aircraft

GP24 0442-10 D/cm

Figure 50

Dielectric

Function:	Resin State Sensor
Critical Data:	Flow Initiation Point, Flow State, Gel Point, End of Cure Point
Equipment:	Tool-Mounted Ceramic Sensors (Reusable) Durable Autoclave Cabling Three Prong Thermocouple-Like Connectors Eight Channel Multiplexer and Interface Boxes System II Microdielectrometer
Advantages:	Easy Hook-Up Does a Good Job With Flow Initiation and Flow State Determinations Good Vendor Support and Equipment Availability Eight Channel Capability Very Durable
Disadvantages:	Not Sensitive Enough to Determine End of Cure Point Filter Mark-Off On Part Surface

GP24-0442-17-D/dmb

Figure 51

Fiber Optics

Function:	Void and Resin State Sensors
Critical Data:	Part Temperature, Resin Pressure
Equipment:	Fiber Optic Temperature Sensor Fiber Optic Pressure Sensor Fiber Optic Extension Cables Fiber Optic Multisensor System (4 Channel)
Advantages:	No Limitation On Cable Length Refractive Index Cure Sensor (In Development) May Be Used In the Same Unit
Disadvantages:	Extension Cables Must Be more Durable

GP24-0442-20-D/dmb

Figure 52

Real-Time Autoclave Control
Benefits

Near Term: Advanced Manufacturing Technology
- Process Development
- Part/Tool Design

Long Term: Composite Production
- Improved Part Quality
- Increased Part to Part Consistency (Resin Content, Thickness, Mechanical Properties)
- Reduced Autoclave Time

GP24-0155-5-D/crr

Figure 53

SENSOR SYSTEM/CONTROL SYSTEM NEEDS/OPPORTUNITIES

- PRE-PROCESS
  - LAY UP AREA
    NON-CONTACT INSPECTION TOOL FOR ORIENTATION, LOCATIONS, DEFECTS
    PRE-PREG INSPECTION TOOL - DEGREE OF CURE, DEGREE OF WETTING, RESIN CONTENT
  - TEXTILE PREFORM QUALITY SENSOR
- PROCESS - SIMPLE, LOW COST, REUSABLE
  - POROSITY LEVEL SENSOR
  - RESIDUAL STRESS SENSOR
  - CURE STATE SENSOR

ATBC

NORTHROP GRUMMAN

A Manufacturing View of Adaptive Process Control

Foster Lamm
United Technologies Research Center
(860) 727-7382

Figure 54

Notes.
from a manufacturing
view any new Technology
MUST impact The financi
Side of The business. IT
is not sufficient To be
"Good Technology"

$

Figure 55

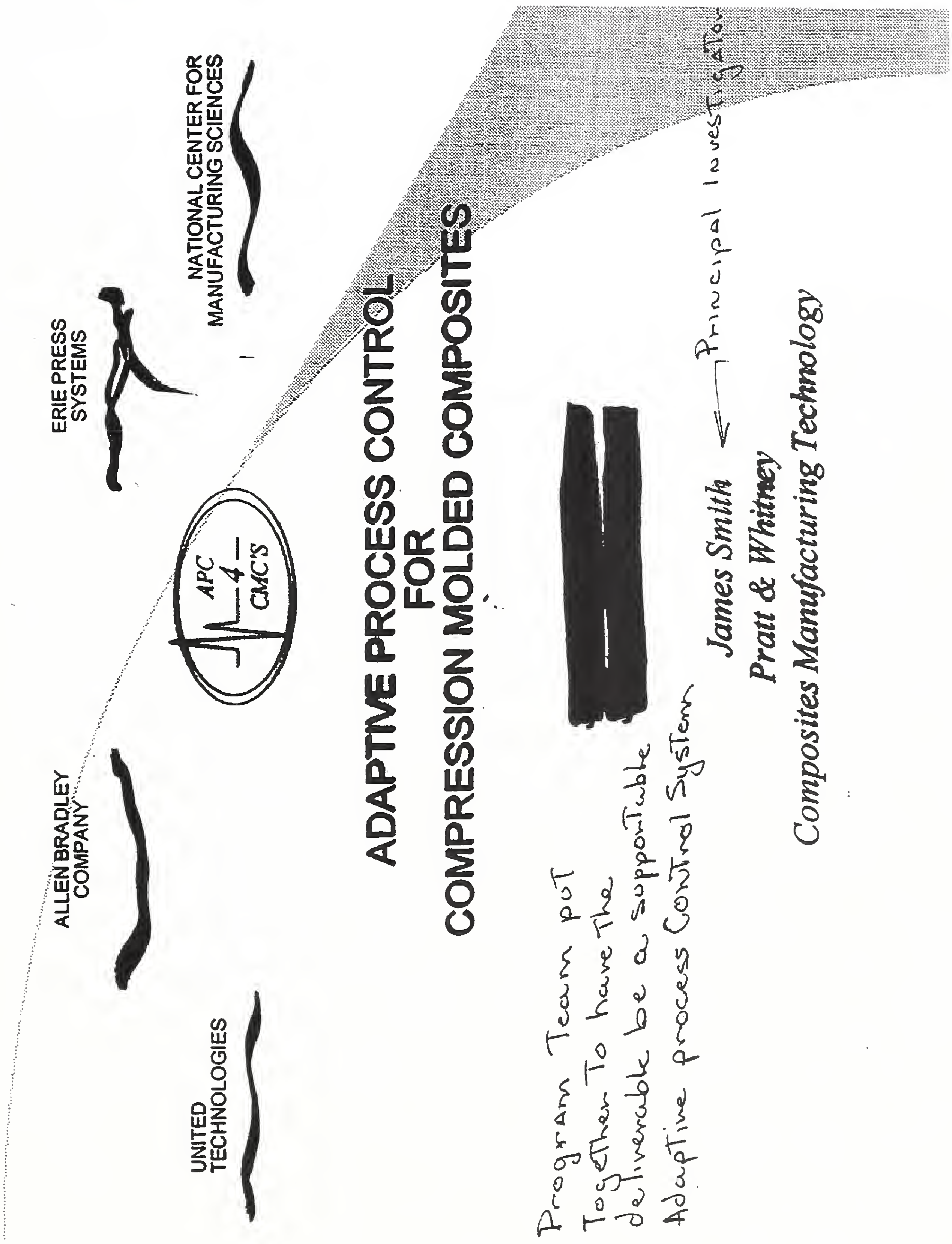

UNITED TECHNOLOGIES
[redacted]
ALLEN BRADLEY COMPANY
[redacted]
ERIE PRESS SYSTEMS
[redacted]
NATIONAL CENTER FOR MANUFACTURING SCIENCES
[redacted]
APC 4 CMC'S
ADAPTIVE PROCESS CONTROL
FOR
COMPRESSION MOLDED COMPOSITES
[redacted]
James Smith
Principal Investigator
Pratt & Whitney
Composites Manufacturing Technology
Program Team put Together To have the deliverable be a supportable Adaptive process Control System

Figure 56

APC 4 CMC'S

ADAPTIVE PROCESS CONTROL DEVELOPMENT EXTENSIONS

- ULTRASONIC SENSOR TO PROCESS DEVELOPMENT
  - THEORETICAL CORRELATION OF ULTRASOUND AND VISCOSITY
  - PRACTICAL USES OF ULTRASOUND ON OTHER PROCESSES AND MATERIALS(DETERMINE RULES)
  - DETERMINE REACTION KINETIC RELATION TO ULTRASOUND
  - FURTHER DEVELOPMENT OF PREDICTIVE MAINTENANCE FOR ULTRASONIC SENSOR

- RULES BASED APPROACH TO ADAPTIVE PROCESS CONTROL
  - PART DESIGN: *CAUSE* - METALS THINKING; *EFFECT* - PROCESS NOT OPTIMIZED
  - PREFORM: *CAUSE* - AERIAL WEIGHT, RESIN VISCOSITY, LAY-UP, DEBULK, THICKNESS; *EFFECT* - MIGRATION, FIBER VOLUME PERMEABILITY, EXOTHERM, MECHANICALS, QUALITY
  - TOOLING: *CAUSE* - HEAT DISTRIBUTION, CAVITY DESIGN; *EFFECT* - VISCOSITY, FLOW VARIATION
  - EQUIPMENT : *CAUSE* - CALIBRATION; *EFFECT* - BLACK MAGIC PROCESSING

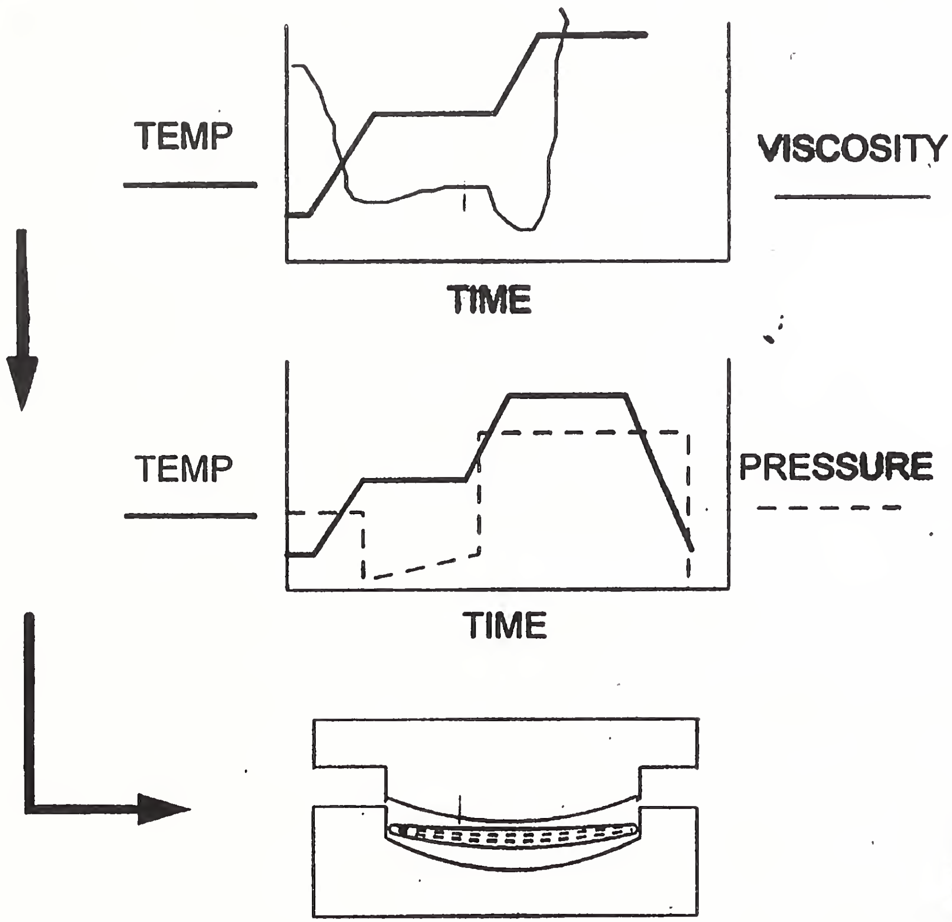
Figure 57

PROGRAM
STATUS

- PRODUCTION SYSTEM DEMONSTRATION COMPLETED WITH WORKING KNOWLEDGE BASE MODEL
- DEVELOPMENT PROGRAM COMPLETED - 5/95 (PER PROPOSAL
- PROGRAM EXTENSION ENCOMPASSING TECHNOLOGY TRANSFER 5/95 - 5/96
- MICROMET PROTOTYPE ULTRASONIC SYSTEM DELIVERED TO PRODUCTION - 8/95; CURRENTLY OPERATIONAL
- PHASE II COST REDUCTION EFFORT STARTED AT MICROMET - NCMS FUNDED
- IMPLEMENTATION PLAN WORKING FOR FULL CONTROL ESA PROCESS BY 11/95

Figure 58

DEFINITION
OF NEED



CONVENTIONAL COMPRESSION MOLDING

Set point control

Reholog run on every lot

Significant process knowledge base developed

Supplier problems Identified And corrected

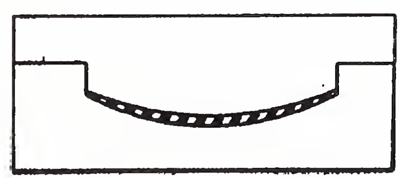


Figure 59

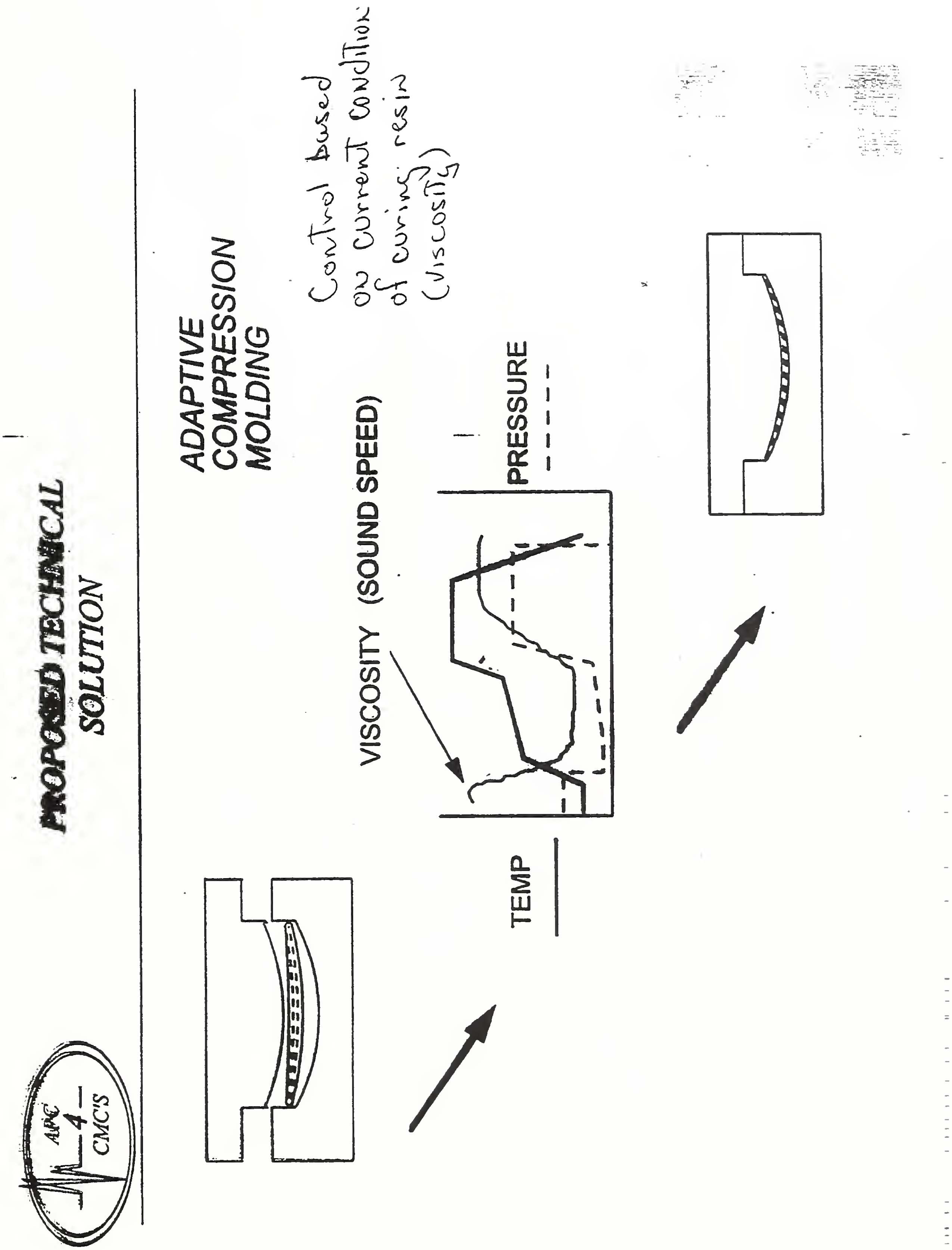

PROPOSED TECHNICAL SOLUTION
ADAPTIVE COMPRESSION MOLDING
Control based on current condition of curing resin (viscosity)
VISCOSITY (SOUND SPEED)
PRESSURE
TEMP
APC
4
CMC'S

Figure 60

APC 4 CMC'S

1. TECHNICAL CASE CRITERIA

NEEDS DEFINITION AND PROPOSED TECHNICAL SOLUTION

- MATERIAL VARIATION PREVENTS PROCESS ALIGNMENT
  - INDIRECT MANUFACTURING COSTS INFLATE OVERHEAD
  - EXCESS DEVELOPMENT TIME IMPEDES MARKET PENETRATION
- PROCESS CERTIFICATION UN-ACHIEVABLE THROUGH CURRENT CONTROL
  - CRITICAL VISCOSITY WINDOW CURRENTLY ESTIMATED
    - REOLOGY MEASUREMENTS MAY BE BIAS DETERMINATIONS OF VISCOSITY
    - THERMAL AND VISCOSITY RESPONSE INTERDEPENDENT
  - RESIN THRESHOLD PRESSURE DEPENDENT ON VISCOSITY
- ADAPTIVE CONTROL FROM SENSOR RESPONSE OF MATERIAL
  - SOUND SPEED IS A MORE DIRECT MEASURE OF VISCOSITY & OTHER NON-LINEAR PROCESS PARAMETERS THAN TIME & TEMP
  - RELIABLE COST EFFECTIVE SENSOR DESIGN
  - USER-FRIENDLY CONTROL SCHEME FOR PROCESS ENGINEER
  - MINIMAL YET PREDICTIVE MAINTENANCE FOR OVERALL SYSTEM

Figure 61

APC 4 CMC'S

PROGRAM BENEFITS

- CONTROL SYSTEM ADDRESSES CURRENT PRODUCTION NEEDS
  - GREATER CONTROL OF LAMINATE CONSOLIDATION
  - PROBLEM IDENTIFICATION THROUGH MEASUREMENT
- ADAPTIVE CONTROL
  - LOWER MANUFACTURING COSTS [redacted] THROUGH HIGHER PRODUCT YIELDS
  - LOWER CAPITAL INVESTMENT ($1000/TON) THROUGH SMARTER CONTROL
- EQUIPMENT DEVELOPMENT EXCEEDS PROGRAM GOALS
  - INTEGRAL SENSOR & CONTROL SYSTEM , SIZE REDUCED 95% SINCE START
  - DEPLOYMENT COSTS WITHIN TARGET
- PROGRAM LEVERAGE > [redacted]

Figure 62

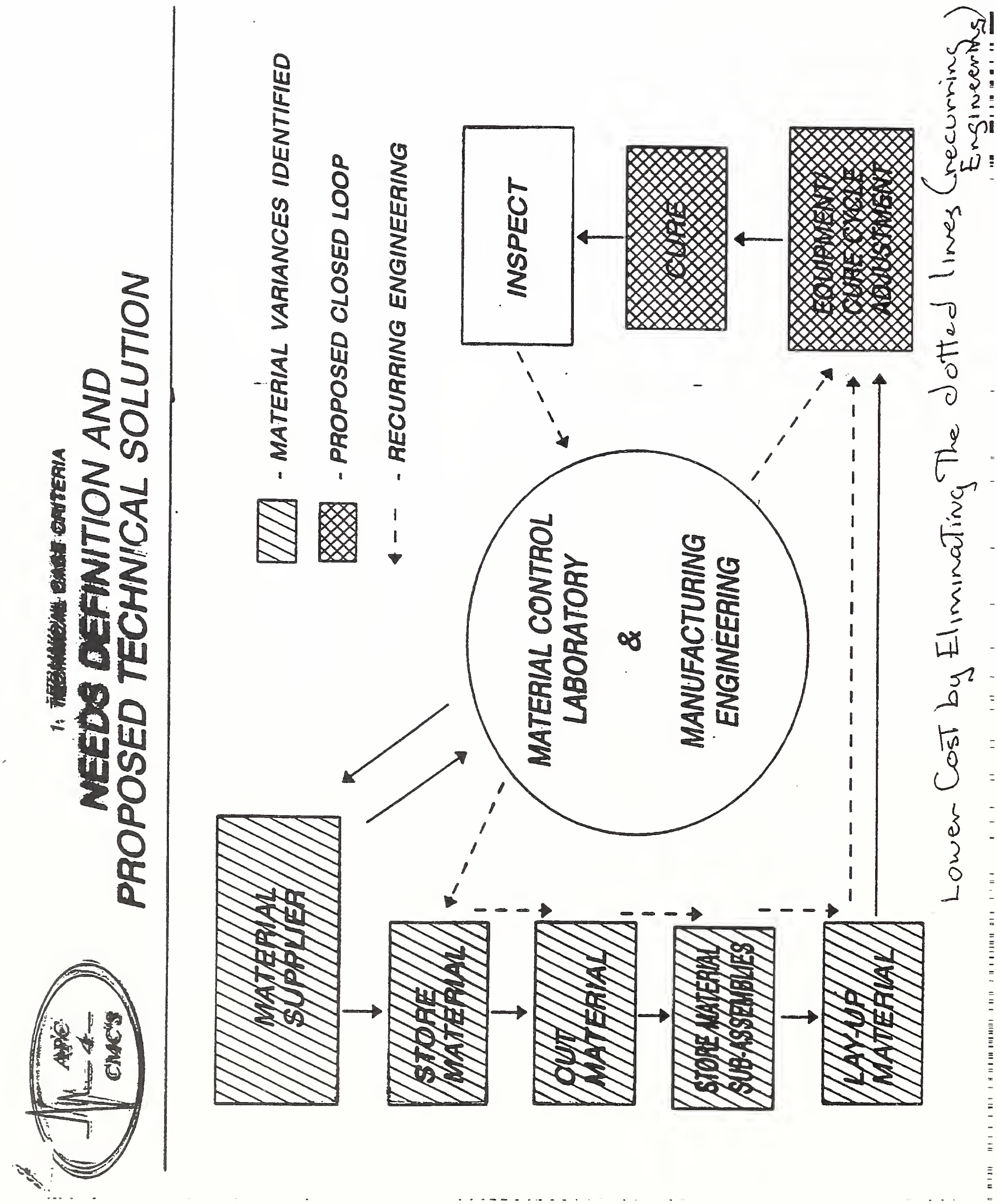
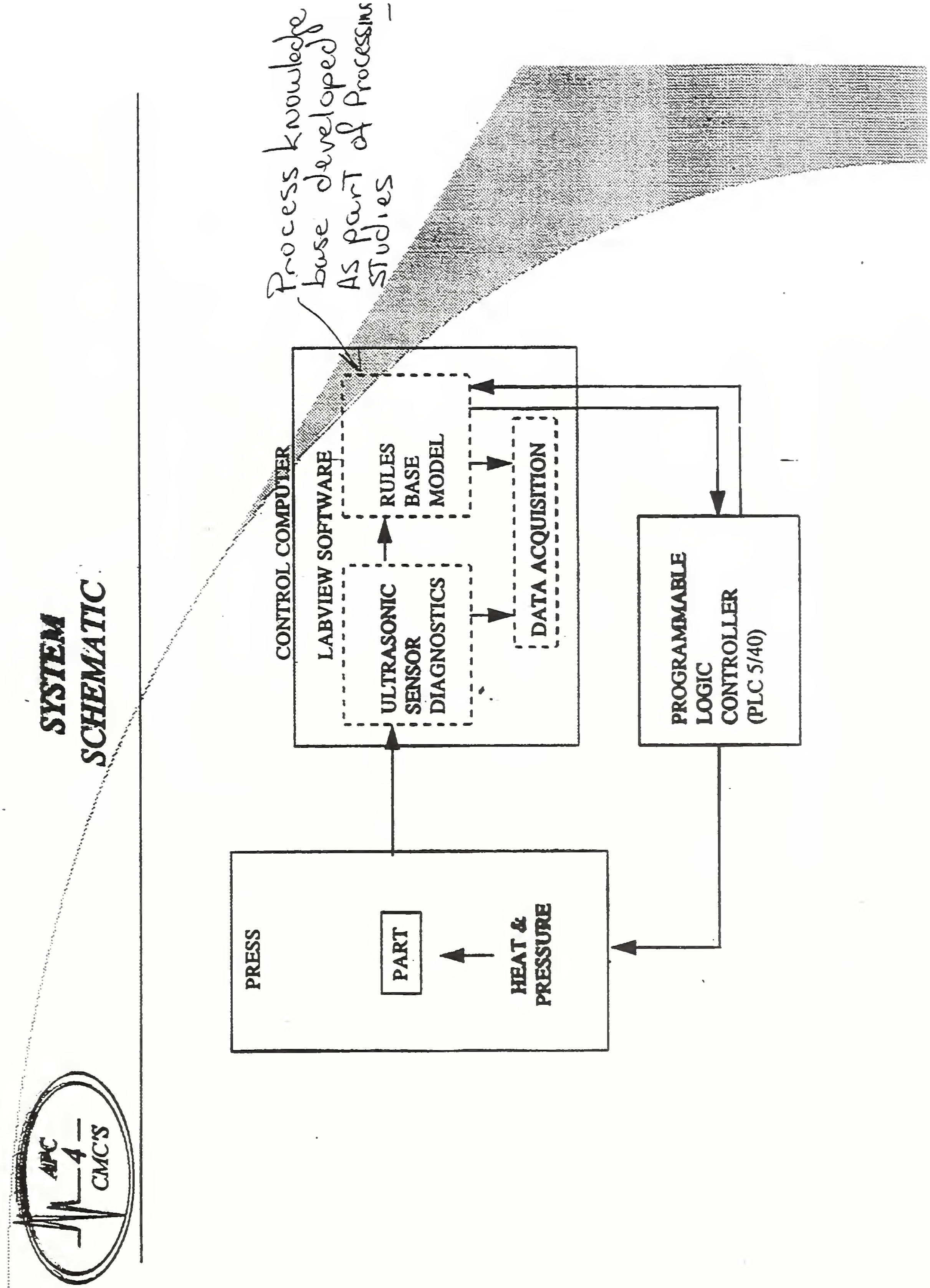

