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PROCESS AND CONTROL SYSTEMS FOR COMPOSITES MANUFACTURING

by

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Summary

A precise control of composite material processing would not only improve part quality, but also directly reduce the overall manufacturing cost. The development and incorporation of sensors will help to generate real-time information for material processing relationships and equipment characteristics. In the present work, the thermocouple, pressure transducer and dielectrometer technologies were investigated. The monitoring sensors were integrated with the computerized control system in three non-autoclave fabrication techniques: hot-press, self contained tool (self heating and pressurizing) and pressure vessel. The sensors were implemented in the parts and tools.

Introduction

Advanced composites, in general, offer enhanced material stiffness, damage tolerance and environmental durability. There have been considerable advances in the design and utilization of the advanced composites in aircraft and aerospace structures. However, the fabrication processes are still conducted on the conventional basis of monitoring the autoclave or vessel environment without a true in-process closed-loop control system on the individual part. Polymeric composites are typically processed to a predetermined time-temperature-pressure profile for a given resin system. These profiles are varied from material batches or environmental exposures. The processing cycles should be determined by measuring some parameters which are truly indicative of cure or consolidation progression [1,2].

In general, the curing profiles monitored inside the autoclave are different from the temperature and

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pressure actually applied on the parts. The actual amount of heat and pressure seen in the resin matrix is a function of material type and fiber layup. They are critical to the integration and compaction of laminates. Therefore, it is important that the actual pressure applied on the resin matrix during the appropriate thermal processing window be monitored and used to control the fabrication. Thermocouples and pressure transducers are the most popular sensors to perform the data collection and process monitoring. The dielectric response of the thermoset resins has also been used to monitor the progression of composite cure [3]. Some of the commercially available micro-dielectric sensors have unique fixed geometries and integral systems [4]. They can reflect the corresponding viscosity data of resins at various electrical frequencies during a thermal process.

The in-situ data of the heat and pressure transfer between tool and part is essential to a qualitative process control. Placing sensors in parts, tools and equipment will enhance the processing technology. An in-process monitor and closed-loop control system can be developed by integrating the sensors to the computerized control units. Such a system would improve the quality of composite parts and potentially reduce the manufacturing cost.

Development, utilization and interpretation of sensor response is a key element in validating materials and developing a scientific processing database. The sensors must be fast in response, accurate over the processing range and cost-effective in the production environment. In the present work, the newly developed thin foil thermocouple, twin-interferometry pressure transducer and micro-dielectric sensors have been investigated and implemented with computer control systems. A self-contained tool and an integrally heated tool were developed for composite fabrication, which have been demonstrated with non-autoclave processing techniques.

Thermocouples

Most thermocouples are constructed of metallic wires with known characteristics. Production-hardened thermocouples are very rugged sensors and are often the least expensive method of temperature measurement. Due to their low mass, thermocouples generally have very rapid response to changes in temperature. The latest development in thermocouple design has been in the area of the thin foil types, which as made from two standard thermocouple materials. The foils are 0.002 inches thick. Two foil leads were first welded in a serpentine junction pattern, and then laminated with Kapton film to be rugged and easy to handle. As shown in Fig.1, the 6-inch long lead offers the distinct advantage of embedding the thermocouple between composite laminate plys with negligible effect. It provides an effective tool to monitor the temperature profile in the composite part during processing.

Pressure Transducers

There are many different designs to bring pressure to the transducer. The common idea is to make a mechanical measurement of the displacement of a diaphragm. The conventional pressure transducers are designed by using strain gage techniques. A Wheatstone bridge wiring is bonded on or embedded in the metallic diaphragm to measure deflections. With a proper design of the measurement system, the sensors are also able to compensate for thermal effects in the operating range. Some applications require a flush mount of the diaphragm onto the tooling surface and others require a hose connected to a pressure port. For the production environment, ruggedness is a major factor to be considered. The total size of the transducer package may become a driving issue in some applications.

Unlike the conventional design, a twin-interferometry system and the laser-optic readout scheme were developed at Massachusetts Institute of Technology (MIT) under a Lockheed contract [5,6]. This Twin-interferometry system uses two parallel optical fibers normal to the diaphragm. The laser beams are transmitted through the fibers onto the diaphragm surface. By counting the interference fringes caused by the reflected lights from the diaphragm, the magnitude and direction of the diaphragm deflections can be determined. As shown in Fig.2, the prototype includes lasers, couplers, optical fibers, a stainless steel diaphragm and electrical box. This system has been demonstrated and proved in numerous laboratory tests. Several critical technical issues have been identified on these sensors for future development.