NEEDS DEFINITION AND
PROPOSED TECHNICAL SOLUTION
- MATERIAL VARIANCES IDENTIFIED
- PROPOSED CLOSED LOOP
- RECURRING ENGINEERING
MATERIAL SUPPLIER
STORE MATERIAL
CUT MATERIAL
STORE MATERIAL SUB-ASSEMBLIES
LAY-UP MATERIAL
MATERIAL CONTROL LABORATORY
&
MANUFACTURING ENGINEERING
INSPECT
CURE
EQUIPMENT/ CURE CYCLE ADJUSTMENT
Lower Cost by Eliminating The dotted lines (recurring Engineering)

Figure 63



SYSTEM SCHEMATIC
APC 4 CMC'S
Process knowledge
base developed
As part of Processin
studies
CONTROL COMPUTER
LABVIEW SOFTWARE
ULTRASONIC SENSOR DIAGNOSTICS
RULES BASE MODEL
DATA ACQUISITION
PROGRAMMABLE LOGIC CONTROLLER (PLC 5/40)
PRESS
PART
HEAT & PRESSURE

Figure 64

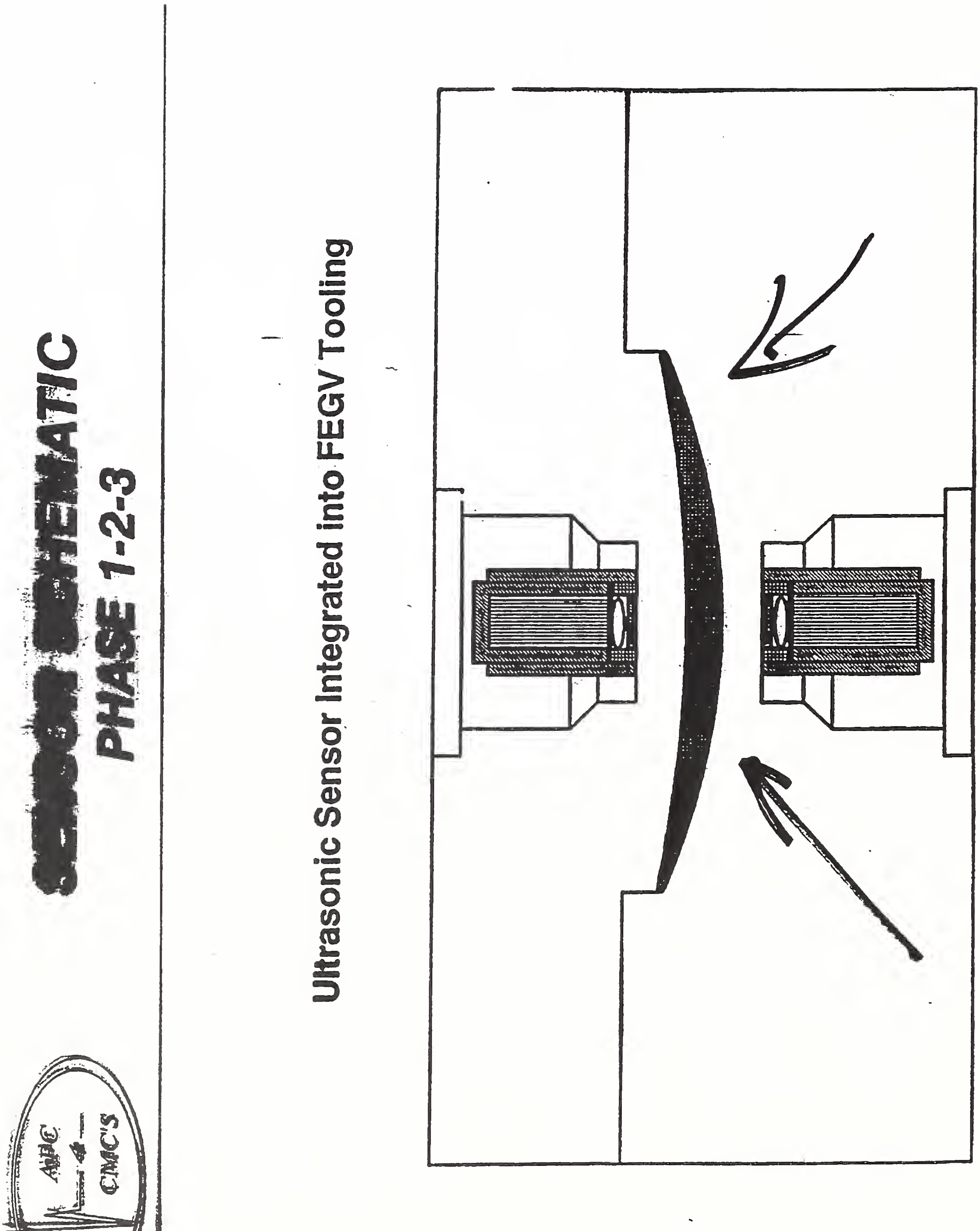

PHASE 1-2-3
Ultrasonic Sensor Integrated into FEGV Tooling
ABC
4
CMC'S

Figure 65

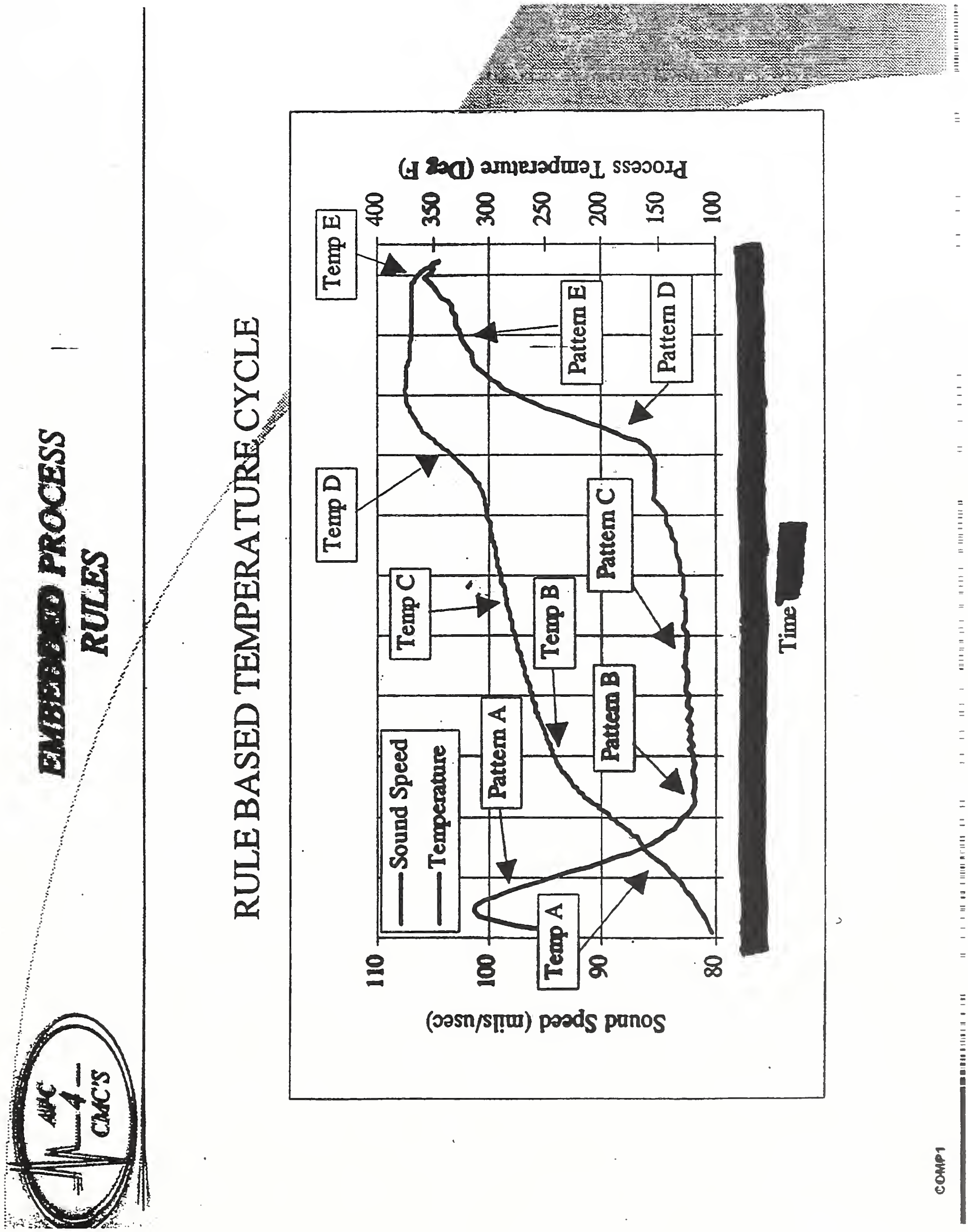
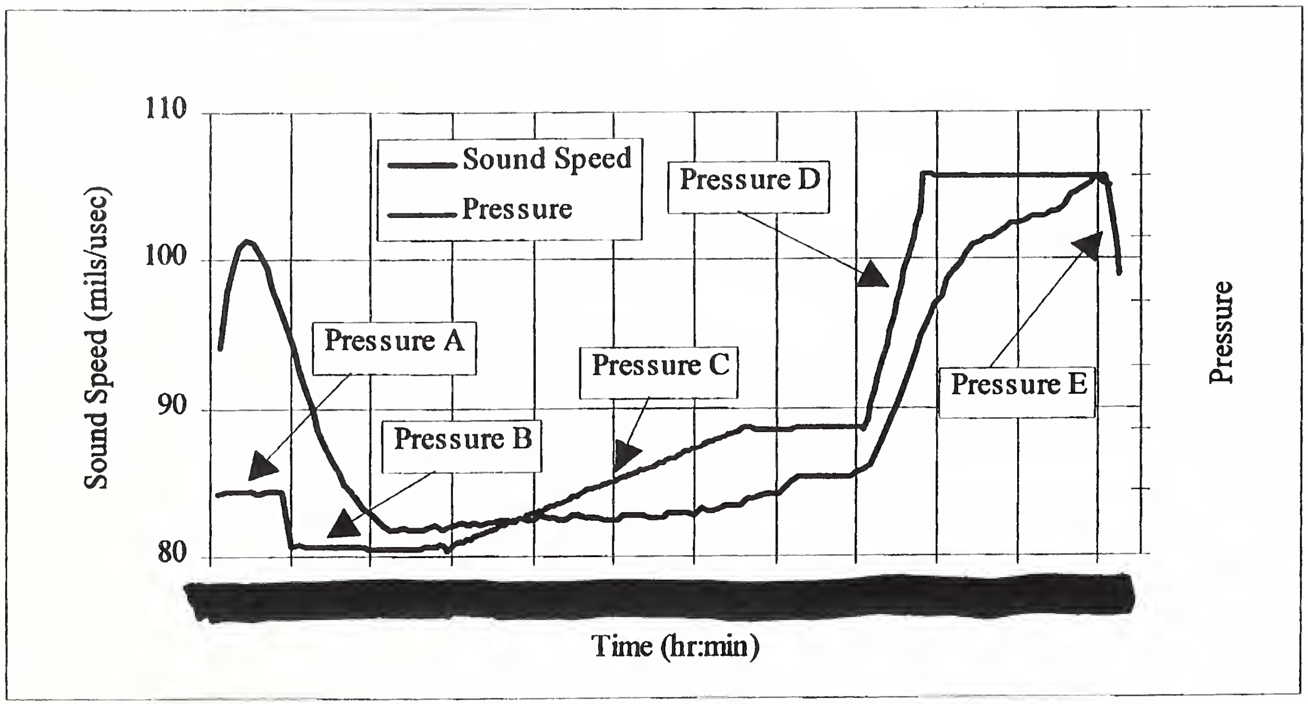

PROCESS RULES
RULE BASED TEMPERATURE CYCLE
Sound Speed
Temperature
Sound Speed (mils/usec)
Process Temperature (Deg F)
110
100
90
80
400
350
300
250
200
150
100
Temp A
Temp B
Temp C
Temp D
Temp E
Pattern A
Pattern B
Pattern C
Pattern D
Pattern E
Time
COMP1

Figure 66

EMBEDDED PROCESS RULES

RULE BASED PRESSURE CYCLE



IN-PROCESS CONTROL OF COMPOSITE FABRICATION

Role of NDE

B. Boro Djordjevic

Robert E. Green, Jr.

CNDE

Center for Nondestructive Evaluation

The Johns Hopkins University

NISTPROC.PRS

Figure 67

Composite Process Monitoring and Verification

	In-Process	Pre-Service
FUNCTION:	Process Control	Certification
	Quality Assurance	Damage Assessment
	Integrity Validation	Integrity Assessment
CONTROL PARAMETERS:	Temperature	Delaminations and Spalling
	Pressure	Adhesion
	Cure	Fiber Break
	Melt and Infiltration	Strain State
	Material Quality	Resin Degradation
	Wrap Process Control	Residual Stress
	Material Compaction	
	Exotherm	

NISTPROC.PRS

Figure 68

DEFECTS IN COMPOSITES

Delaminations	Missing adhesive
Disbond	Misoriented fibers/plys
Porosity	Wavy fibers
Contamination	Mislocated plys/details
Improper cure	Impact damage
Resin rich/poor	Thickness variance
Damaged fiber	Dimensional problems
Voids	Interfaces integrity
Cracks	Structure specific problems

NISTPROC.PRS

Figure 69

NDE PRACTICES FOR COMPOSITES

- Ultrasonic
- Acoustic emission
- Tap test
- Resonance
- X-ray
- Visual
- Optical
- Thermal

ADVANCED TECHNIQUES

- X-ray Computed Tomography
- Laser ultrasonic
- Holography
- Laser-optical
- Vibro-thermography
- Acousto-ultrasonic
- D-sight
- Neutron radiography
- Microwaves

NISTPROC.PRS

Figure 70

In- Process Control

THERMOSET:	THERMOPLASTIC:
Cure (Polymerization)	Crystallinity
Temperature	Melt Stability
Exotherm	Melt Temperature
Viscosity	Viscosity
Modulus	Fiber/Resin Ratio
Tg Shifts	Density
Fiber/Resin Ratio	Porosity
Density	Degradation of Resin
Porosity	Delaminations
Fiber Orientation	Consolidation
Delaminations	Fiber Orientation
Overall Material Integrity	Overall Material Integrity
Others	Others

Parameters and properties that can be nondestructively monitored for process control of organic matrix composites.

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Figure 71

Nondestructive Evaluation, In-process Enabling Technologies

THERMOSET:

- Thermocouple
- Acoustical Waveguide
- Optical Fibers
- Capacitance
- Conductivity
- Dielectric
- Thermal
- FT-IR
- Ultrasonic
- Magnetostrictive Wire

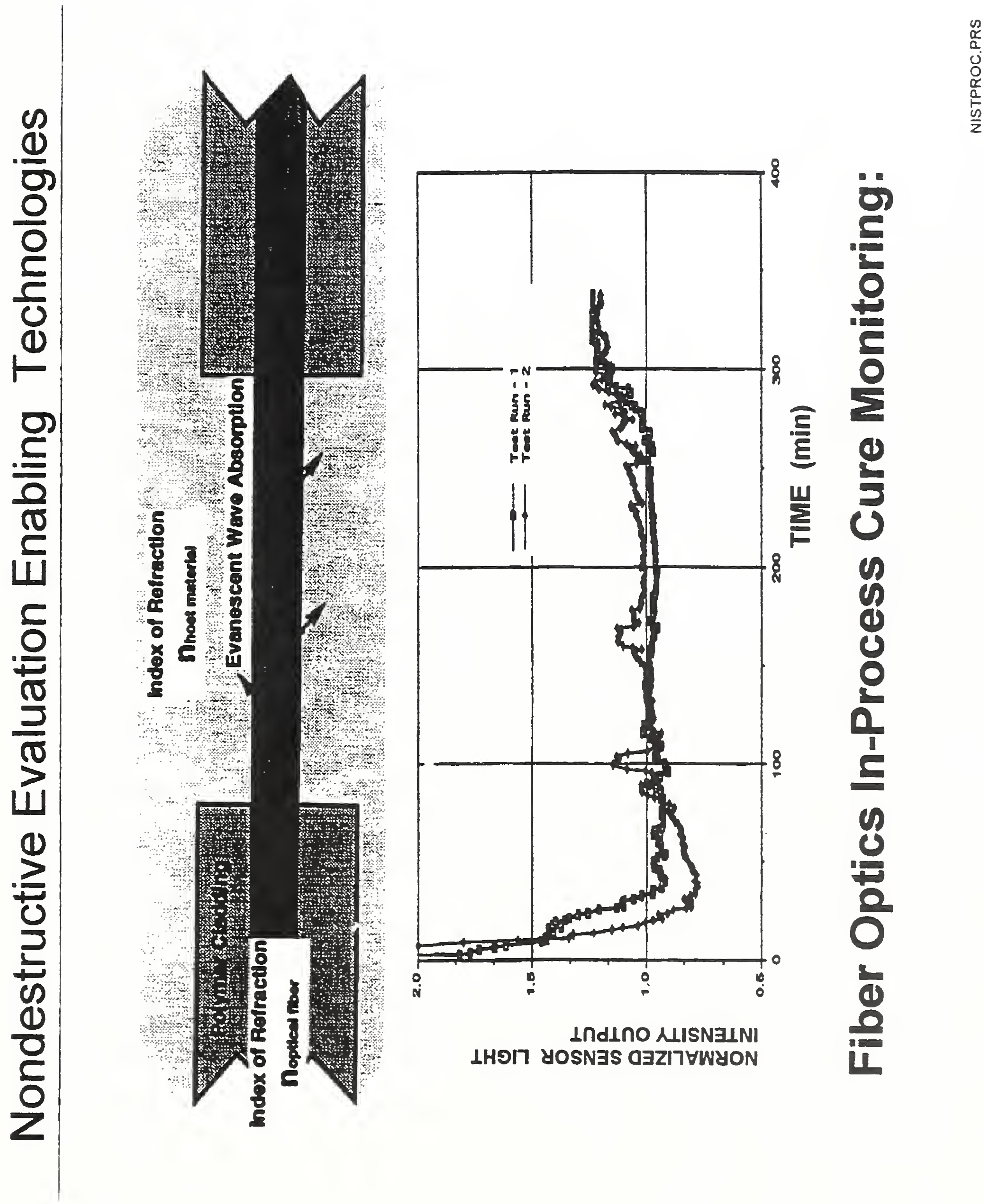
THERMOPLASTIC:

- Acoustic Waveguide
- Optical Fibers
- Thermal
- Ultrasonics
- Magnetostrictive Wire

Potential devices for process monitoring of organic matrix composite materials.

NISTPROC.PRS

Figure 72



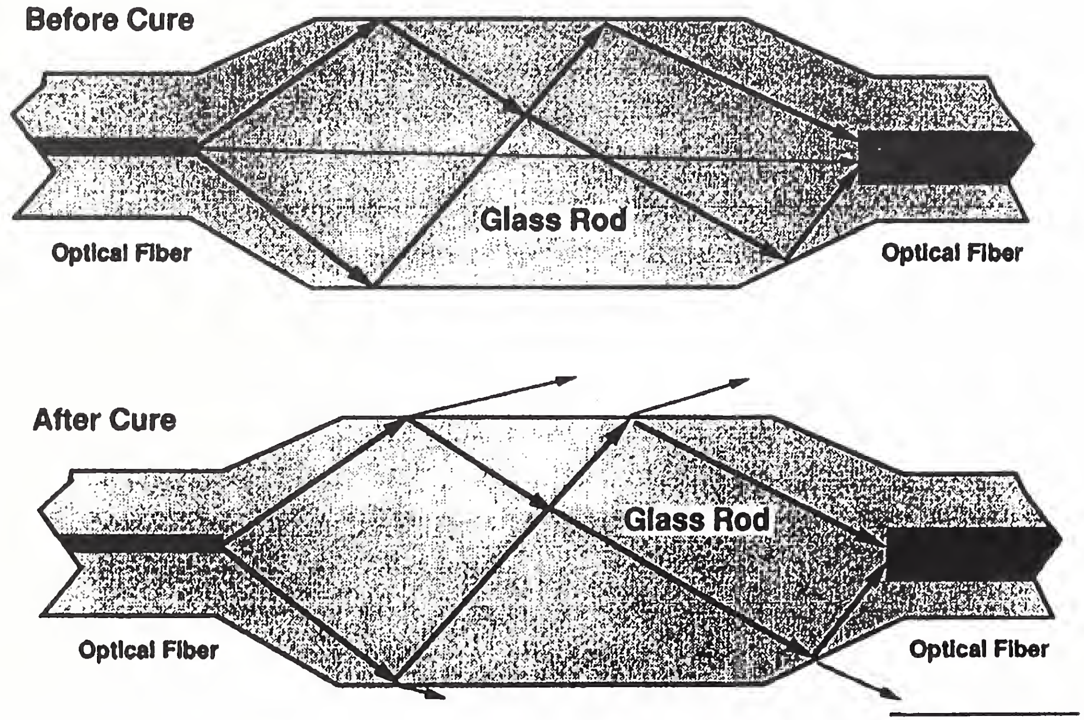
Nondestructive Evaluation Enabling Technologies
Index of Refraction
$n_{host\ material}$
Evanescent Wave Absorption
Index of Refraction
$n_{optical\ fiber}$
NORMALIZED SENSOR LIGHT INTENSITY OUTPUT
2.0
1.5
1.0
0.5
0
100
200
300
400
TIME (min)
Test Run - 1
Test Run - 2
Fiber Optics In-Process Cure Monitoring:
NISTPROC.PRS

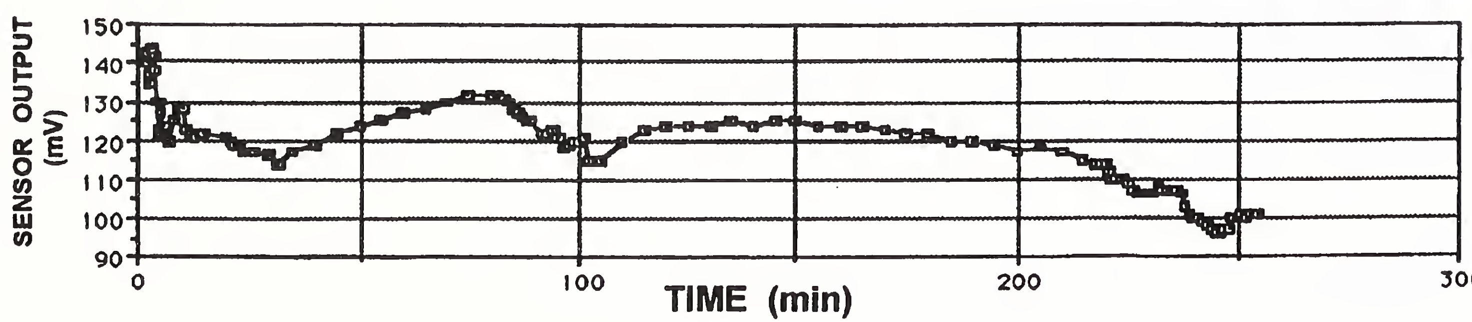
Figure 73

Nondestructive Evaluation Enabling Technologies

Optical-Fiber/Glass-Rod

Cure Monitoring Set-up:





NISTPROC.PRS

Figure 74

UT Sensors for In- Process Control

Embedded Acoustic Sensors

- Flexural Mode

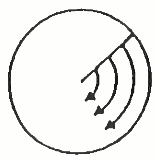
  Dispersive for aspect ratios < 1.2

  Velocity ⟶ 0 as aspect ratio ⟶ 0

a= 0.05 cm
λ= 10 cm
a/λ = 0.005

- Torsional Mode

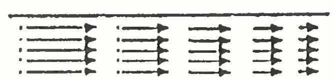
  Non-dispersive for all aspect ratios



$$\text{Velocity} = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{8.2 \times 10^{10}\ \text{Pa}}{8420\ \text{kg/m}^3}} = 3120\ \text{m/s}$$

- Extensional Mode

  Dispersive for aspect ratios from 0.1 to 1.2, non-dispersive elsewhere.



For long wavelengths where $a/\lambda < 0.1$

$$\text{Velocity} = \sqrt{\frac{E}{\rho}} = \sqrt{\frac{2.14 \times 10^{11}\ \text{Pa}}{8420\ \text{kg/m}^3}} = 5041\ \text{m/s}$$

ABNT395-03/10/95-X

Center for Nondestructive Evaluation
The Johns Hopkins University

Figure 75

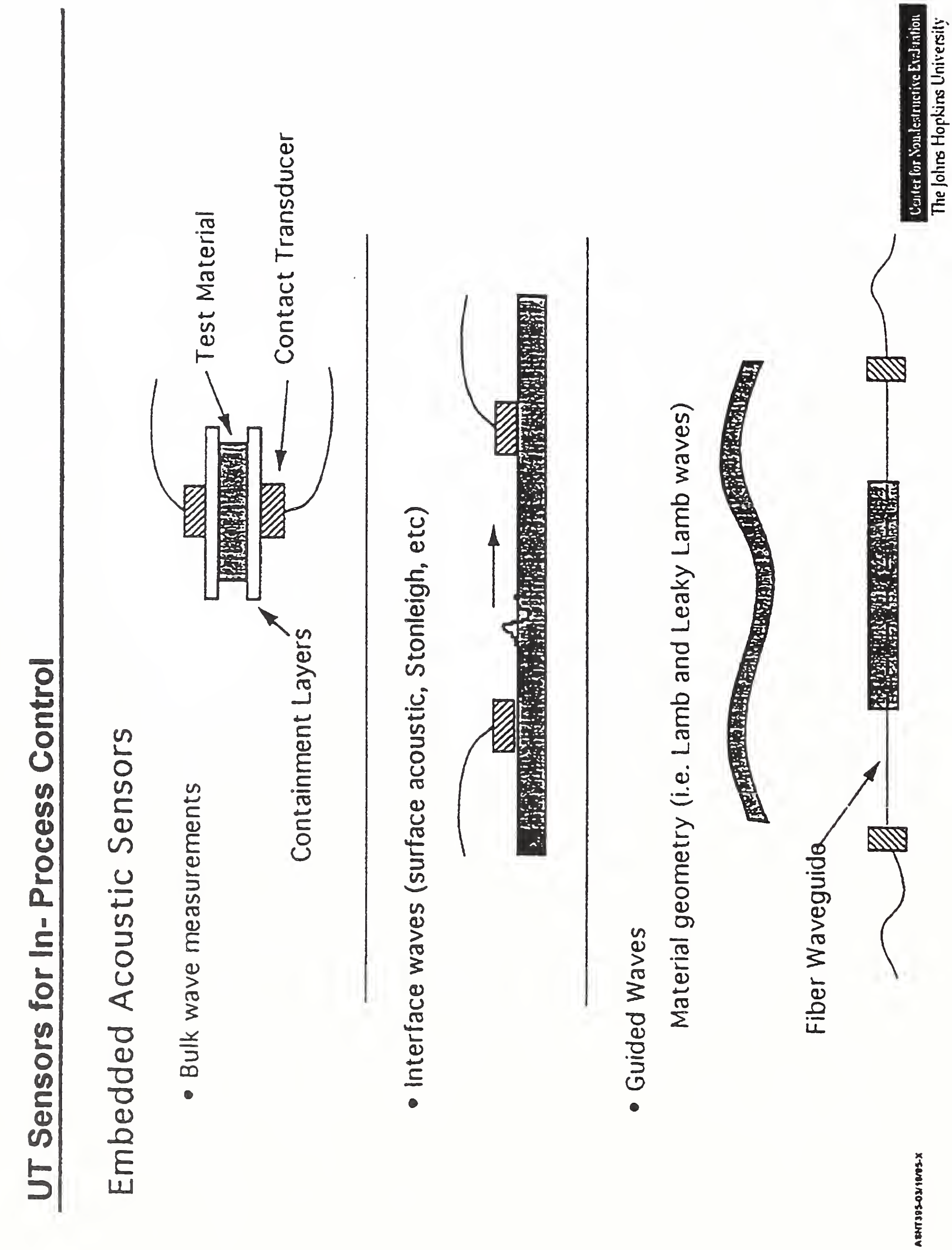
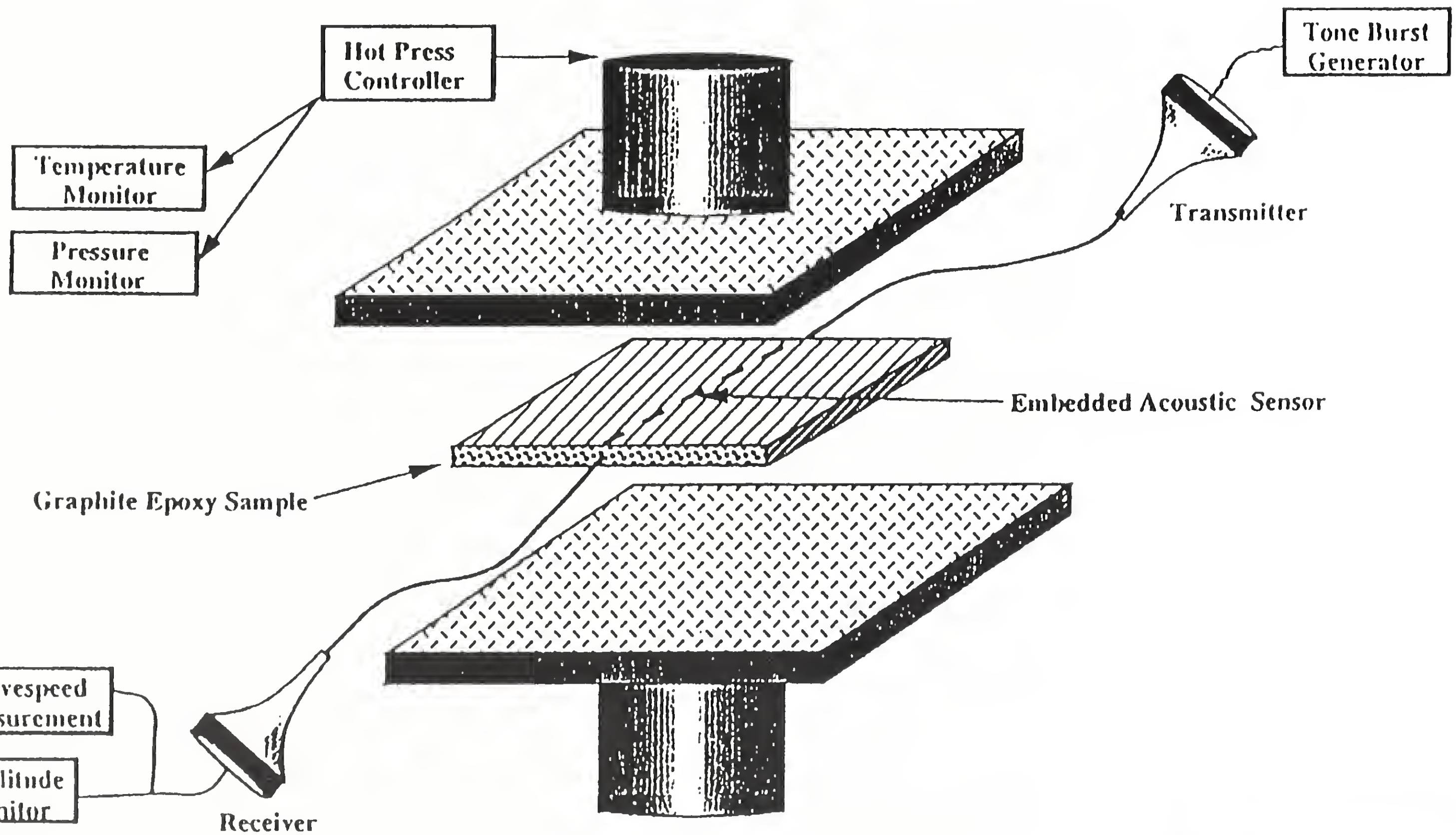

UT Sensors for In- Process Control
Embedded Acoustic Sensors
• Bulk wave measurements
Test Material
Contact Transducer
Containment Layers
• Interface waves (surface acoustic, Stonleigh, etc)
• Guided Waves
Material geometry (i.e. Lamb and Leaky Lamb waves)
Fiber Waveguide
Center for Nondestructive Evaluation
The Johns Hopkins University

Figure 76

UT Sensors for In- Process Control

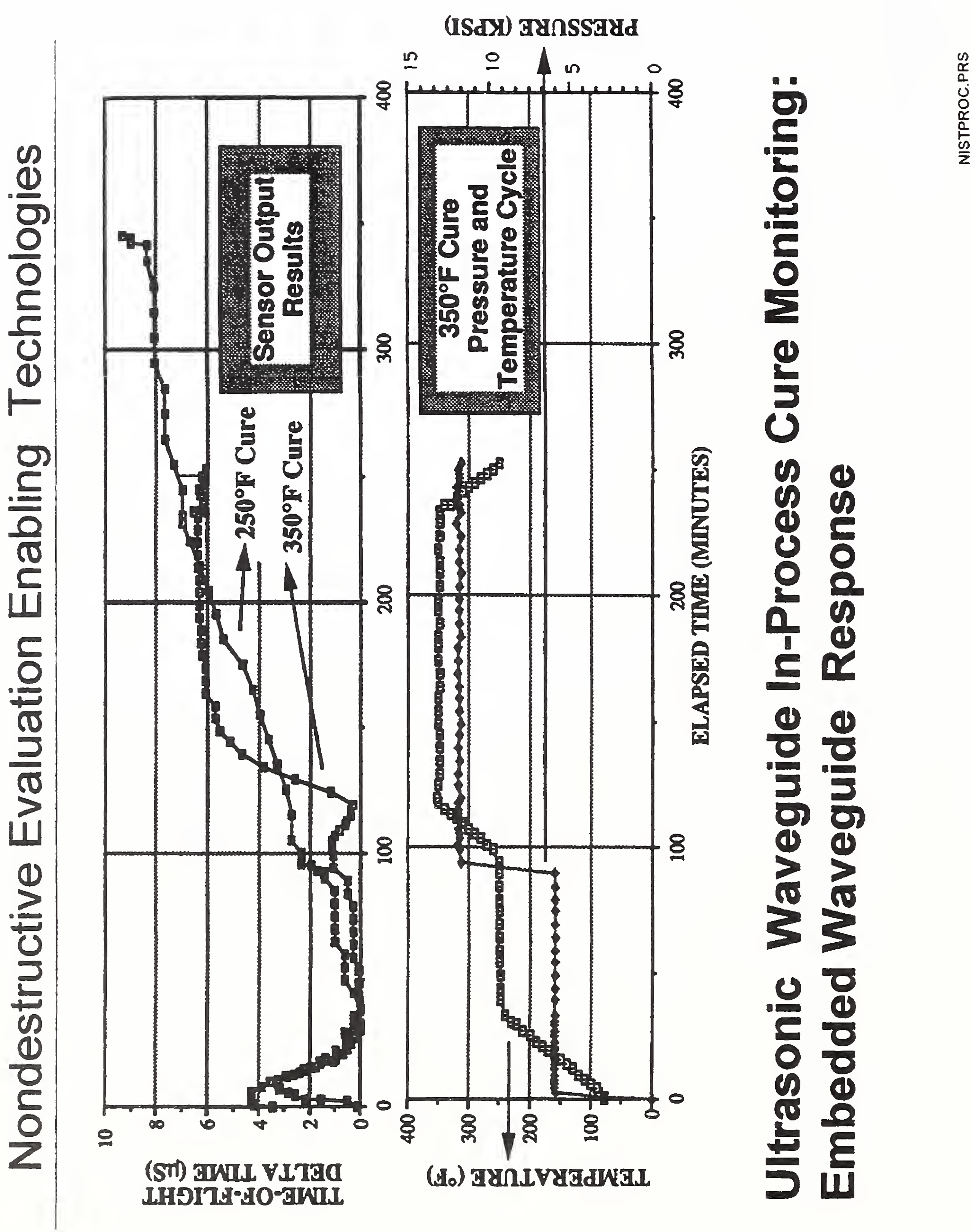
Embedded Acoustic Sensors



ABNT395-03/10/95-X

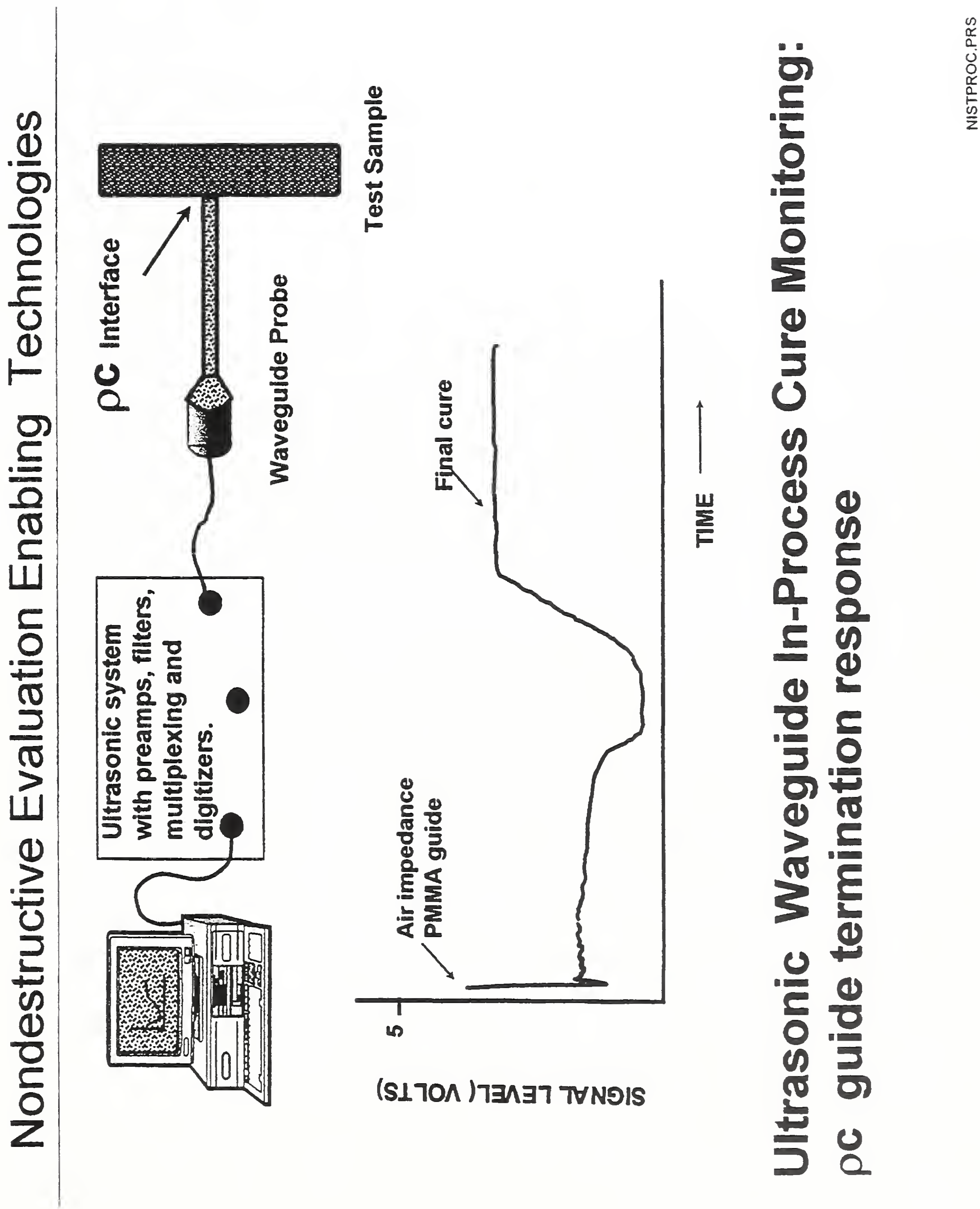
Center for Nondestructive Evaluation
The Johns Hopkins University

Figure 77



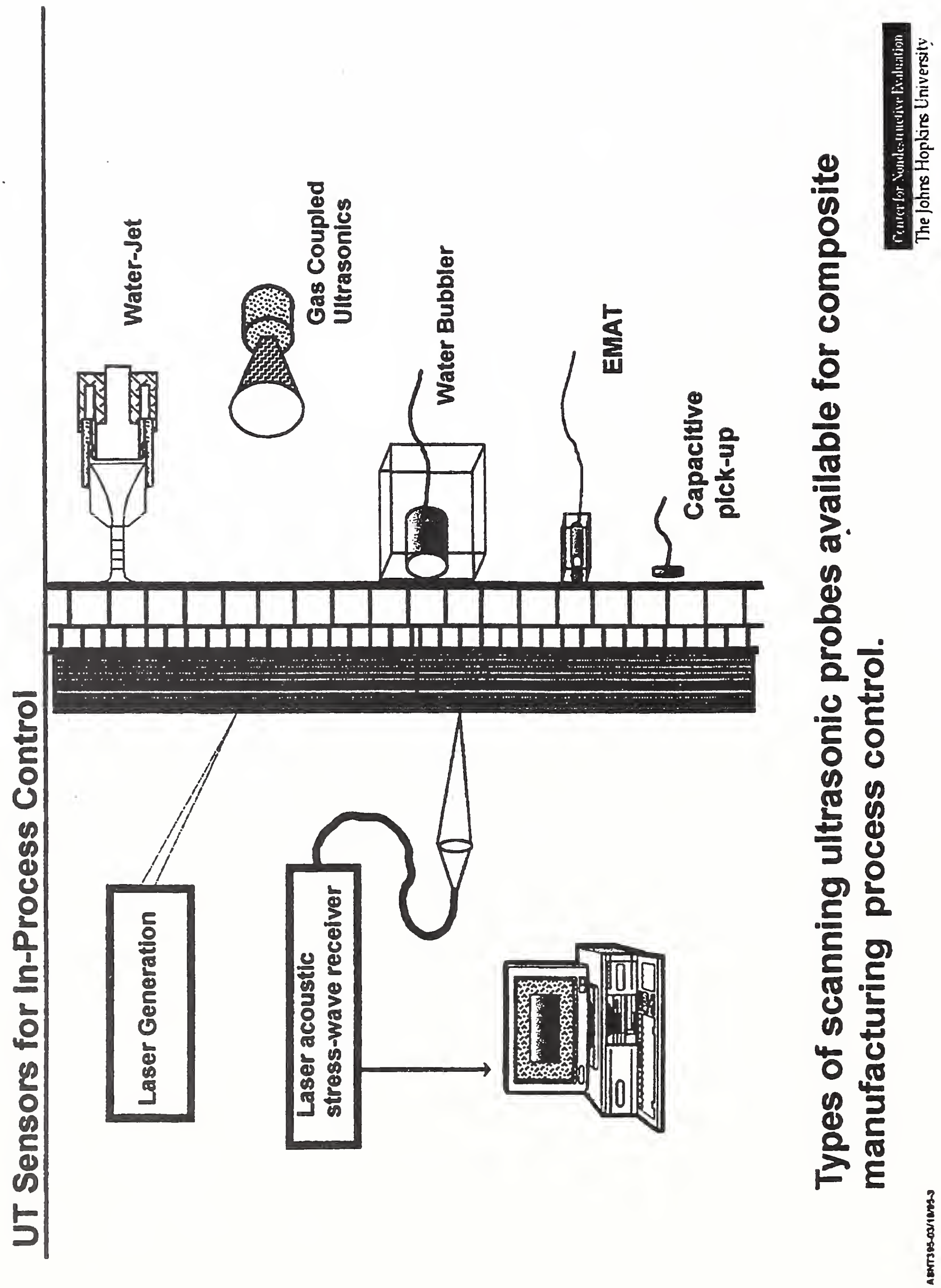
Nondestructive Evaluation Enabling Technologies
Sensor Output Results
250°F Cure
350°F Cure
TIME-OF-FLIGHT DELTA TIME (µS)
350°F Cure Pressure and Temperature Cycle
TEMPERATURE (°F)
PRESSURE (KPSI)
ELAPSED TIME (MINUTES)
Ultrasonic Waveguide In-Process Cure Monitoring:
Embedded Waveguide Response
NISTPROC.PRS

Figure 78



Nondestructive Evaluation Enabling Technologies
Ultrasonic system with preamps, filters, multiplexing and digitizers.
ρc Interface
Waveguide Probe
Test Sample
SIGNAL LEVEL(VOLTS)
5
Air impedance PMMA guide
Final cure
TIME
Ultrasonic Waveguide In-Process Cure Monitoring:
ρc guide termination response
NISTPROC.PRS