Dielectric Sensors Technology

During the cure process, changes of polymeric resin properties are reflected in their dipole alignment and ion movement. By measuring their dielectric values, the degree of reaction and resin viscosity can then be characterized. Dielectric response of polymeric composites has been used to monitor the progression of thermoset composite cure [3,4]. It has contributed significantly toward identification of specific material or process deficiencies. This method produces consistent and reproducible data. The newly developed micro-dielectric sensors by Micromet are rugged and production ready. It is an effective process monitoring technique.

Non-Autoclave Fabrication Techniques

The conventional fabrication method for advanced composites is to utilize an autoclave, which provides the required heat and pressure for curing or consolidation. However, the autoclave process has many technical limitations and high operational cost. The primary problem is that the heat in the autoclave is not uniformly distributed and difficult to predict flow. The uneven cure or consolidation of composite components can happen due to the complexity and varieties of the geometries of parts and tools. In order to maintain uniform heating, additional setup and ducting in the autoclave may be necessary. Thus, the batching task of production parts and the nesting placement in the autoclave becomes very important and time consuming. Besides, it is not feasible in equipment cost and capacity scale-up to keep numerous autoclaves available and adaptable for the changing production requirements and schedules. Alternative non-autoclave fabrication techniques have been developed for such needs and feature improved part quality and reduced manufacturing cost.

In order to achieve a uniform and complete heating on a complex composite part, a self-heated tool should be the most efficient technique. The tool is heated by independent power units at different heating zones, which are designed upon the thicknesses and dimensions of the part. A more advanced tool, such as a self-contained tool, includes additional pressure and cooling systems. The self-contained tools have been developed and implemented for fabricating graphite/epoxy composite parts in earlier programs [7,8]. The parts were cured at 350 ^{o}F under a pressure of 100 psi. Because of the higher temperature (~600 ^{o}F) and pressure (200 psi) necessary to consolidate graphite/PEEK thermoplastic composites, a self-contained tool is not practical. The alternative is to heat the part using a powerful integrally heated tool and pressurizing it inside a pressure vessel. Recently, a composite reinforced ceramic integrally heated tool was developed for the high-temperature thermoplastic composite consolidation [9]. The tool was instrumented with a power control system.

In-Process Closed-Loop Control System

A computerized data acquisition and control system has been developed by Applied Polymer Technology (APT) Inc. Named the Composite Automated Process System (CAPS), it is designed specifically for composite fabrication. CAPS performs an intelligent management of the predefined process parameters: temperature, pressure and vacuum. It will adjust the processing cycle according to the real-time sensor signals. As shown in Fig. 3, each control window should be signaled by the sensors during the process cycle. In other words, the degree of cure or consolidation of the composite part is monitored by a dynamic control system with the sensor placement.

In the present work, the computer was integrated with sensors, microprocessors and power controller to establish an in-process closed-loop control system. All sensing data was recorded by the CAPS 210 computer during the process cycle. CAPS will print a summary throughout the process as well as a quality control data report at the end of each run. The Barber-Colman 560 series microprocessors were set up to control the setpoints using the current proportioning technique, instead of the conventional time proportioning technique. Each setpoint controlled one heating power unit. Thermocouples measured temperatures in the part and at the heaters. Vacuum and pressure were monitored by transducers mounted on the tool or the pressure vessel. An instrumented tool can detect the thermal and mechanical changes of tool and part. Sensor placement consider bag, tool and part positions, which become critical decisions in terms of monitoring.

Demonstrations

Three in-process closed-loop control systems have been developed in this program. The incorporation and placement of sensors in the parts and tooling systems provides an advanced processing technique.

Case 1: Hot press and dielectrometery system

As illustrated in Fig.4, a Tetrahedron hot press was used to fabricate graphite/epoxy (Hercules Magnamite graphite prepreg tape AS4/2220-3) flat panels. The press has a 24 inches by 24 inches platen with a programmable control system. It was integrated with an IBM personal computer, Micromet Eumetric system and the microdielectrometers. The sensors were embedded between laminate plies, as seen in Fig.5. Because of the conductive property of graphite fiber, a piece of glass fabric must be placed on the top of the sensor to prevent a short circuit. A low conductivity integrated circuit dielectric sensor was used for measurement at five different frequencies (1, 10, 100, 1000, 10000 Hz). The curing cycle was to heat from ambient at 5 ^{o}F/minute to 350 ^{o}F and hold for 120 minutes and cool down under 85 psi pressure. A Micromet developed critical point control software was modified and implemented as the monitor/control program.

Case 2: Self-contained tool and twin-interferometry pressure transducer system

A self-contained tool was used for graphite/epoxy (Hercules Magnamite graphite prepreg tape AS4/2220-3) flat panel fabrication. As shown in Fig.6, inside the bolt tightened steel tool, there is an expandable silicon rubber bag, a printed circuit heater, cover caul plates, composite laminates and insulation. A Tayco foil type thermocouple was bonded on the heater for closed-loop control. The heater was connected to a power unit and the Barber-Colman controllers. The MIT developed twin-interferometry pressure transducer and a commercially available Kulite semiconductor sensor were threaded into the tool and flushed with the tooling surface, as seen in Fig.7. The pressurized air bag applied pressure on the cauls and laminates. Both sensors measured the actual applied pressure during the heating process. In Fig.8, the CAPS system was interfaced with a power cart and printed circuit heater. Two Barber-Colman micro-processors were used for setpoint control on the heater. Pressurized air was manually controlled and safe guarded by a regulator.

Case 3: Integrally heated tool and thermocouples in a pressure vessel

Pressure vessel processing, as shown in Fig.9, is a proven low cost, time saving method of forming and consolidating thermoplastic composite parts [9]. This is accomplished through the use of an integrally heated tool that heats the part up to processing temperature within an unheated pressurized vessel that supplies pressure to the part. The pressure vessel described in this work is 11 ft. long and 6 ft. diameter. The vessel is capable of providing 200 psi pressure. As illustrated in Fig.10, the CAPS was interfaced with a power cart and the integrally heated tool. The integrally heated tool was made of graphite reinforced ceramic matrix from Comtool Technology [8]. It displayed low watt density requirements to achieve ramp cycles of less than 30 minutes to 750 ^{o}F. This tool demonstrated improved mechanical properties, reduced specific heat and lowered coefficient of thermal expansion. The pressure vessel is supplied with electrical ports for the tool heaters and zone controllers. It is also equipped with numerous vacuum and thermocouple ports such that part temperatures can be easily monitored and controlled in specific locations of the part. The heating power of the tool was closed-loop controlled by the Barber-Colman microprocessors and CAPS controller. This processing system was demonstrated by fabricating a contoured shape thermoplastic composite (ICI APC-2, AS4/PEEK) part, as shown in Fig.11.

Conclusion

In this program, the following technologies have been investigated:

- Thermocouple, pressure sensor and dielectrometer
- Advanced tooling technology
- Integration of sensors and tooling
- Non-autoclave fabrication techniques
- In-process closed-loop monitor/control systems

The in-process closed-loop monitor/control systems have been demonstrated in three different fabrication techniques. Thermoset or thermoplastic composites were chosen in each demonstration, based upon the manufacturing cost effectiveness. The demonstrated processes require a fraction of the time required with conventional autoclaves and resulted in good quality parts at a lower cost. In the pressure vessel application, because of no elevated temperatures, the plumbing of vacuum ports and thermocouple outlets is simplified for rapid and easy hook-up. The bagging and sealant tapes no longer have the high temperature requirements of the autoclave. Therefore, they are less expensive, easier to work with and require roughly 75% less time to bag a part.

Those accomplishments were conducted only on the concept developmental level. Many details in optimizing and controlling the fabrication cycles still need continued study. The time-temperature-pressure processing profile should be controlled on a logical basis [10]. The goals are to esablish consistent part quality and reduce the manufacturing cost.