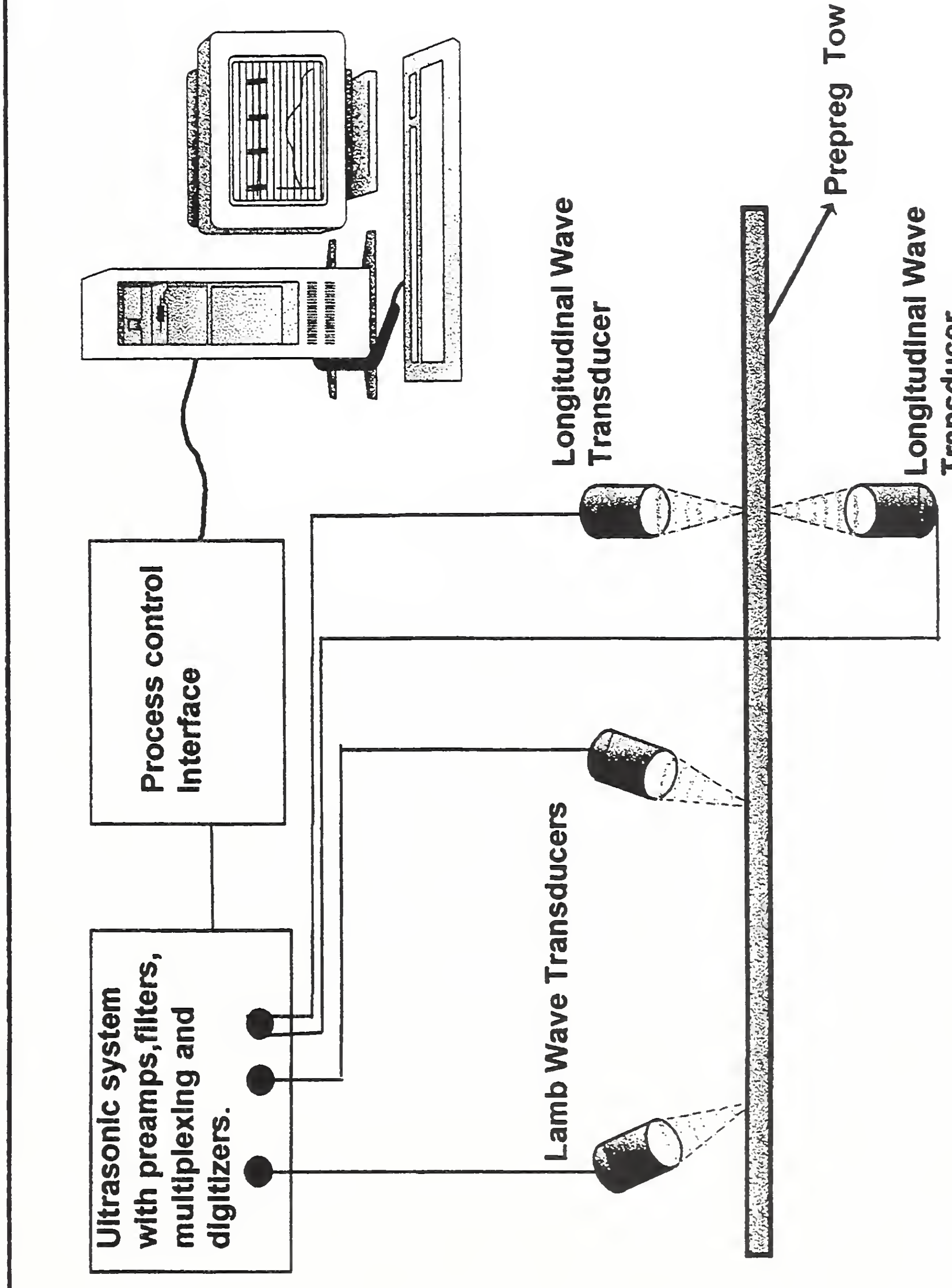
Figure 79



UT Sensors for In-Process Control
Water-Jet
Gas Coupled Ultrasonics
Water Bubbler
EMAT
Capacitive pick-up
Laser Generation
Laser acoustic stress-wave receiver
Types of scanning ultrasonic probes available for composite manufacturing process control.
Center for Nondestructive Evaluation
The Johns Hopkins University

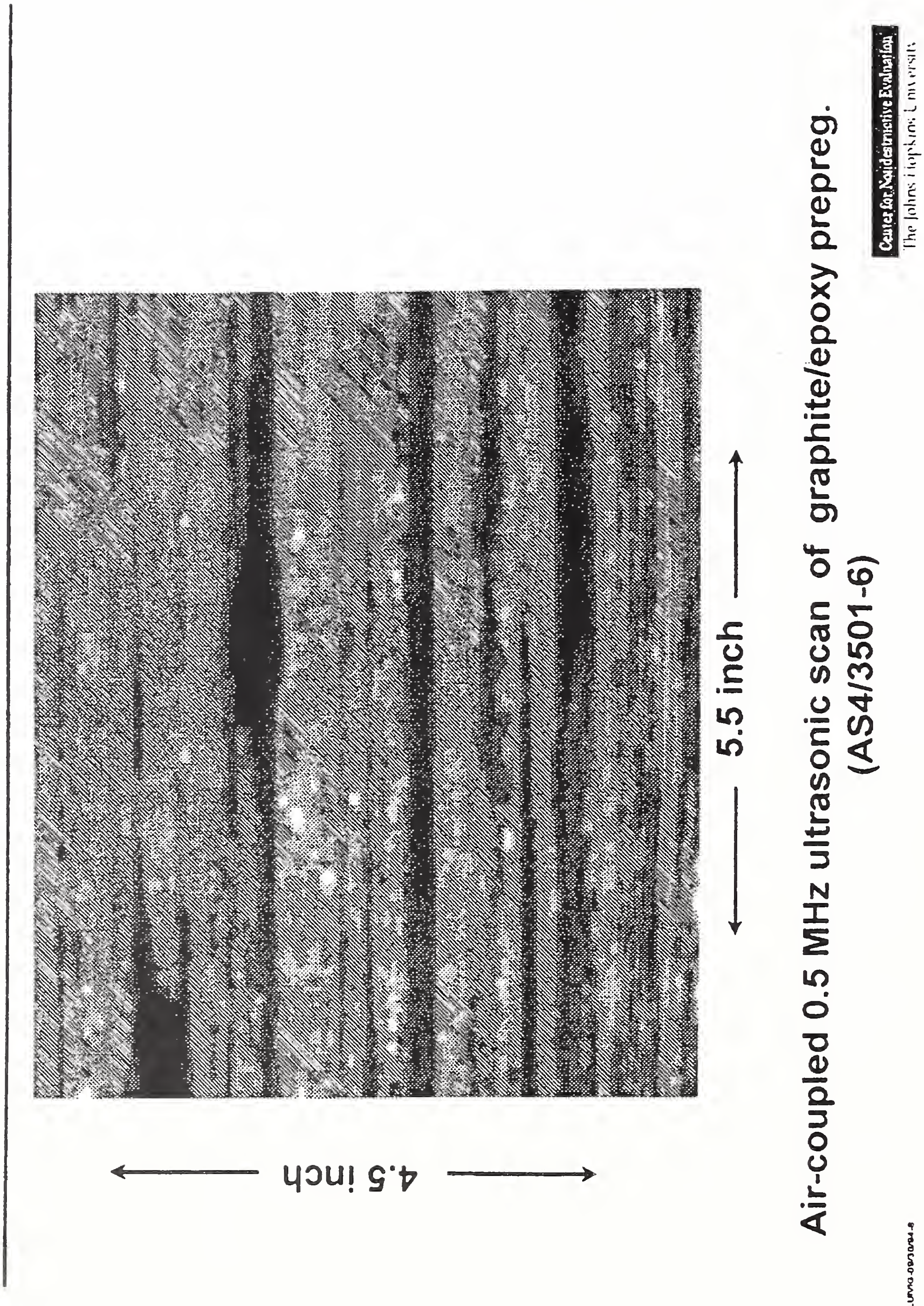
Figure 80

Non-contact UT for Process Control



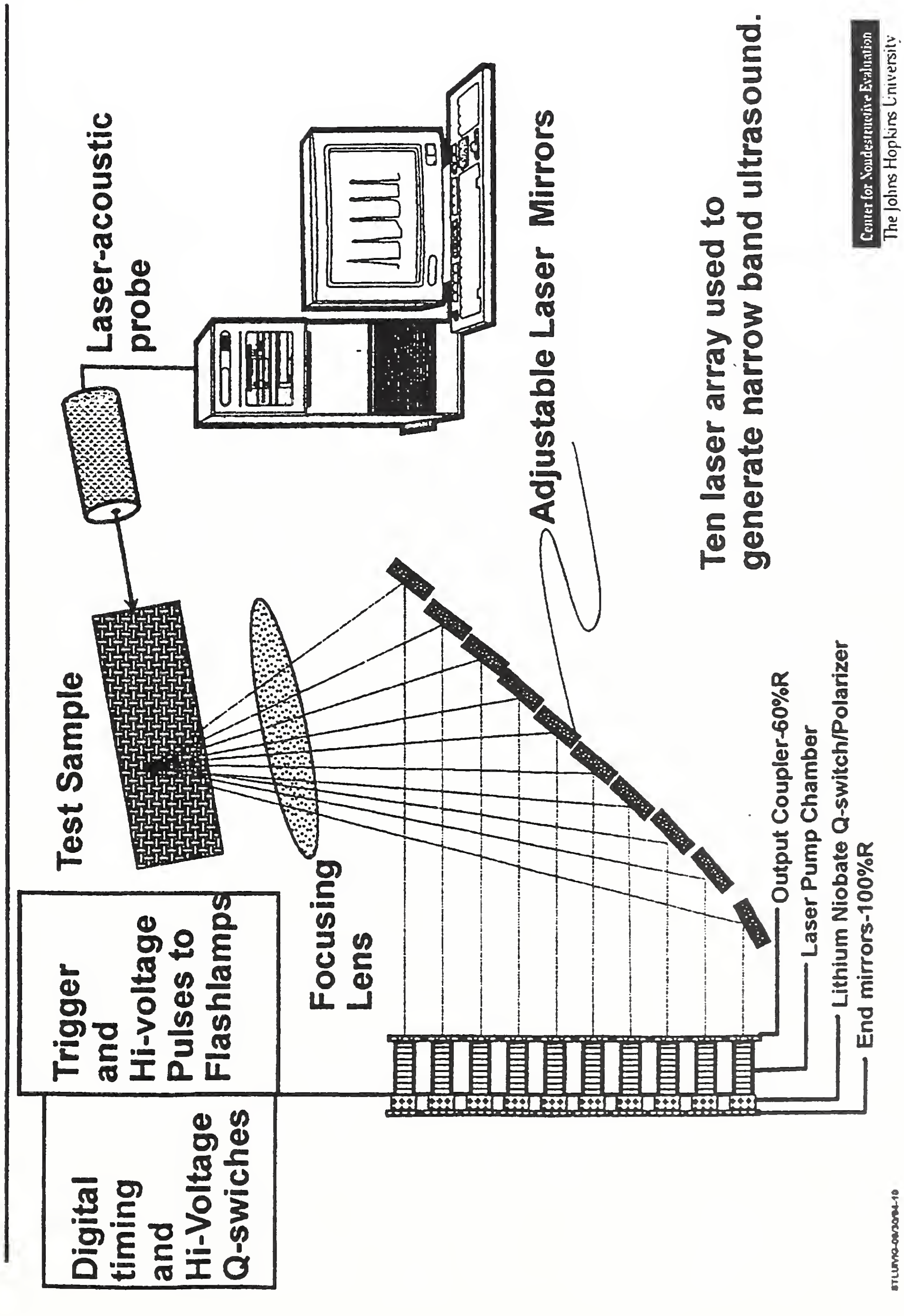
Air-coupled ultrasound system for on-line monitoring of prepreg tows.

Figure 81



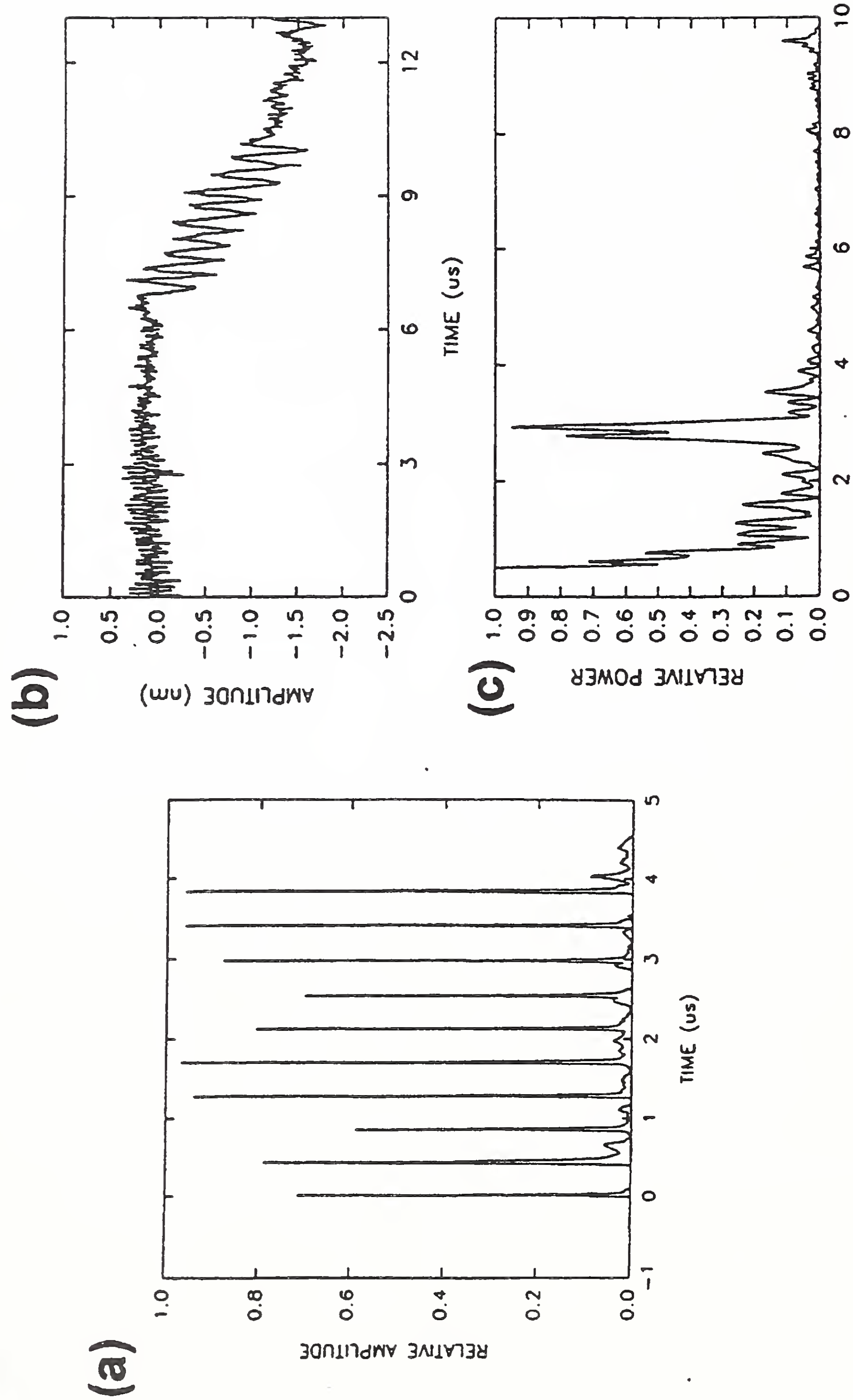
Air-coupled 0.5 MHz ultrasonic scan of graphite/epoxy prepreg. (AS4/3501-6)

Figure 82



Digital timing and Hi-Voltage Q-swiches
Trigger and Hi-voltage Pulses to Flashlamps
Test Sample
Laser-acoustic probe
Focusing Lens
Adjustable Laser Mirrors
Output Coupler-60%R
Laser Pump Chamber
Lithium Niobate Q-switch/Polarizer
End mirrors-100%R
Ten laser array used to generate narrow band ultrasound.
Center for Nondestructive Evaluation
The Johns Hopkins University

Figure 83



Laser pulse signal from the ten cavity laser system (a), generating ultrasonic signals (b), that exibit narrow bandwith centered at 3 MHz (c).

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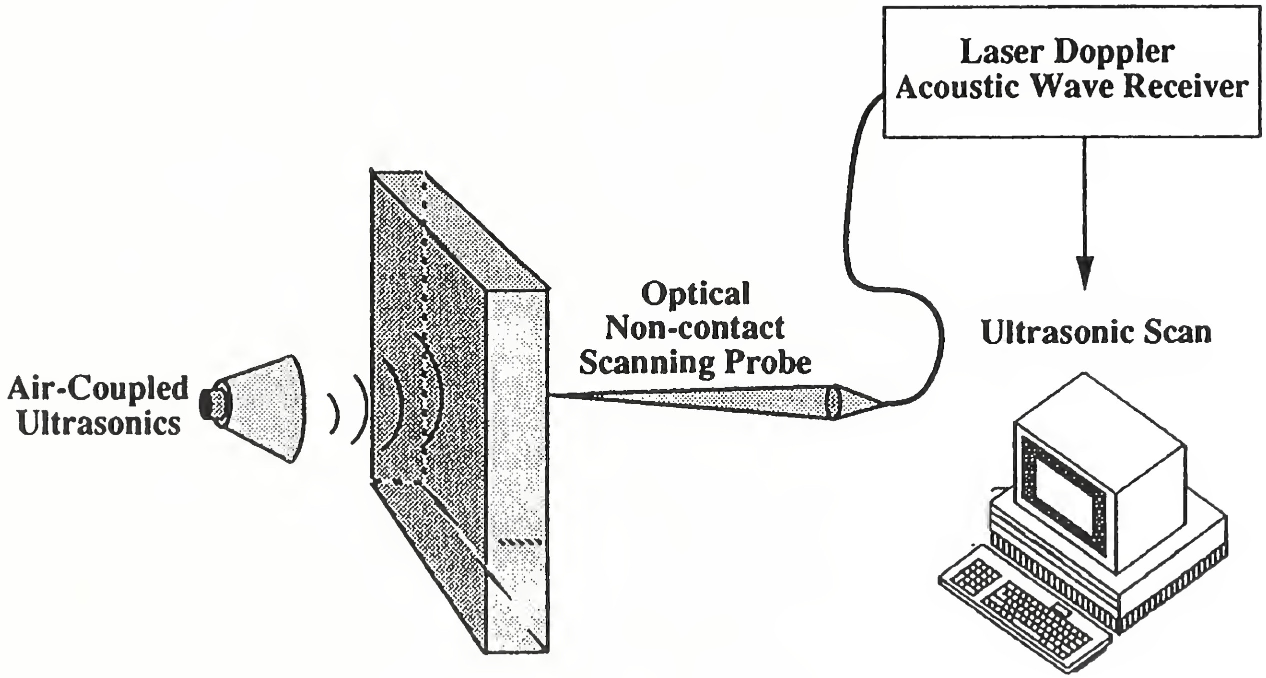
The Johns Hopkins University

Figure 84

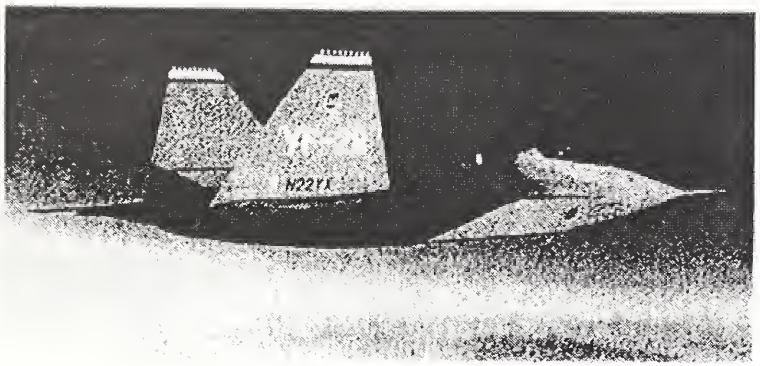
Nondestructive Evaluation - Ultrasonic Scan Technology



BD0793Austria

Figure 85

Nondestructive Evaluation, In-process Enabling Technologies



Composites manufacturing requires in-process controls and new sensors to enable viable use of these materials.

Nondestructive tools currently in use are old and focused to final product inspection.

New, non-traditional sensors are required to enable effective process control in manufacturing of composite structures.

Composite materials can meet many new commercial and DoD requirement but potential utilization is limited due to expense and lack of in-process monitoring technology.