References

1. Campbell, F., Mallow, A., Muncaster, F., Boman, B. and Blase, G., "Computer - Aided Curing of Composites", AFWAL-TR-86-4060, McDonnell Aircraft Company, St. Louis, MO, July, 1986.
2. Stone, R., "Manufacturing Science of Complex Shape Thermoplastics", Air Force Contract No. F33615-86-C- 5008, Lockheed Aeronautical Systems Company, Burbank, CA, 1990.
3. Bromberg, M.L., Day, D.R., Lee, H.L. and Russell, K.A., “New Applications for Dielectric Cure Control,” Proc. of the 42nd Annual Conf. Composites Institute, SPI, Feb. 2 - 6, 1987, Sec.22 - E, pp.1 - 5.
4. Leonard, L.,”Microdielectrometry: Tiny Sensors Close The Cure Control Loop,” Advanced Composites, January/February, 1987, pp.49-52.
5. Young, A.M., Goldsburry, J.E., Haritonidis, J.H., Smith, R.I. and Senturia, S.D., "A Twin-Interferometer Fiber-Optic Readout for Diaphragm Pressure Transducers", presented in the IEEE Workshop on Solid-State Sensors, Hilton Head, SC, June, 1988.
6. Young, A.M., "A Twin-Interferometer Fiber-Optic Readout for Diaphragm Pressure Transducers", M.S. thesis, Elec.Eng'g and Computer Sci. Dept., M.I.T., Cambridge, MA, Jan.1989.
7. Wirz-Safranek, D.L., "Curing Composite Materials Using Self-Contained Tools," Proc. of the 31st International SAMPE Symposium, Anaheim, CA, April 7-10, 1986, pp.491-500.
8. Wirz-Safranek, D.L., "Implementation of Automated In-Process Control System for Fiber Reinforced Composite Part Production," Report No. CMRI-2142, Manufacturing Research Dept., Lockheed Aeronautical Systems Co., Burbank, CA, Jan.31, 1987.
9. Woolum, D., "Integrally Heated High-Temperature Tooling", No. TE88-213, presented in SME Conference "Tooling for Composites '88", Los Angeles, CA, May 10-11, 1988.
10. Abrams, F., Garrett, P., Lagnese, T., LeClair, S., Lee, C. and Park, J., "Qualitative Process Automation (QPA) for Autoclave Curing of Composites", AFWAL-TR-87-4083, AFWAL Materials Laboratory, Wright-Patterson AFB, OH, Nov., 1987.

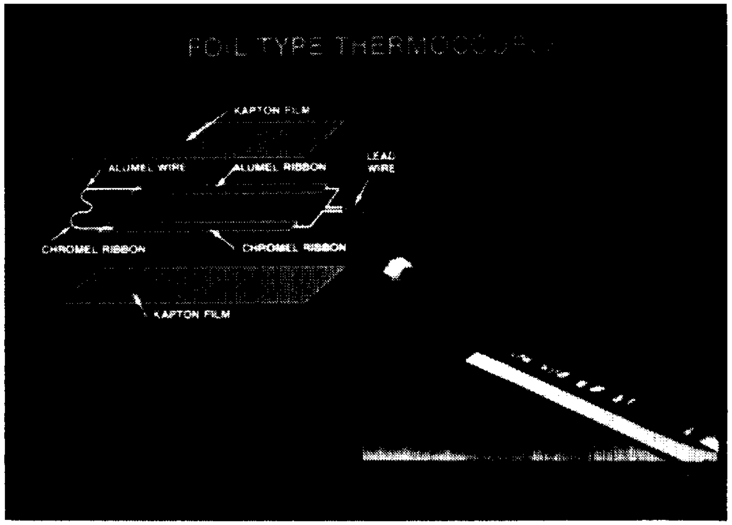

Fig. 1 Thin Foil Type Thermocouple

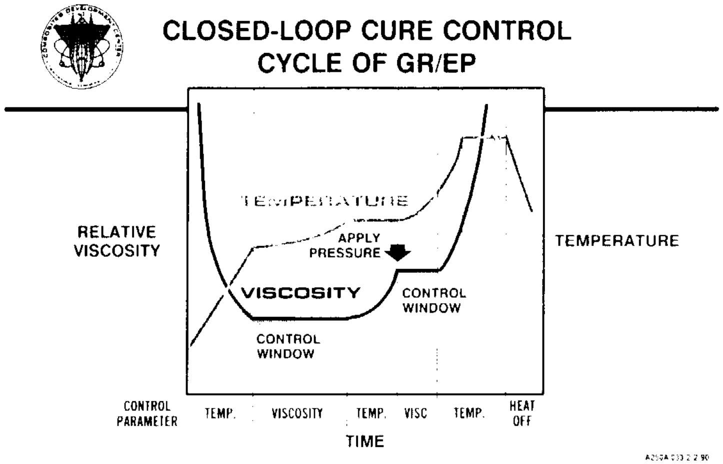

Fig.3 Closed-Loop Cure Control Cycle of Graphite/Epoxy Composites

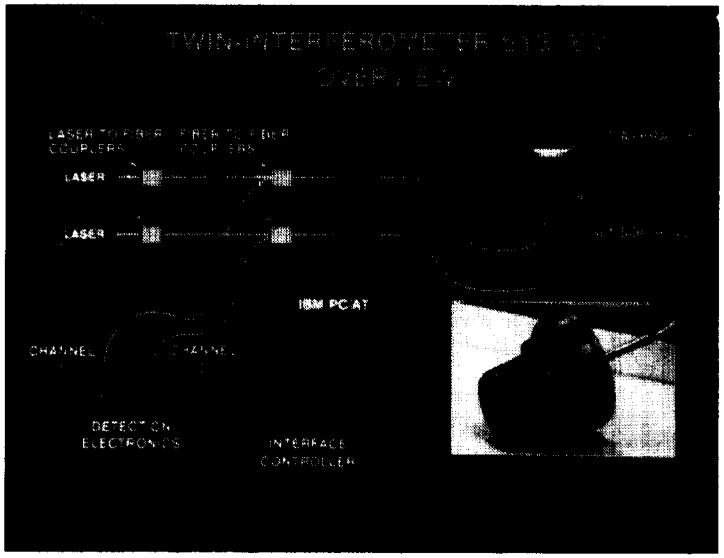

Fig. 2 Twin-Interferomery System Overview

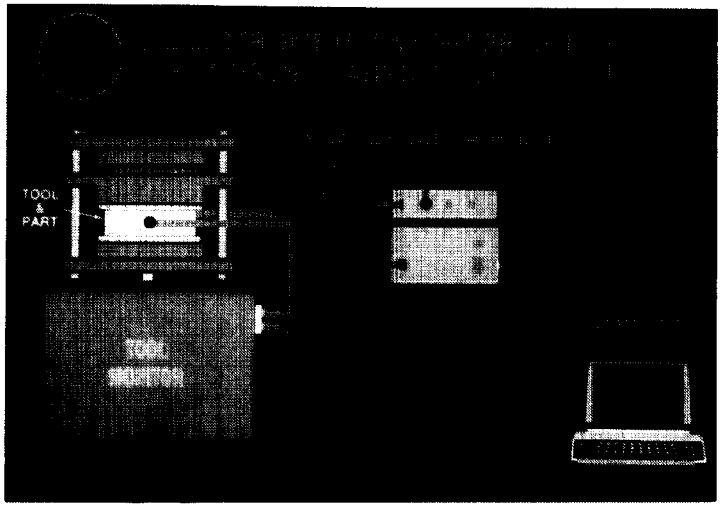

Fig. 4 Dielectrometry Monitor/Control Hot Press Fabrication System