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THE Budd COMPANY

TECHNICAL CENTER

HIGH SPEED PROCESSING OF COMPOSITES

BRUCE GREVE

SR. STAFF ENGINEER

Figure 86

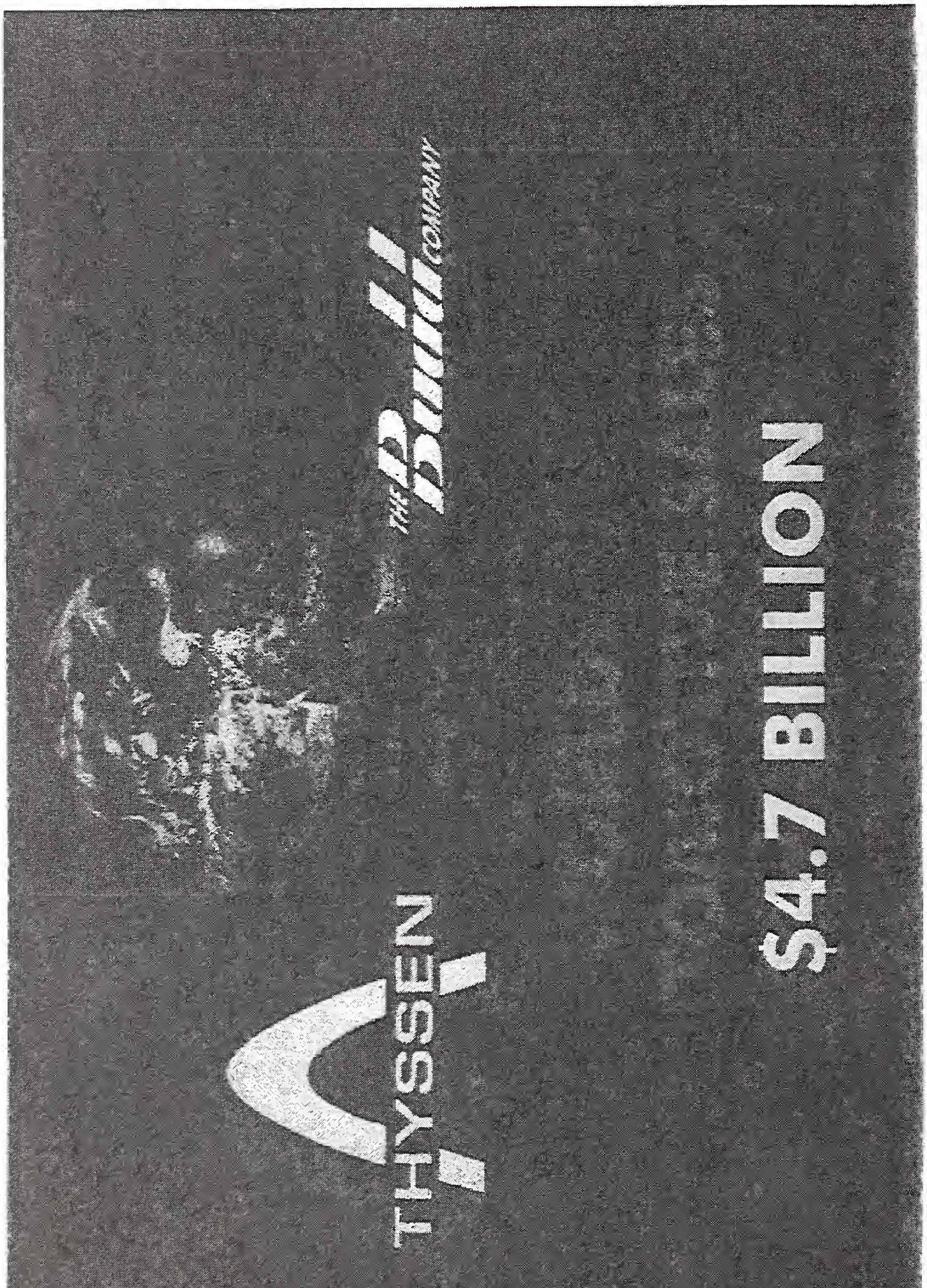


Figure 87

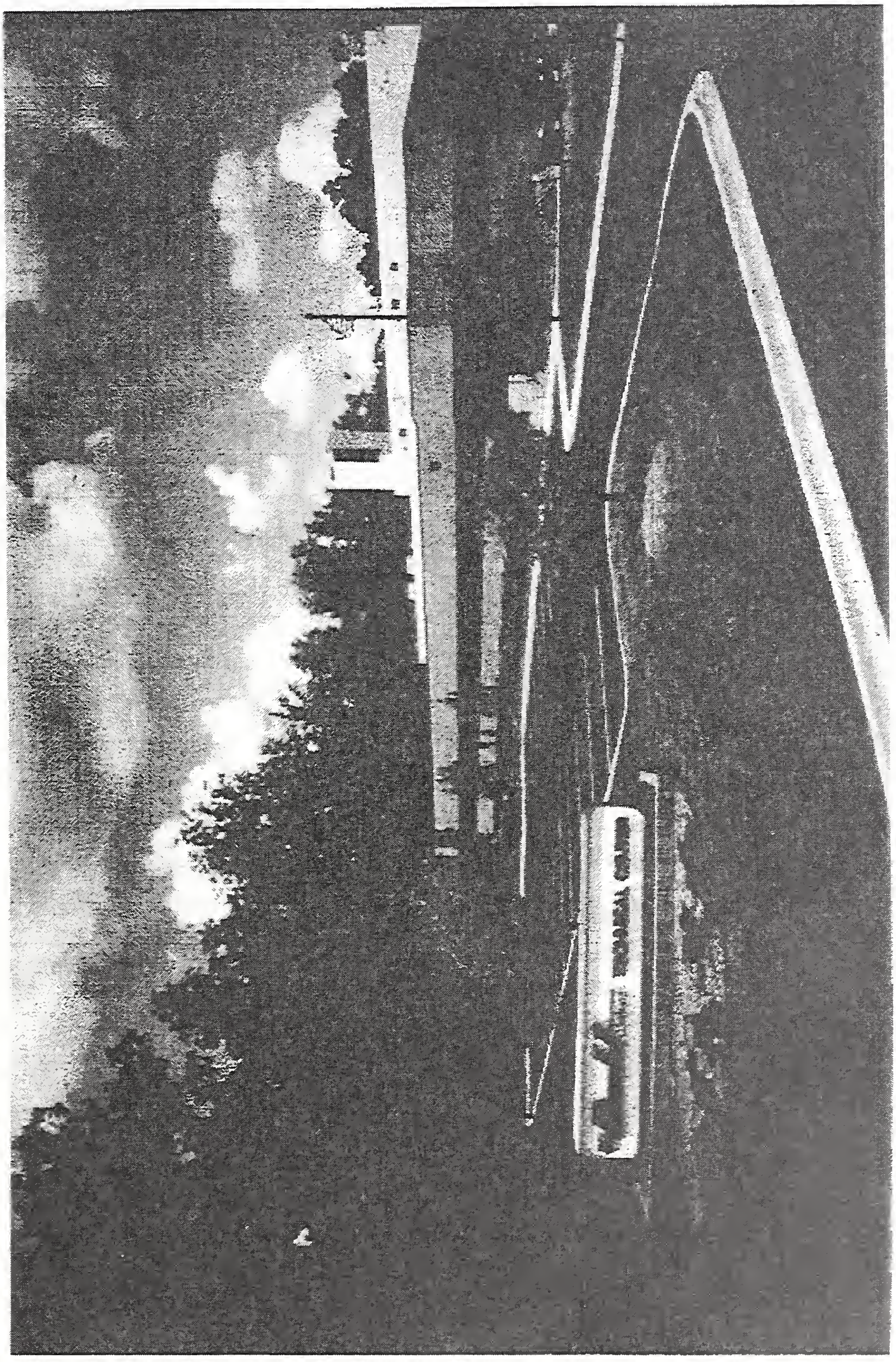


Figure 88

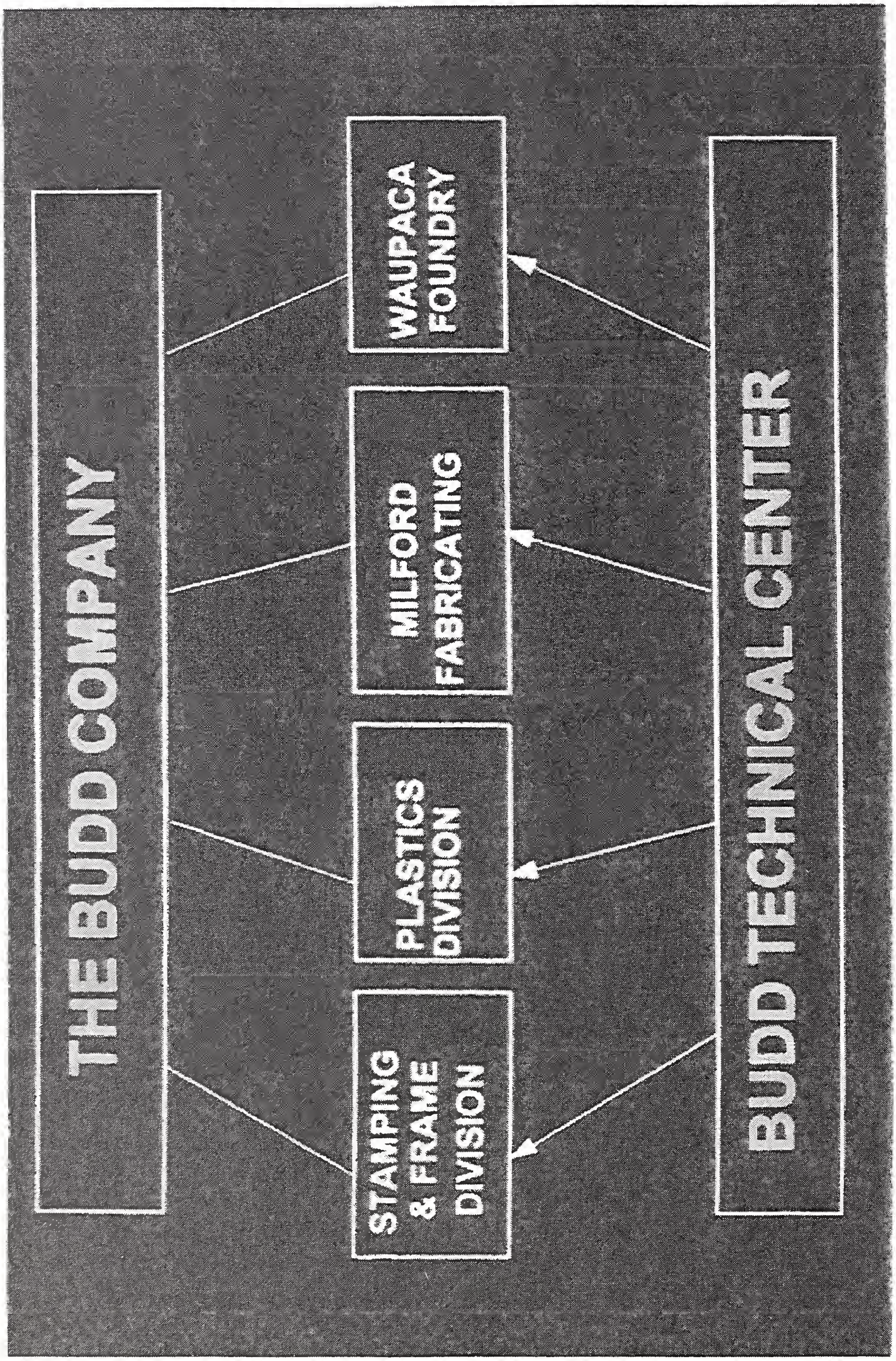

THE BUDD COMPANY
STAMPING & FRAME DIVISION
PLASTICS DIVISION
MILFORD FABRICATING
WAUPACA FOUNDRY
BUDD TECHNICAL CENTER

Figure 89


SMC APPLICATIONS
300 Different SMC Components
On 100 Domestic and Import Passenger Car and Truck Lines
Used by 28 Vehicle Manufacturers