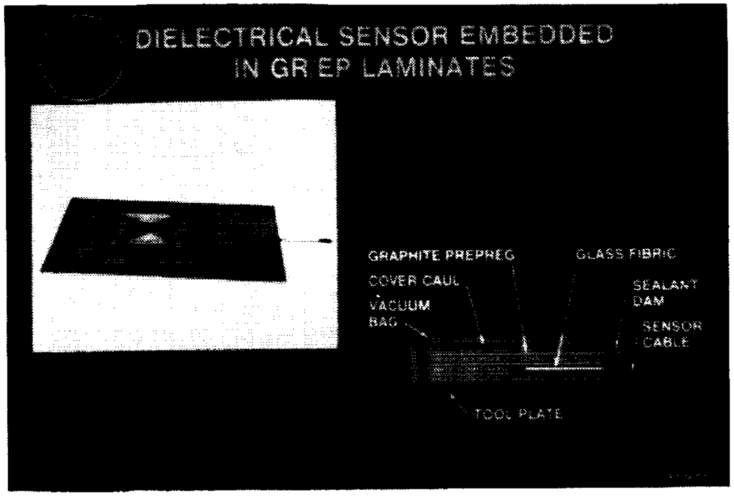

Fig. 5 Dielectrical Sensor Embedded in Graphite/Epoxy Laminates

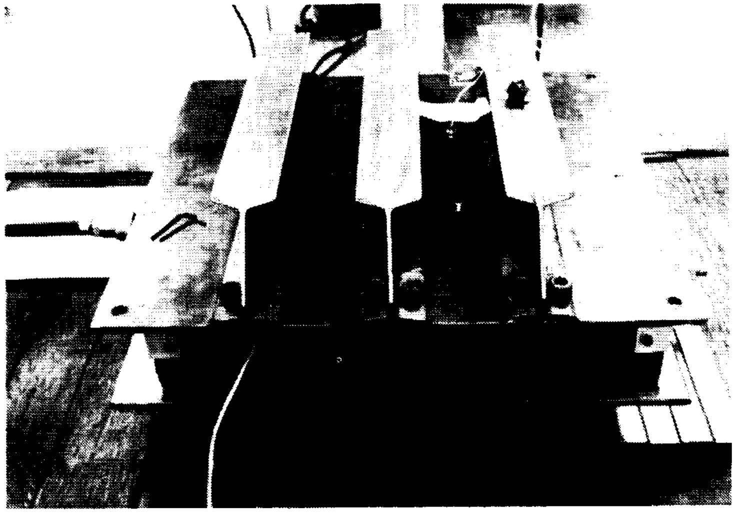

Fig. 7 Pressure Transducers and Self-Contained Tool

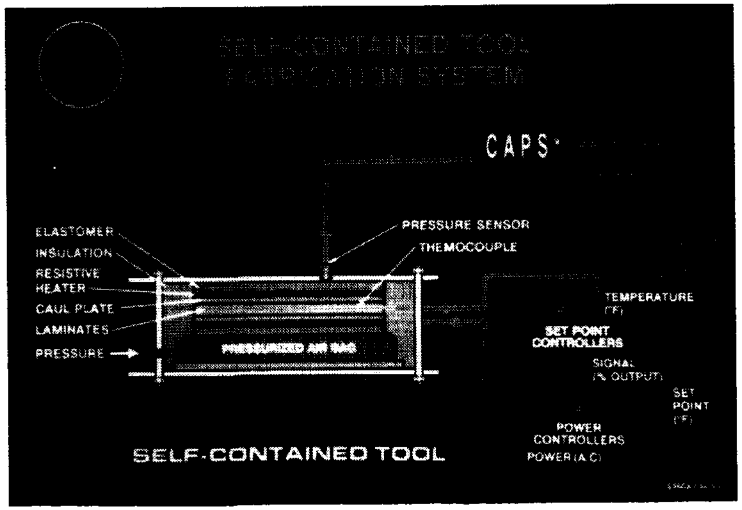

Fig. 6 Self-contained Tool Fabrication System

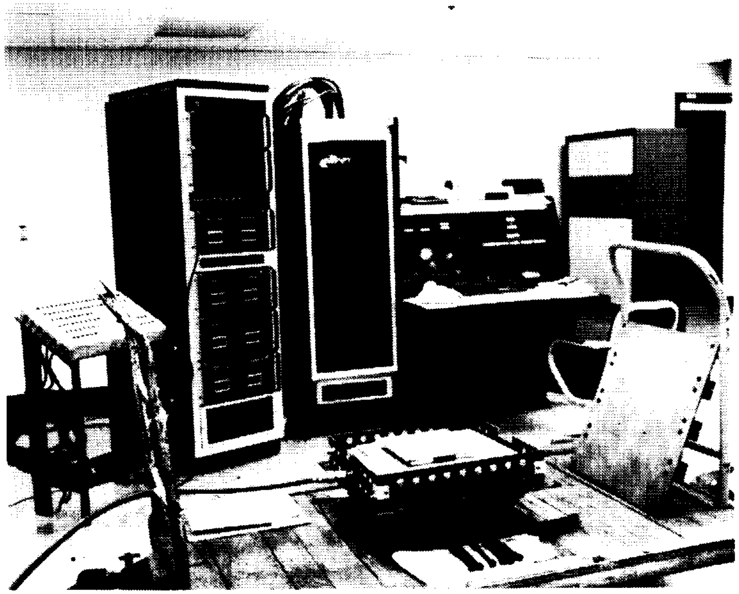