Figure 90

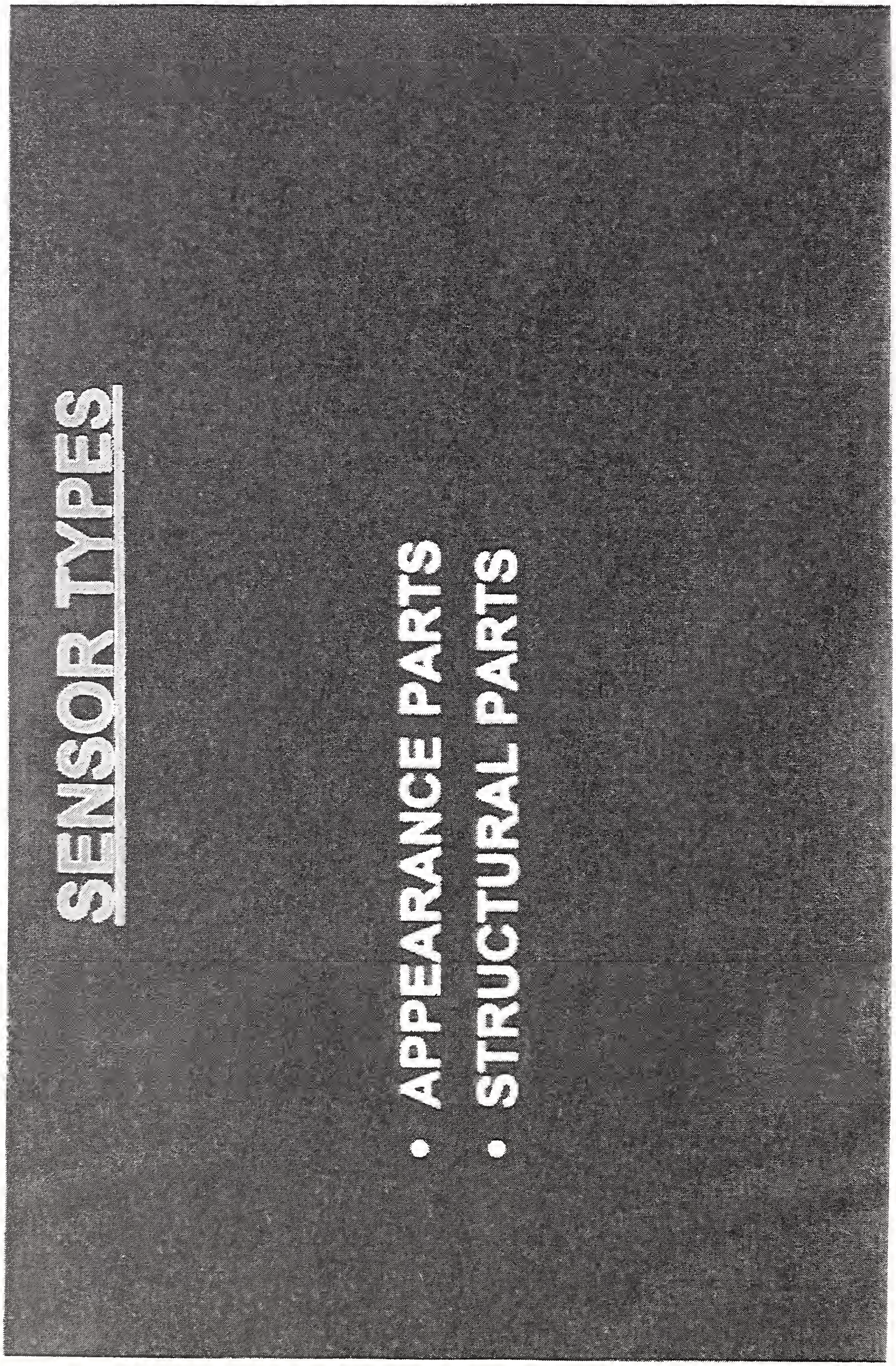


Figure 91

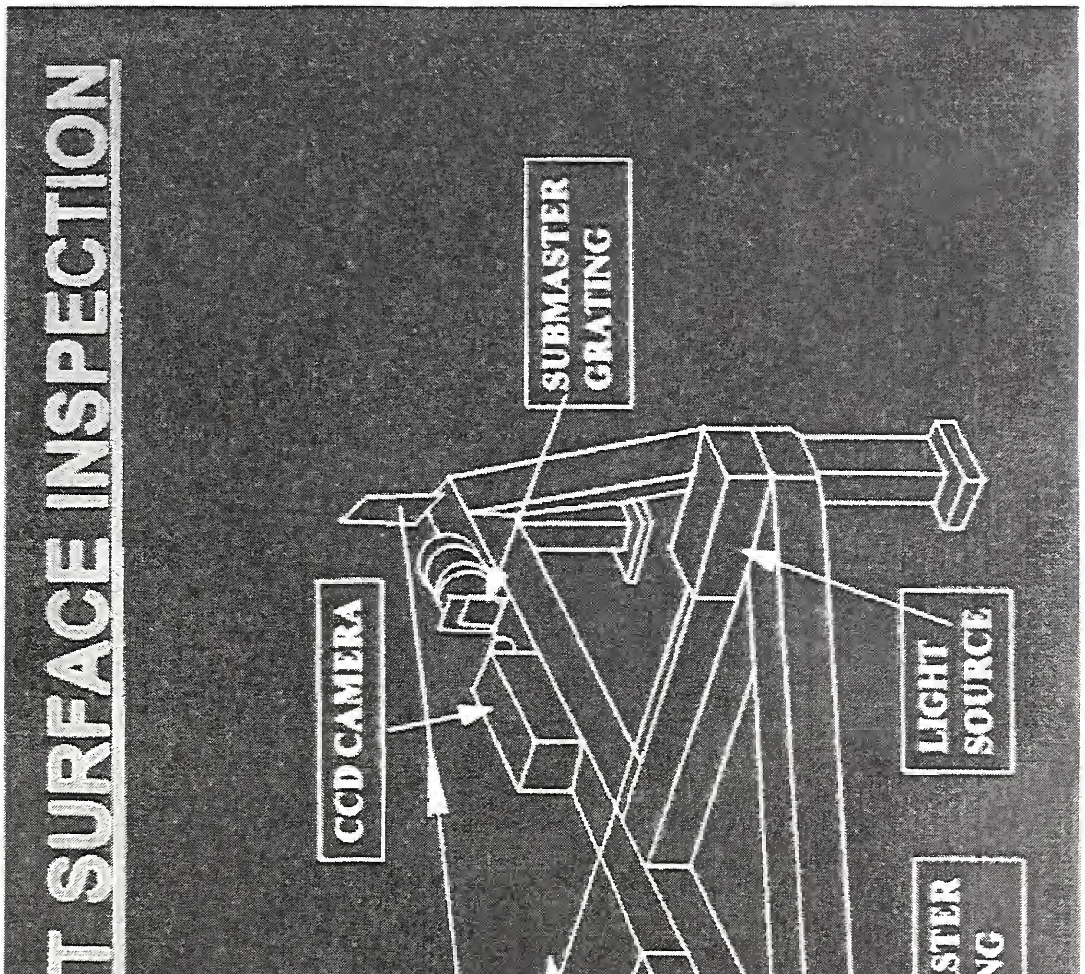

FULL COMPONENT SURFACE INSPECTION
SUBMASTER GRATING
CCD CAMERA
LIGHT SOURCE
SUBMASTER GRATING
CCD CAMERA

Figure 92

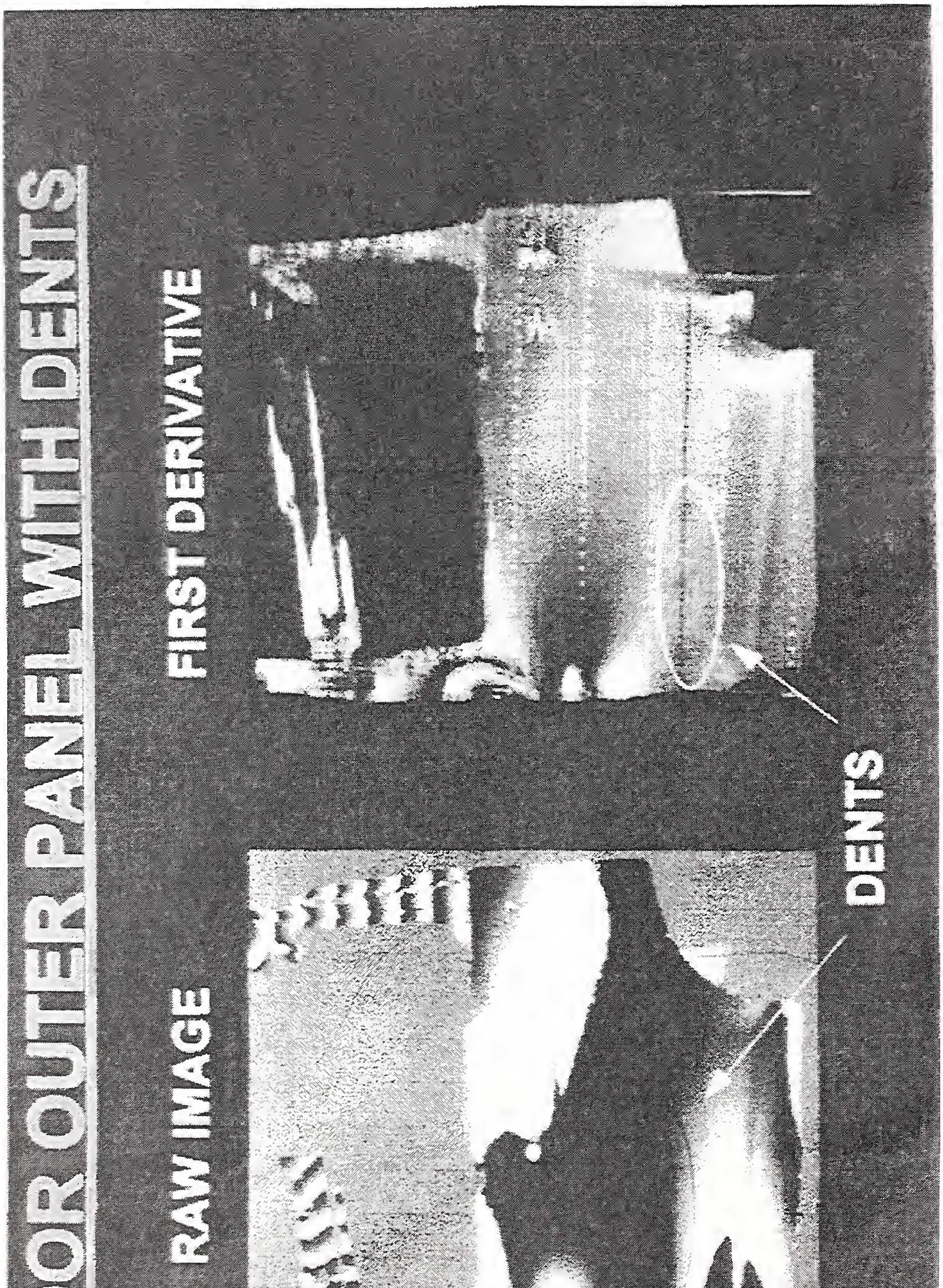

DOOR OUTER PANEL WITH DENTS
RAW IMAGE
FIRST DERIVATIVE
DENTS

Figure 93

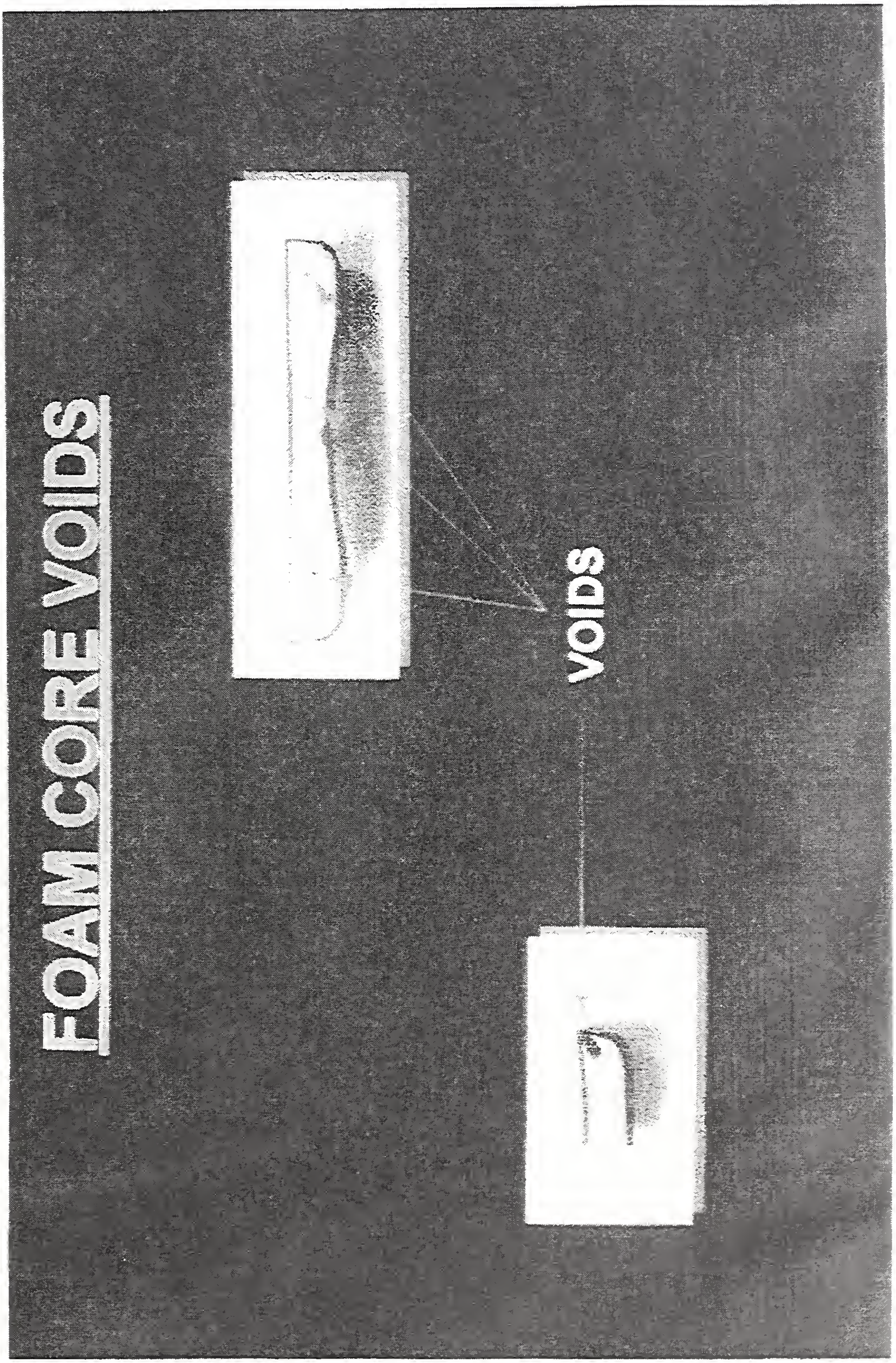


Figure 94

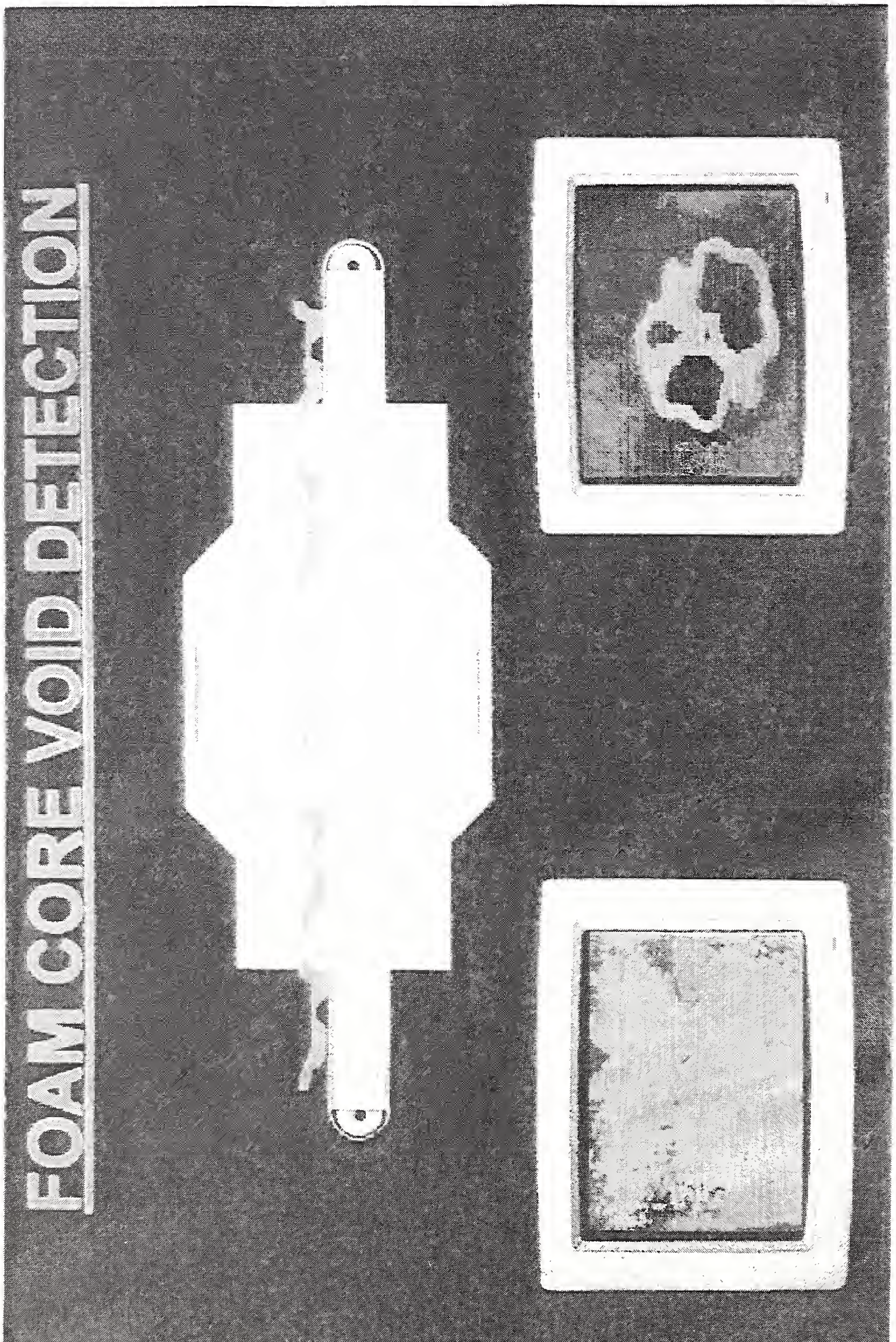


Figure 95

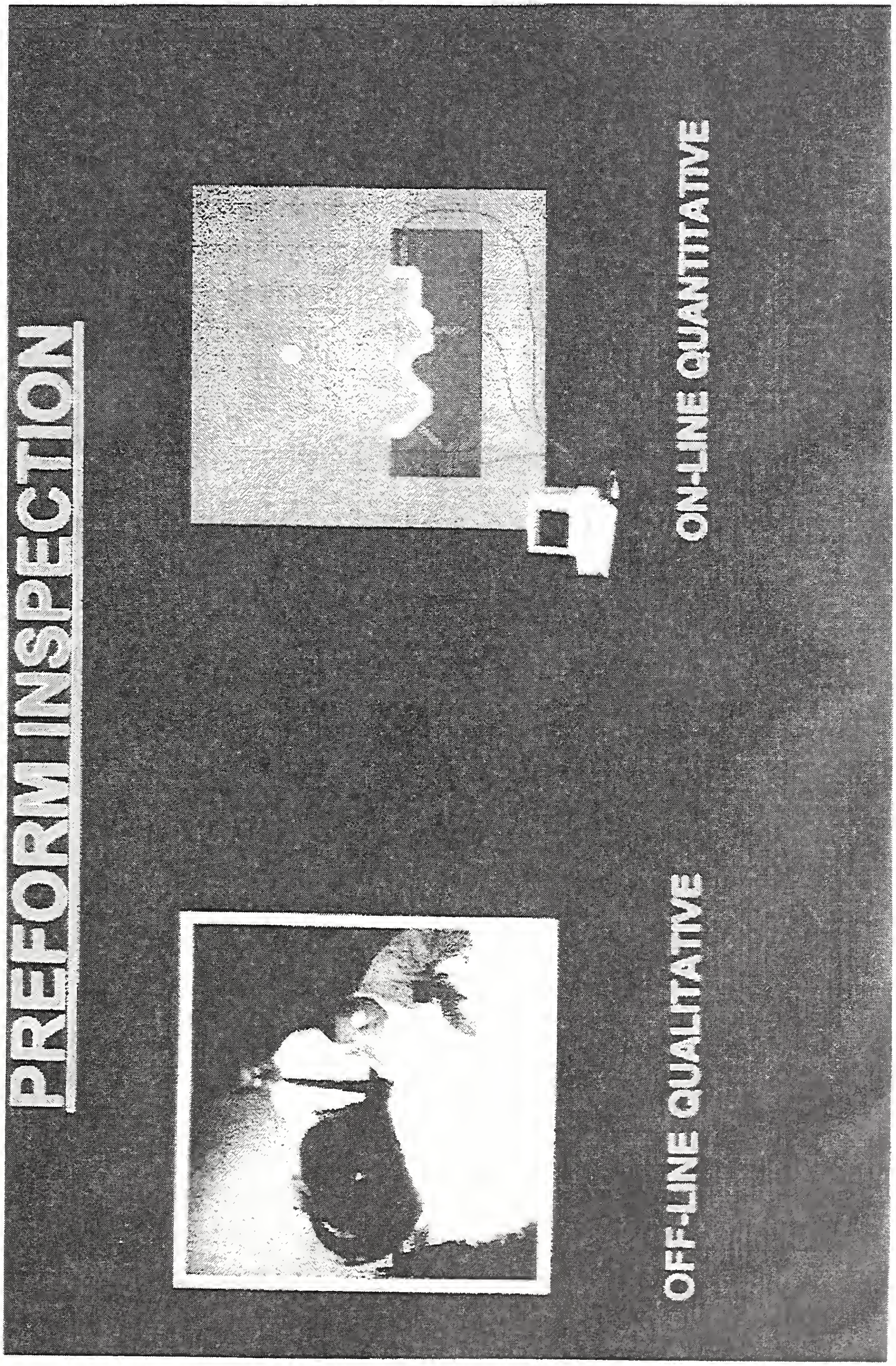

PREFORM INSPECTION
OFF-LINE QUALITATIVE
ON-LINE QUANTITATIVE

Figure 96

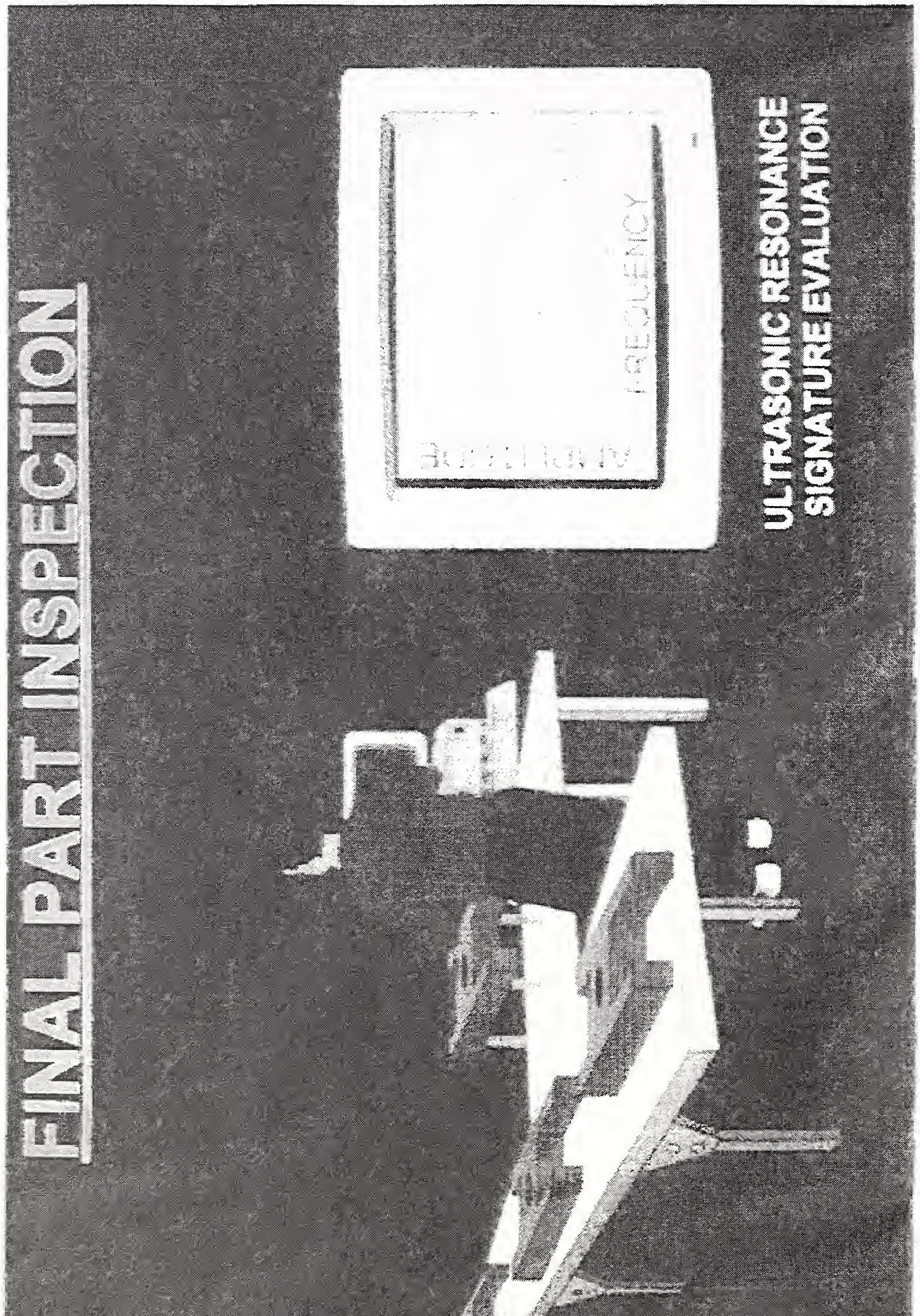

FINAL PART INSPECTION
ULTRASONIC RESONANCE SIGNATURE EVALUATION

Figure 97

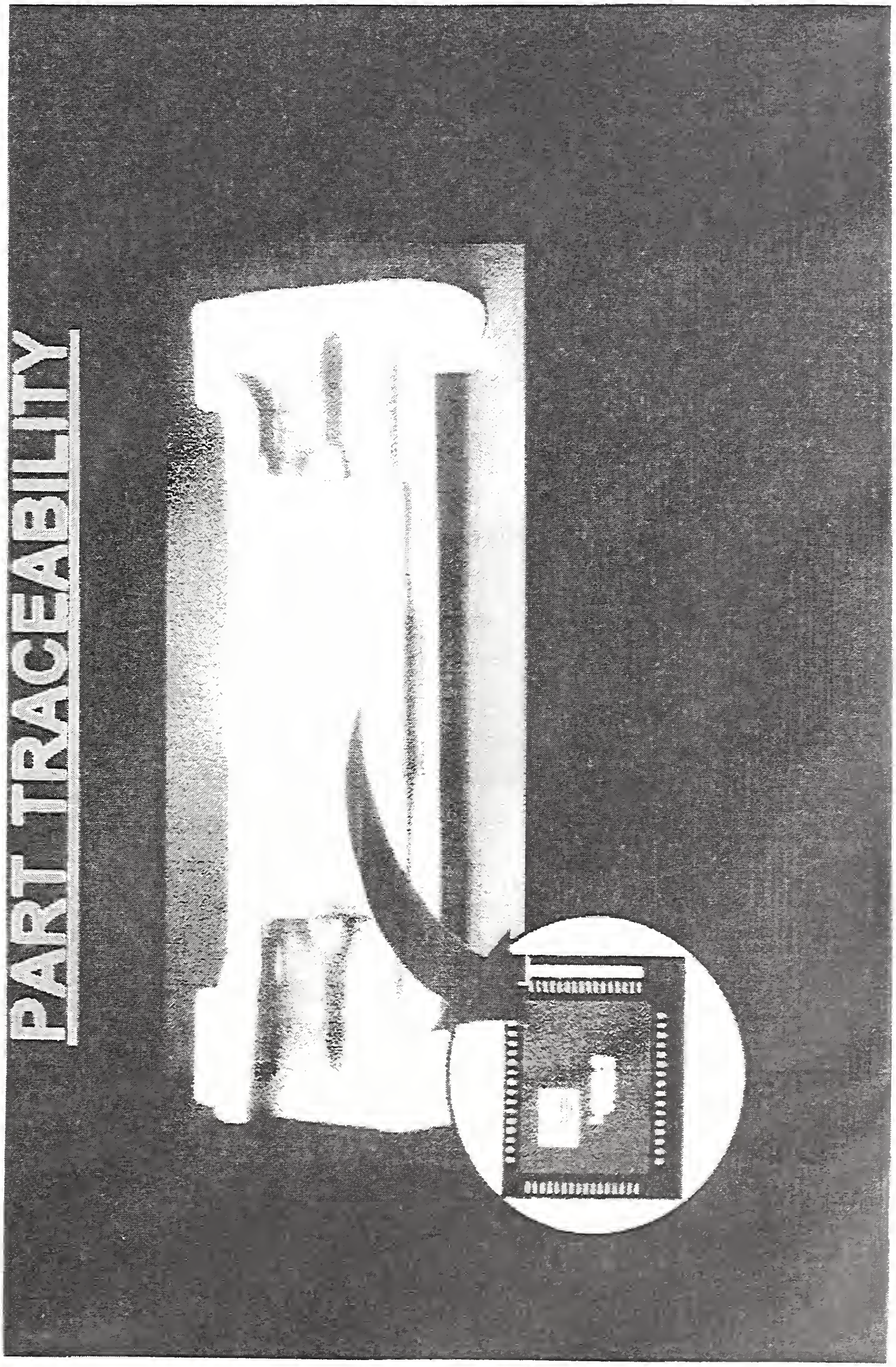


Figure 98

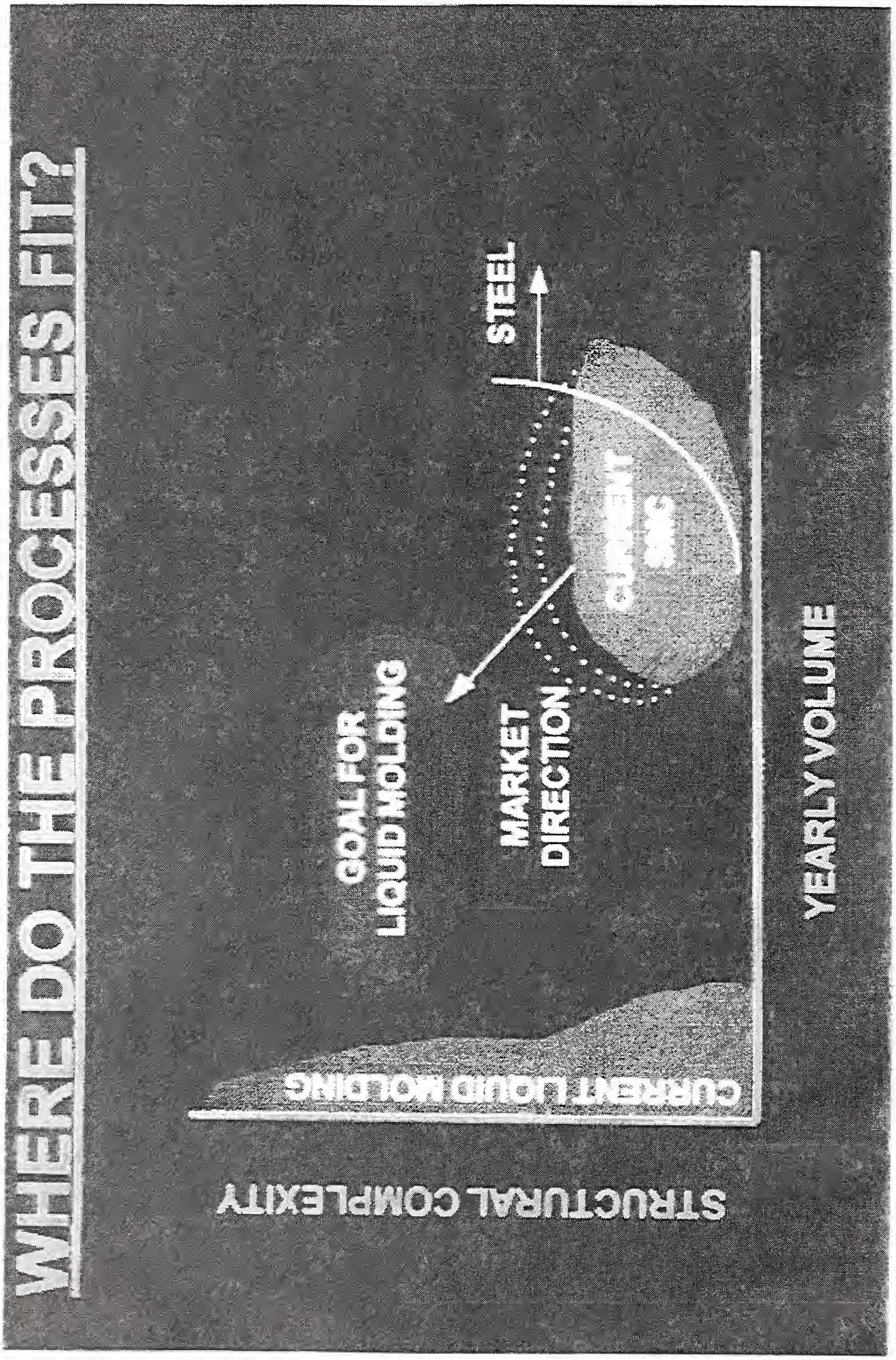

WHERE DO THE PROCESSES FIT?
STEEL
GOAL FOR LIQUID MOLDING
MARKET DIRECTION
YEARLY VOLUME
CURRENT LIQUID MOLDING
STRUCTURAL COMPLEXITY