Fig. 8 CAPS, Power Unit, Sensors and Self-Contained Tool

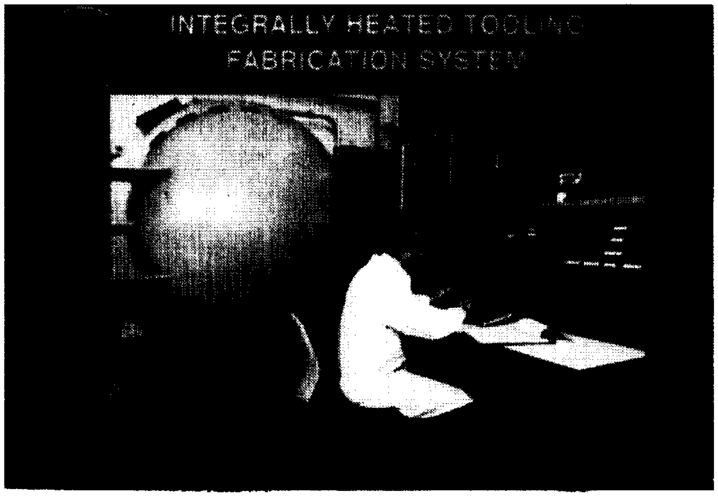

Fig.9 Computer Controlled Pressure Vessel Fabrication

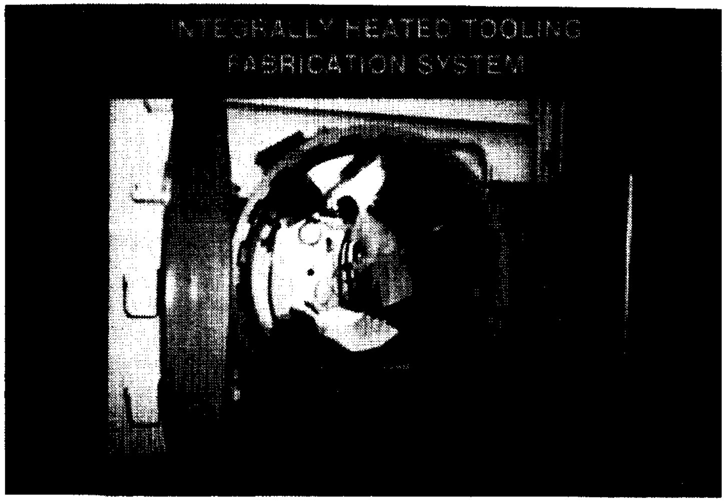

Fig. 11 Integrally Heated Tool and Pressure Vessel Fabrication System

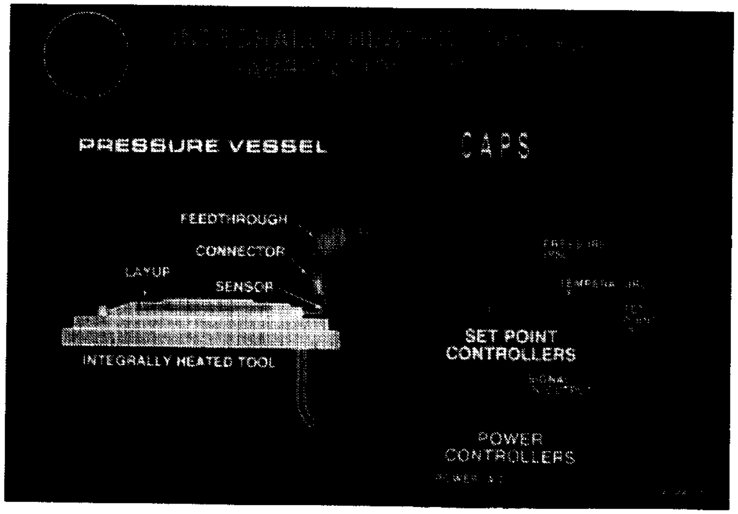

Fig. 10 Integrally Heated Tool and Pressure Vessel Fabrication System