Figure 99

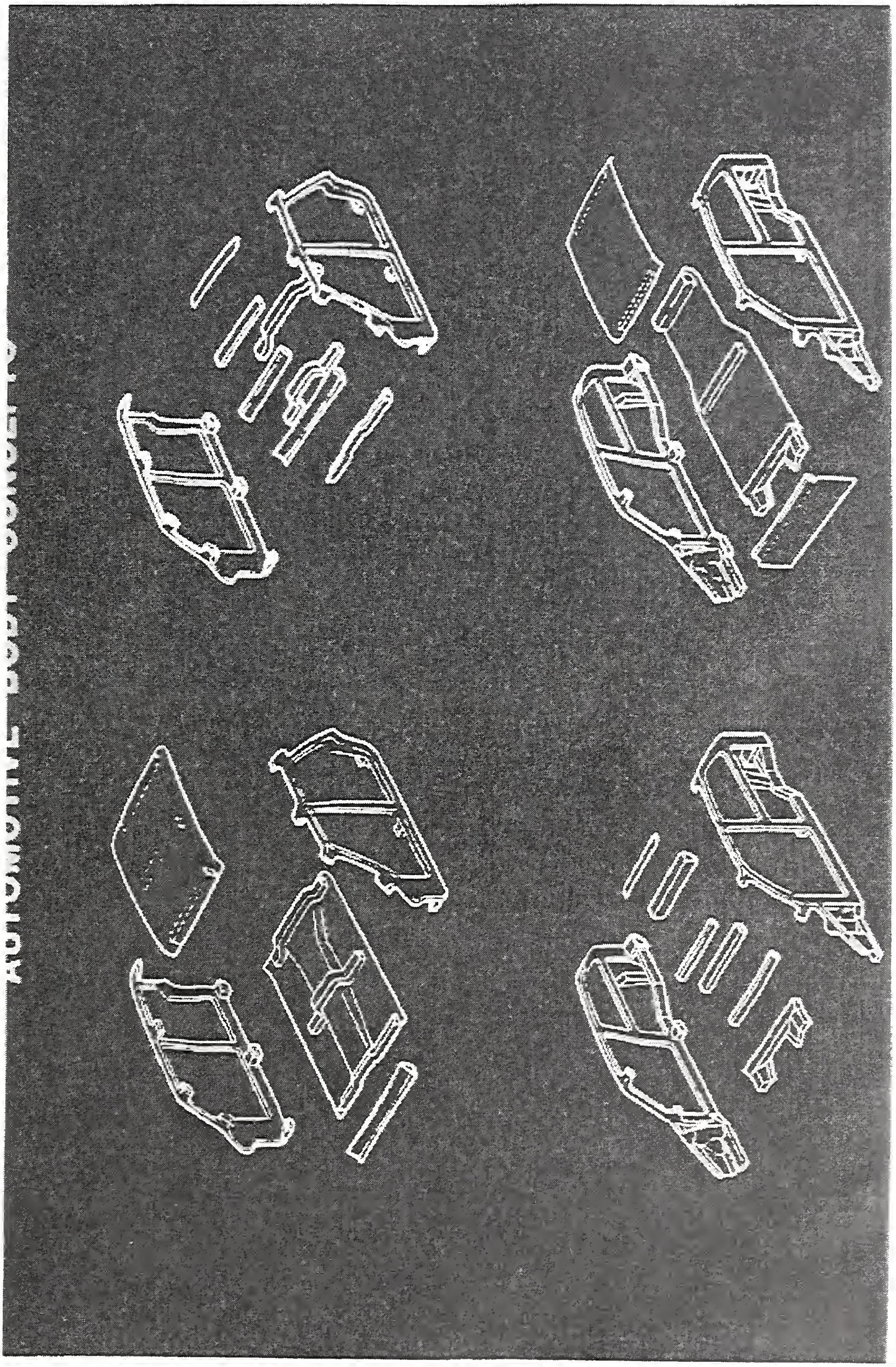


Figure 100

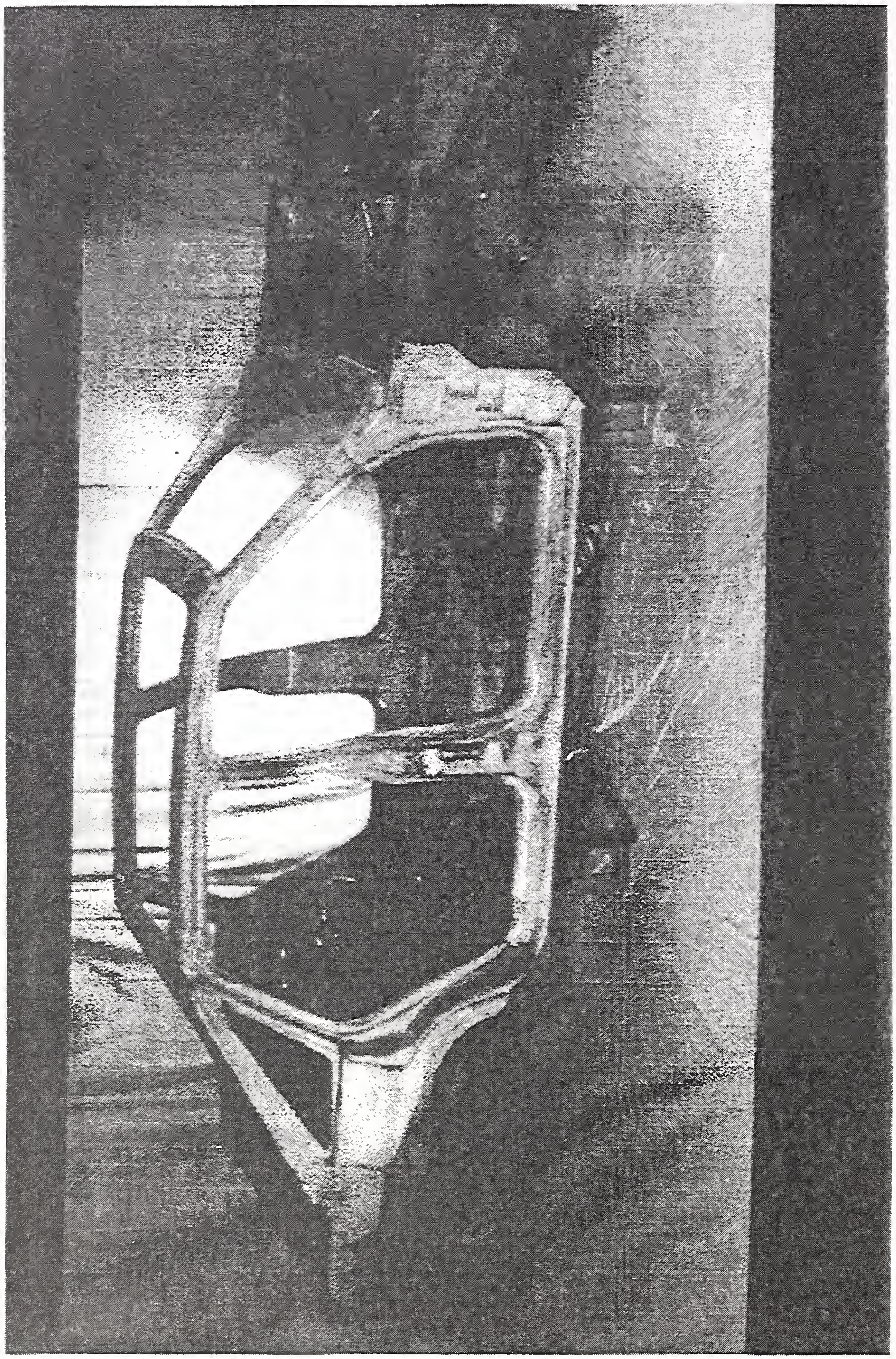


Figure 101

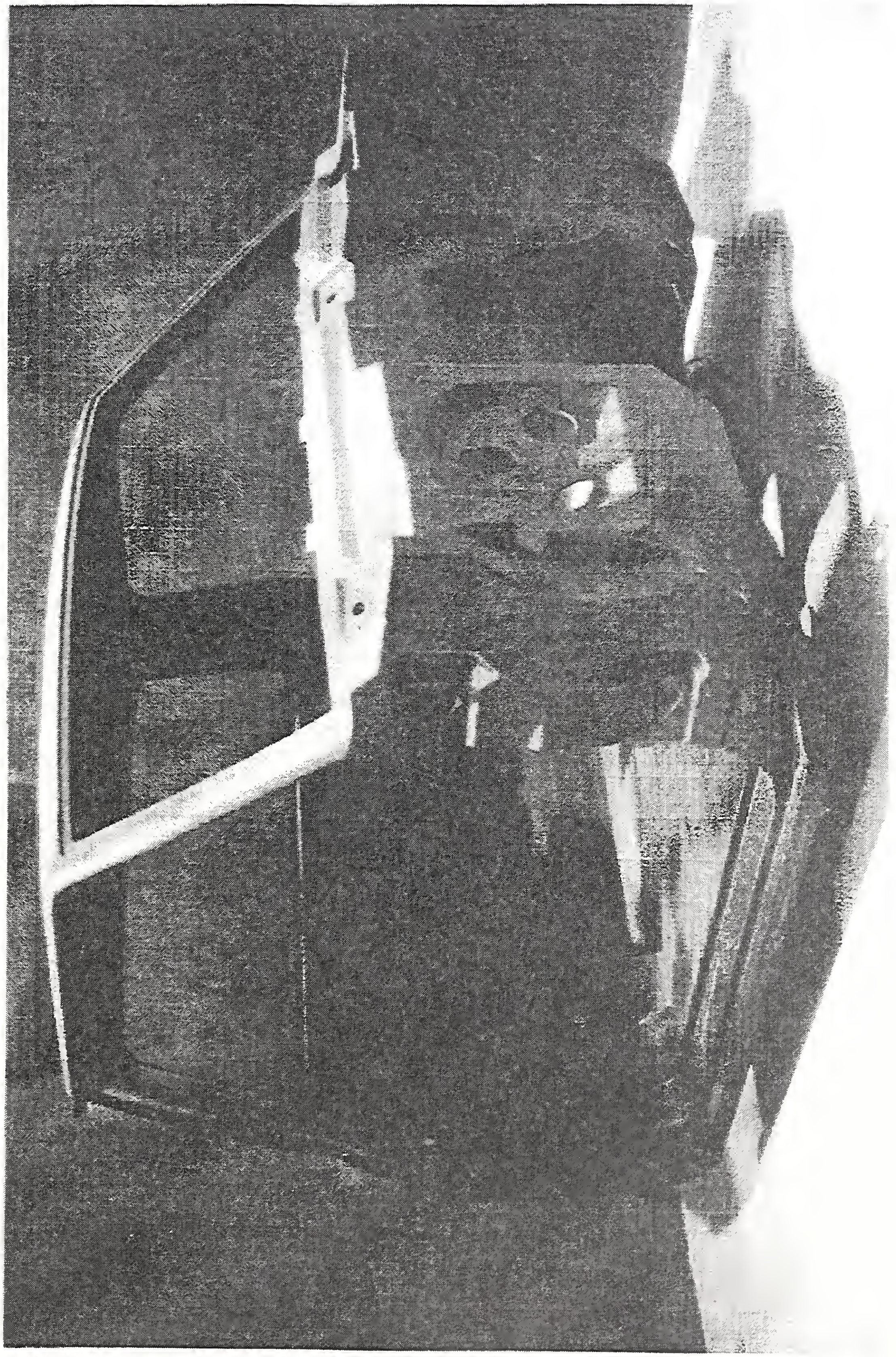


Figure 102

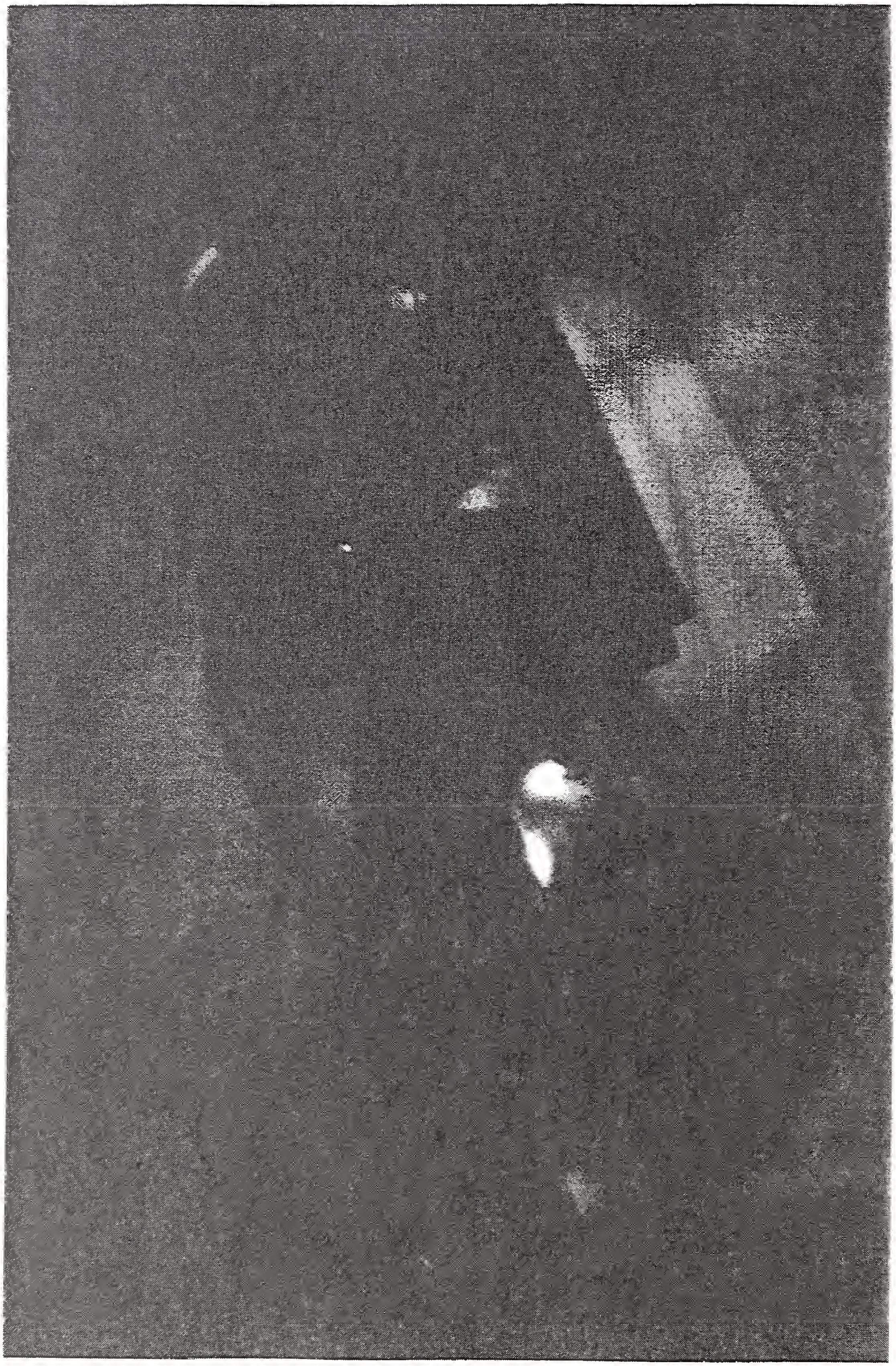


Figure 103

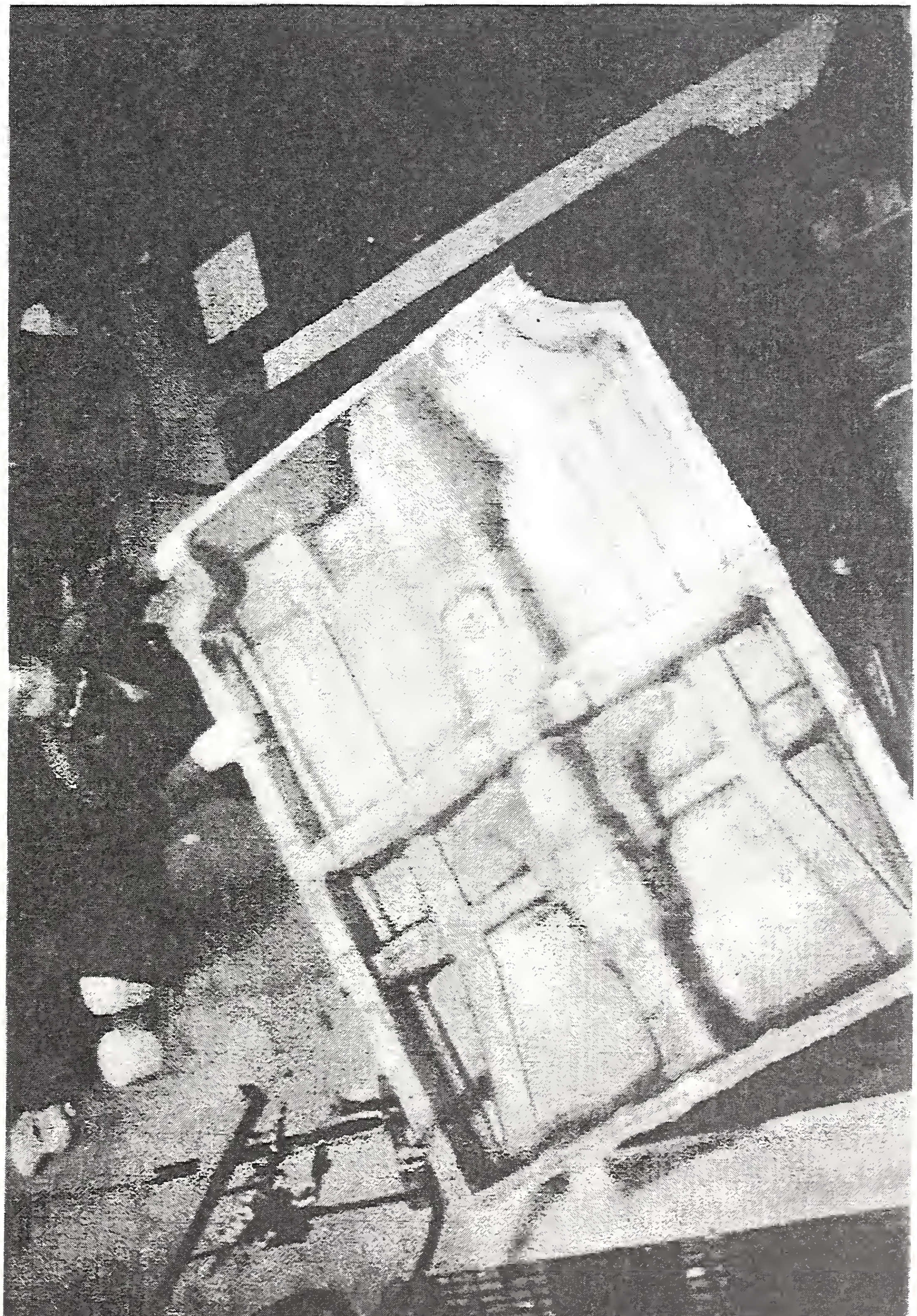


Figure 104

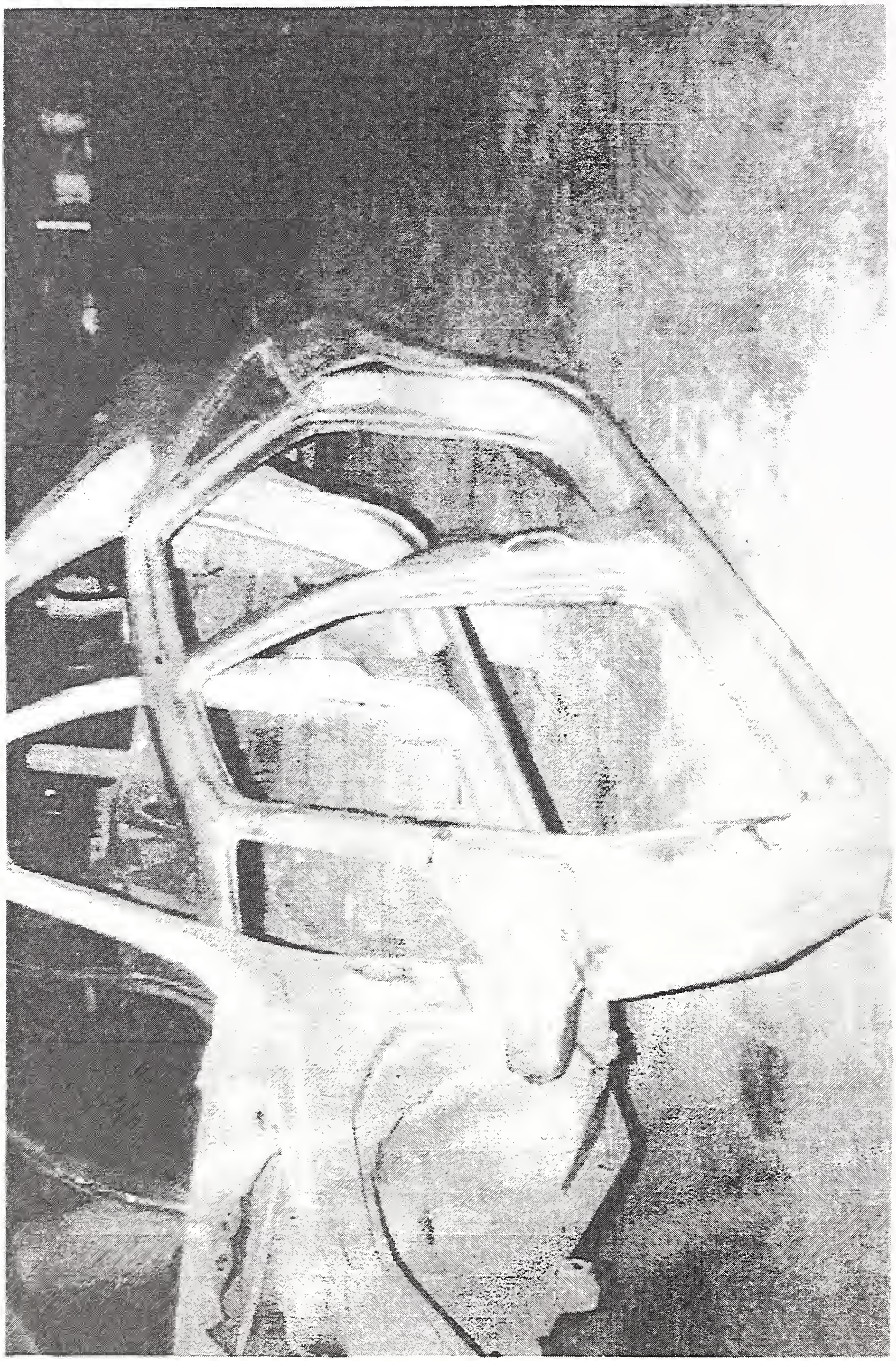


Figure 105

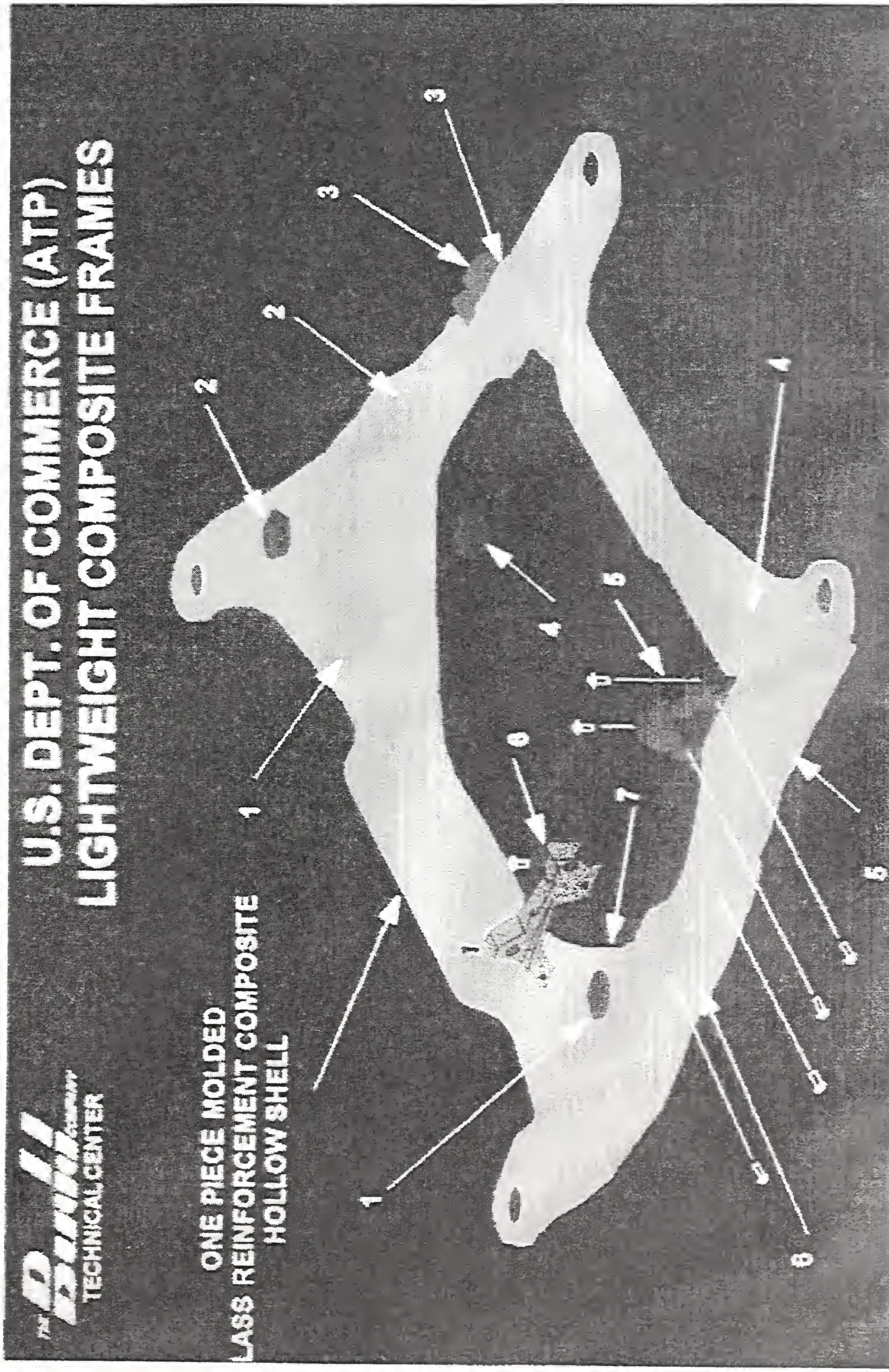

U.S. DEPT. OF COMMERCE (ATP)
LIGHTWEIGHT COMPOSITE FRAMES
TECHNICAL CENTER
ONE PIECE MOLDED
LASS REINFORCEMENT COMPOSITE
HOLLOW SHELL
1
1
1
2
2
3
3
4
4
5
6
7
8

Figure 106

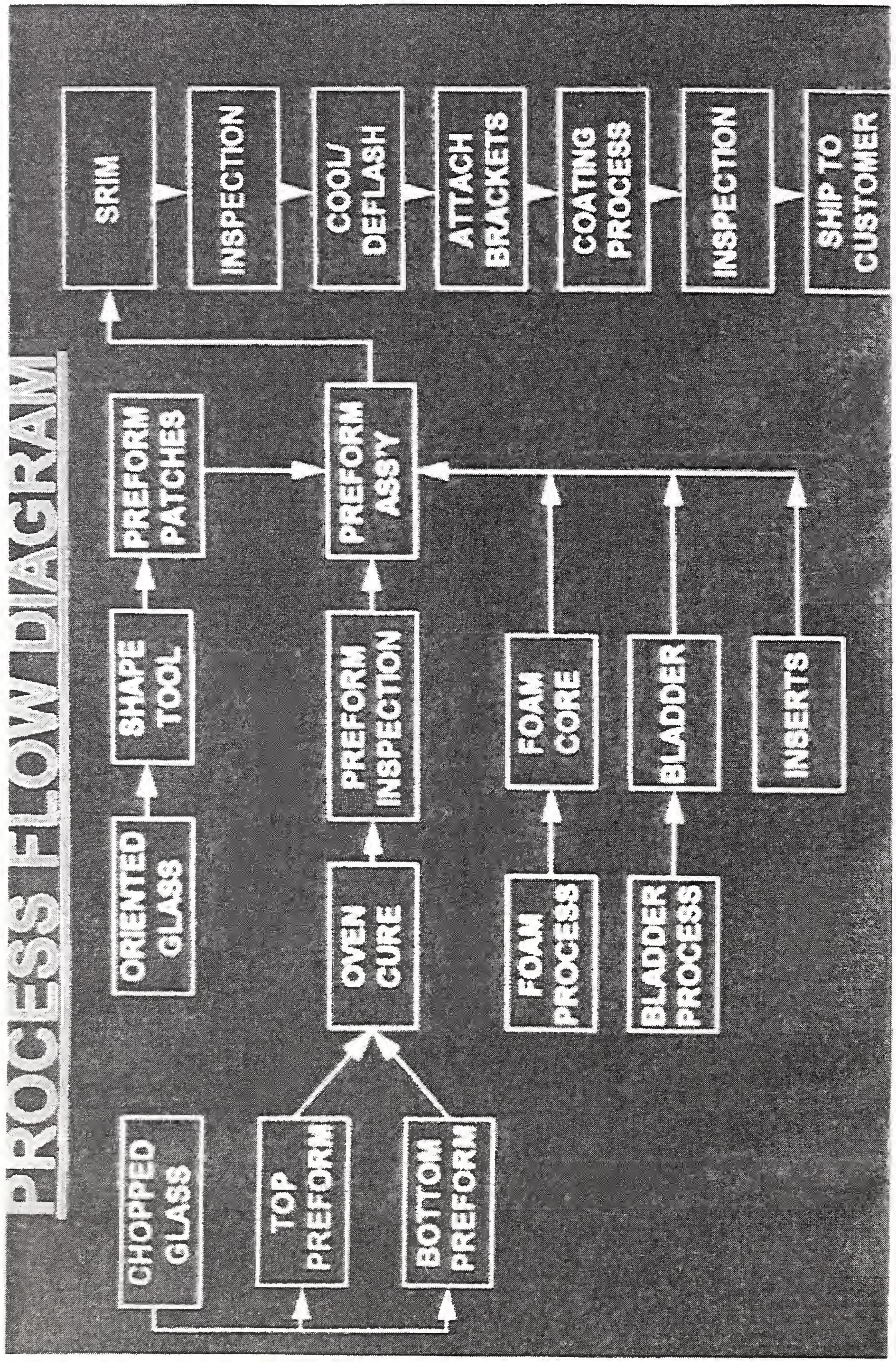

PROCESS FLOW DIAGRAM
CHOPPED GLASS
TOP PREFORM
BOTTOM PREFORM
OVEN CURE
PREFORM INSPECTION
ORIENTED GLASS
SHAPE TOOL
PREFORM PATCHES
PREFORM ASS'Y
FOAM PROCESS
FOAM CORE
BLADDER PROCESS
BLADDER
INSERTS
SRIM
INSPECTION
COOL/ DEFLASH
ATTACH BRACKETS
COATING PROCESS
INSPECTION
SHIP TO CUSTOMER

Figure 107

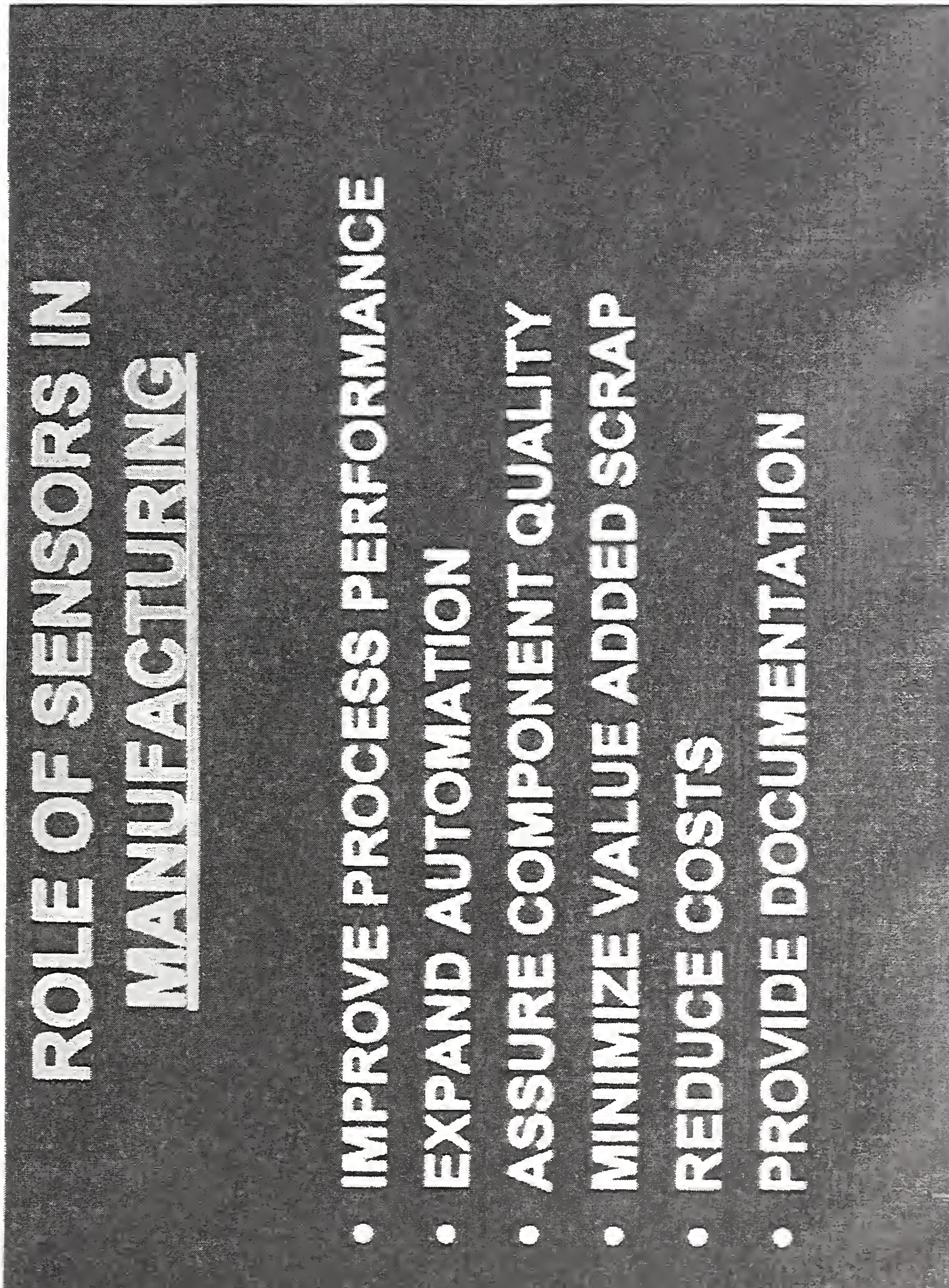

ROLE OF SENSORS IN
MANUFACTURING
• IMPROVE PROCESS PERFORMANCE
• EXPAND AUTOMATION
• ASSURE COMPONENT QUALITY
• MINIMIZE VALUE ADDED SCRAP
• REDUCE COSTS
• PROVIDE DOCUMENTATION

Figure 108


SENSOR REQUIREMENTS
• Manufacturing Environment
• Response Times <1minute
• Low Maintenance

Figure 109

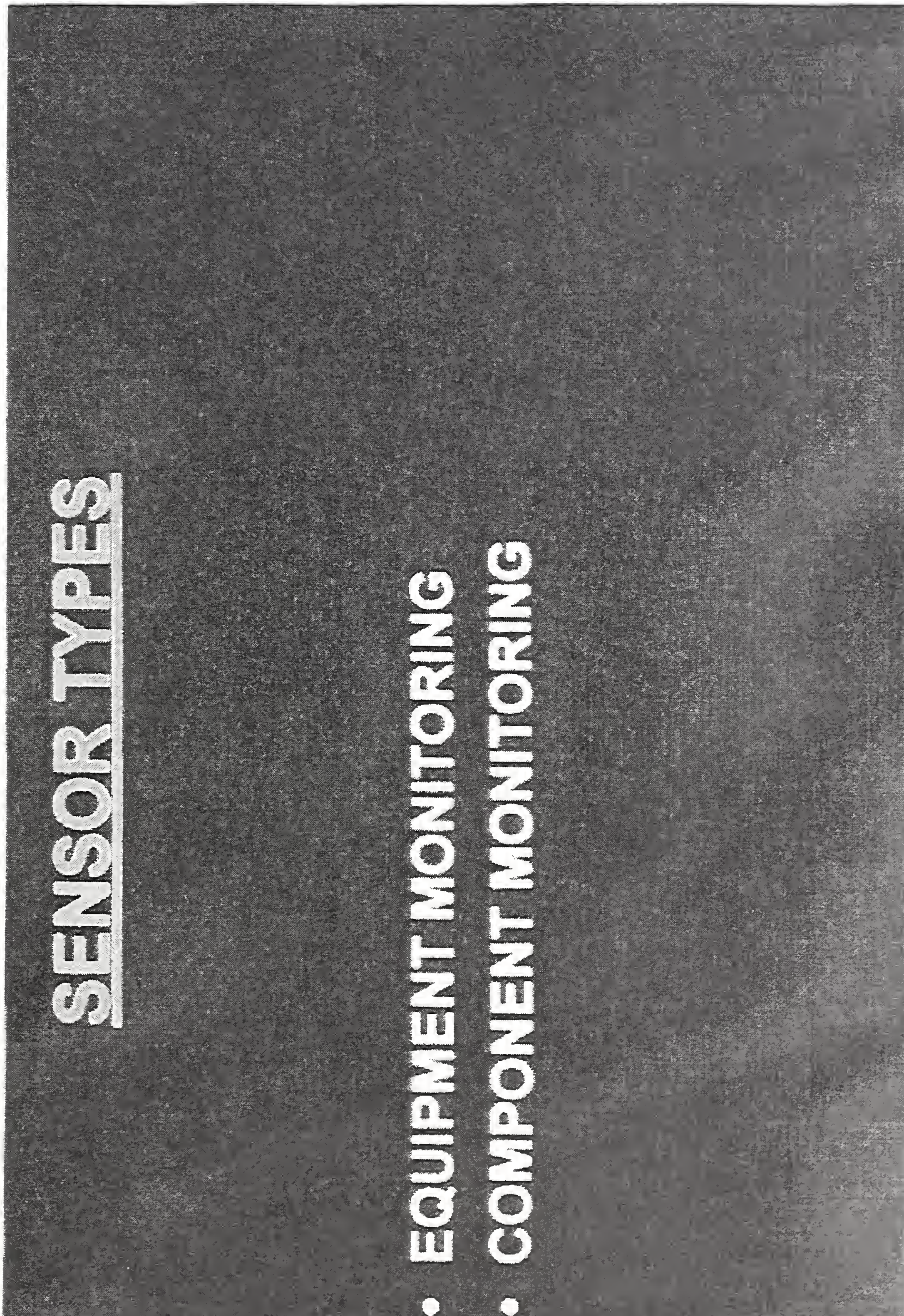
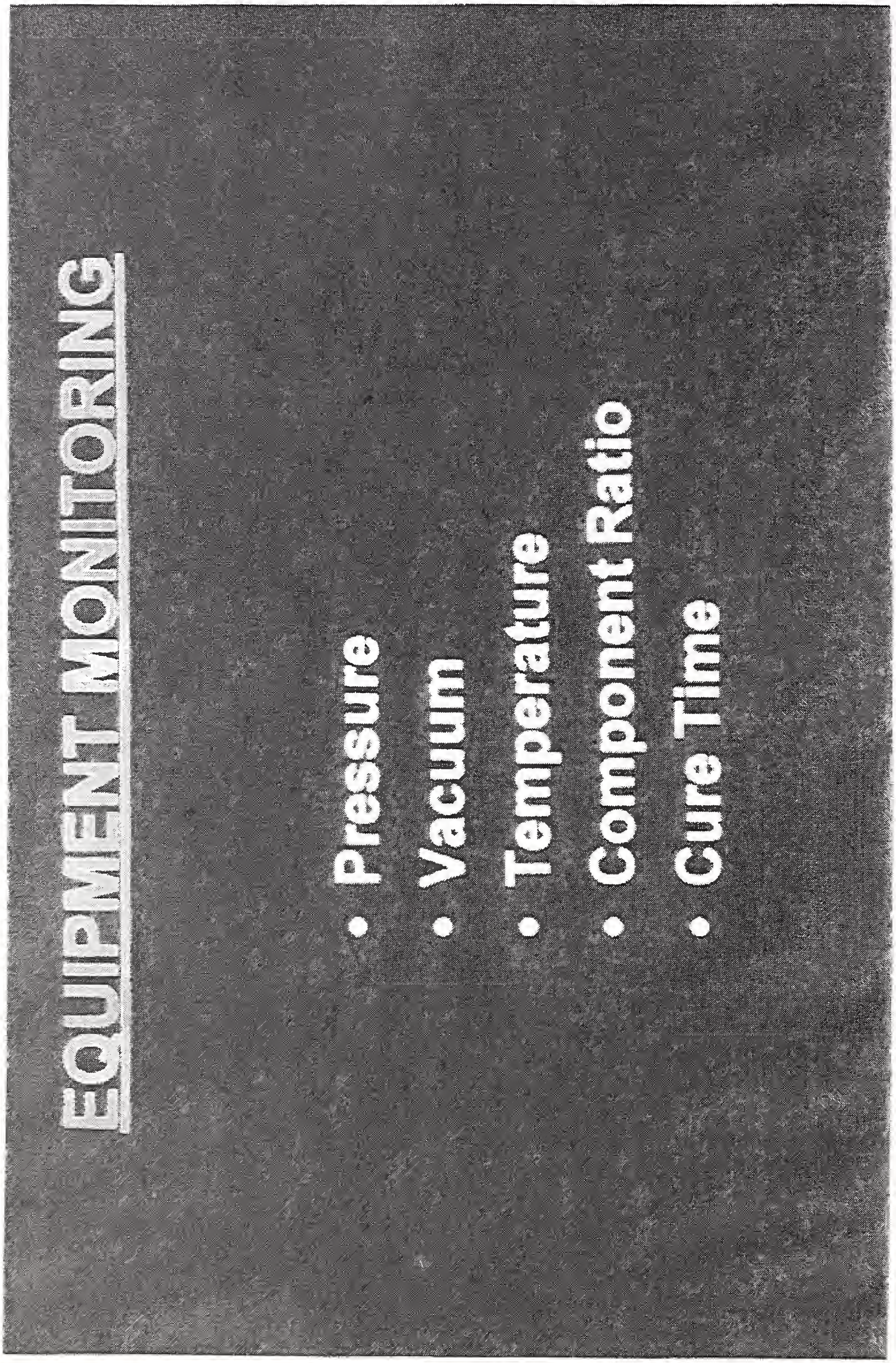


Figure 110



EQUIPMENT MONITORING
• Pressure
• Vacuum
• Temperature
• Component Ratio
• Cure Time

Figure 111

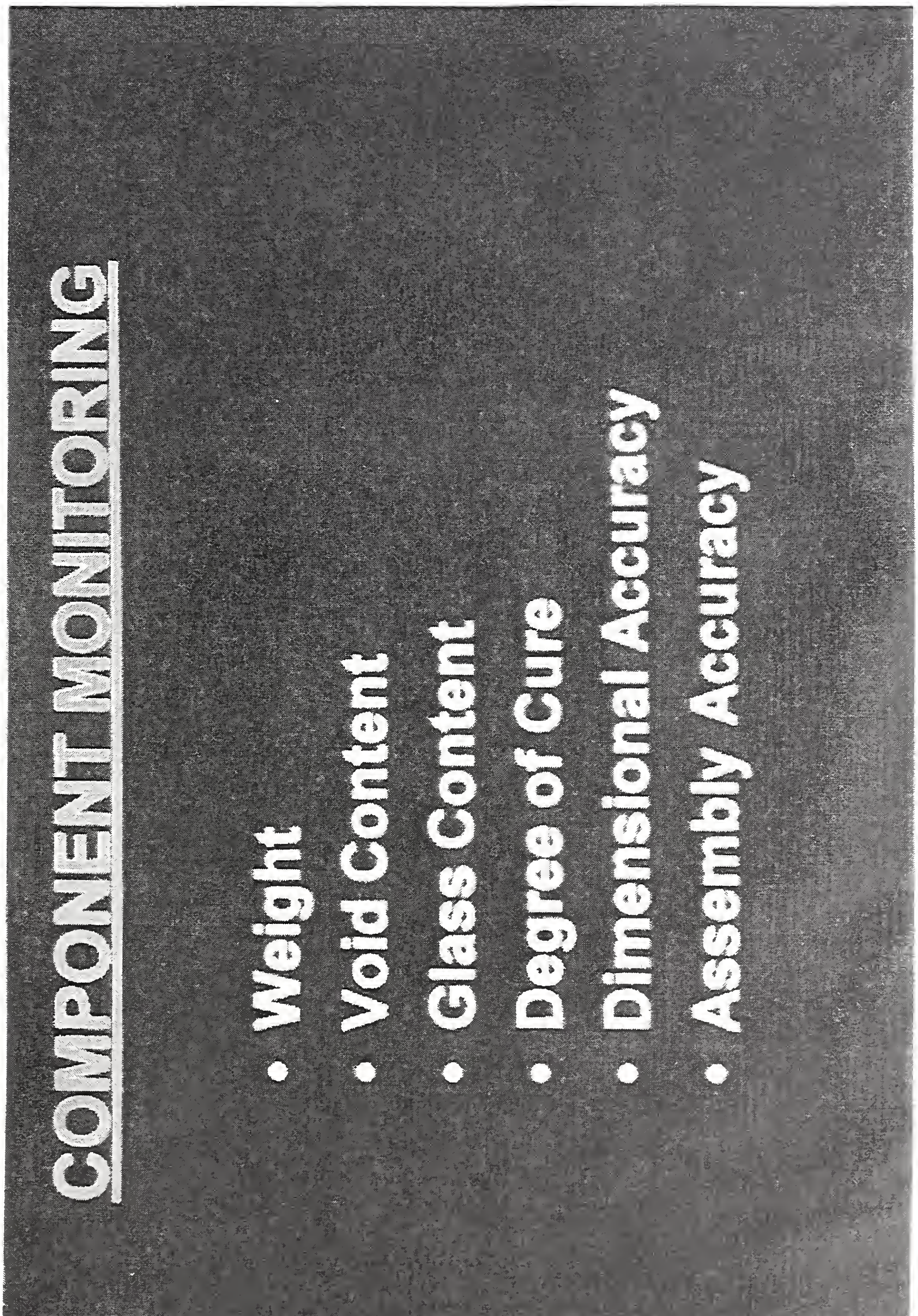

COMPONENT MONITORING
• Weight
• Void Content
• Glass Content
• Degree of Cure
• Dimensional Accuracy
• Assembly Accuracy

Figure 110

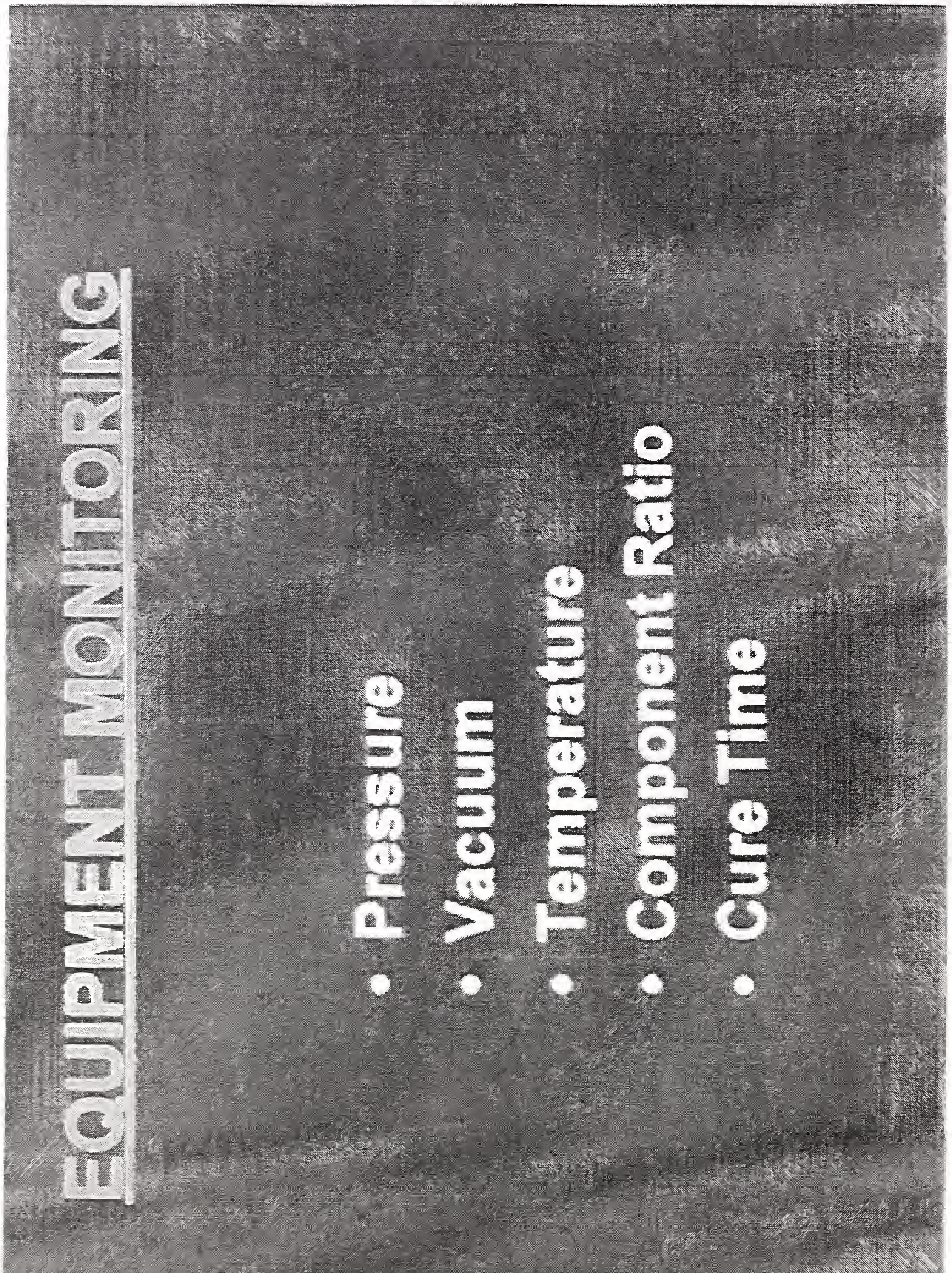
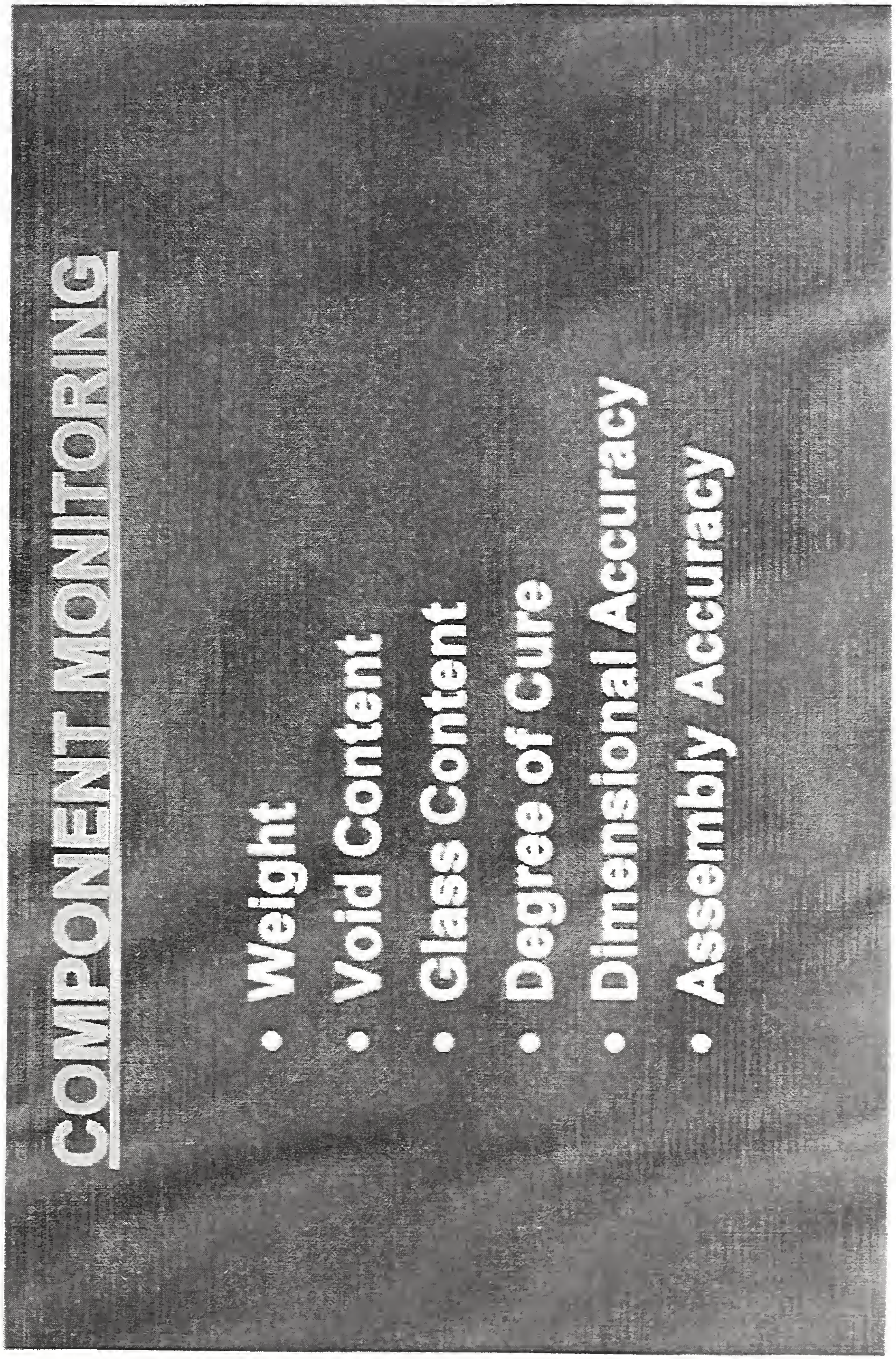

EQUIPMENT MONITORING
• Pressure
• Vacuum
• Temperature
• Component Ratio
• Cure Time

Figure 111


COMPONENT MONITORING
• Weight
• Void Content
• Glass Content
• Degree of Cure
• Dimensional Accuracy
• Assembly Accuracy