

Autoclave Cure Systems

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AN AUTOCLAVE SYSTEM allows a complex chemical reaction to occur inside a pressure vessel according to a specified schedule in order to process a variety of materials. The evolution of materials and processes has taken autoclave operating conditions from 120 °C (250 °F) and 275 kPa (40 psi) to well over 760 °C (1400 °F) and 69 000 kPa (10 000 psi). The materials processed in autoclaves range from metal bonding adhesives; reinforced epoxy laminates; thermoplastic laminates; metal, ceramic, and carbon matrix materials; to many other aerospace and electronic components. Although the autoclave system is tailored to specific process requirements, the basic design and subsystems described here are standard for most autoclaves. Shown in Fig. 1 is an 8-m (25-ft) diam by 18-m (60-ft) long autoclave system, one of the world's largest in diameter.

The major elements of an autoclave system (and their functions) are: a vessel to contain pressure, sources to heat the gas stream and circulate it uniformly within the vessel, a subsystem to pressurize the gas stream, a subsystem to apply vacuum to parts covered by a vacuum bag, a subsystem to control operating parameters, and a subsystem to load the molds into the autoclave.

Pressure Vessel

The pressure vessel shell provides the means to retain pressure inside the work space. The pressure vessel typically is fabricated from pressure vessel quality carbon steel. Plates up to 150 mm (6 in.) thick are rolled to shape and joined by arc welding. The dome-shaped heads or ends are fabricated from similar material and either press-formed or spun.

The most critical portion of the vessel is the closure, or breech lock, which is fabricated from three distinct rings fitted with lugs. One ring is welded to the vessel, one is welded to the door, and one rotates. When the door is closed, the locking ring is rotated, and the lugs of the closure engage with the lugs of the head. There are also matched wedges on the lugs to clamp the door surfaces against the seal area. A silicone or fluorocarbon rubber material is normally used in this area to allow good sealing without requiring metal-to-metal contact at the door face. The door is usually hinged or carried

to one side by a crane. All hinge structures should be adjustable in all directions of motion to allow realignment, as needed.

It is mandatory to design and fabricate all pressure vessels to American Society of Mechanical Engineers (ASME) requirements. These include material specifications and design stress levels allowable in the vessel, but do not cover any other mechanisms or subsystems within the autoclave. If ASME requirements are met, the vessel will be so stamped after hydrostatic testing. National Board Registration is strongly suggested for future traceability, and is mandatory in some states.

The autoclave owner must have an ASME-approved organization modify or maintain the pressure vessel; any improperly made modification or repair may compromise the integrity of the vessel and subsequent safety. All autoclave vessels and closures should be inspected annually by a recognized inspection agency. Normally, this will reveal any potentially dangerous situations. If properly maintained and inspected, the life of a pressure vessel should exceed 50 years.

Internal Structure. The vessel, upon completion and subsequent testing, is prepared for installation of the internal structure, which provides insulation, duct work, and support for all components to be mounted in the autoclave.

The insulation is used to reduce energy costs by preventing heat transfer to the vessel. It is typically a ceramic wool material, in sheet or blanket form, attached to the vessel with pins. The insulation should not rely on internal duct work for support nor should it be in direct contact with the autoclave atmosphere. The insulation is covered with sheet metal, normally 16- and 18-gage aluminized steel or stainless steel, which is attached in such a way as to allow thermal expansion and protect the insulation from the gas stream in the autoclave.

The internal insulation is very important to the prevention of excessive shell temperature and energy loss. The maximum shell temperature on the autoclave surface should not exceed 60 °C (140 °F) at maximum operating temperature, and external insulation should never be required on a modern autoclave.

The annular duct is attached after insulation, providing a channel for the gas to be circulated

in the autoclave. Care must be used in the design to allow for thermal expansion. Because the vessel shell does not get hot, the differential expansion between the interior and exterior may exceed 75 mm (3 in.) on large, high-temperature autoclaves. Provisions for tracks for carts to bring the molds into the autoclave and for structural attachments for internal systems are made at this time.

Gas Stream Heating and Circulation Sources

Currently, several heating methods are available for autoclave systems. The most common method for large autoclaves is indirect gas firing, in which products of combustion from an external chamber are passed through an internal, stainless alloy coil. This system is reliable and, if properly engineered, can be controlled to allow thermal cycling. The materials selected and the design technique must be adequate for the service temperatures and thermal cycling. The gas-fired systems provide substantial operating savings over electrical systems when direct energy and demand charges are considered. Gas heating is regularly used in autoclaves with maximum operating temperatures of 450 to 540 °C (850 to 1000 °F).

In the past, hot oil was used as a heating medium in gas-fired systems in which the oil was circulated from an external heater to an internal coil. These systems are now nearly obsolete because of the potential for contami-

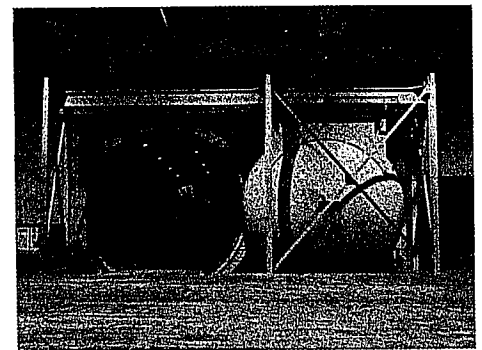


Fig. 1 Autoclave system. Courtesy of Beech Aircraft

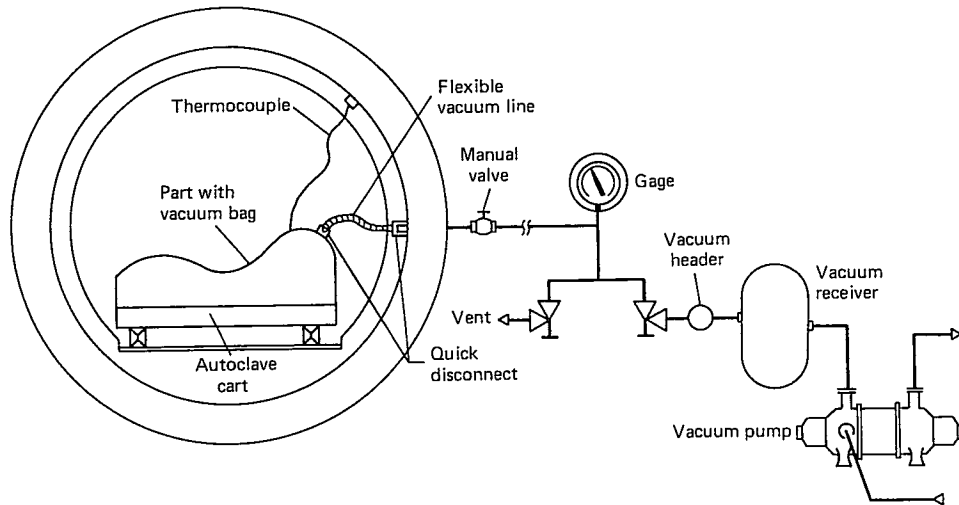


Fig. 2 Conventional vacuum system

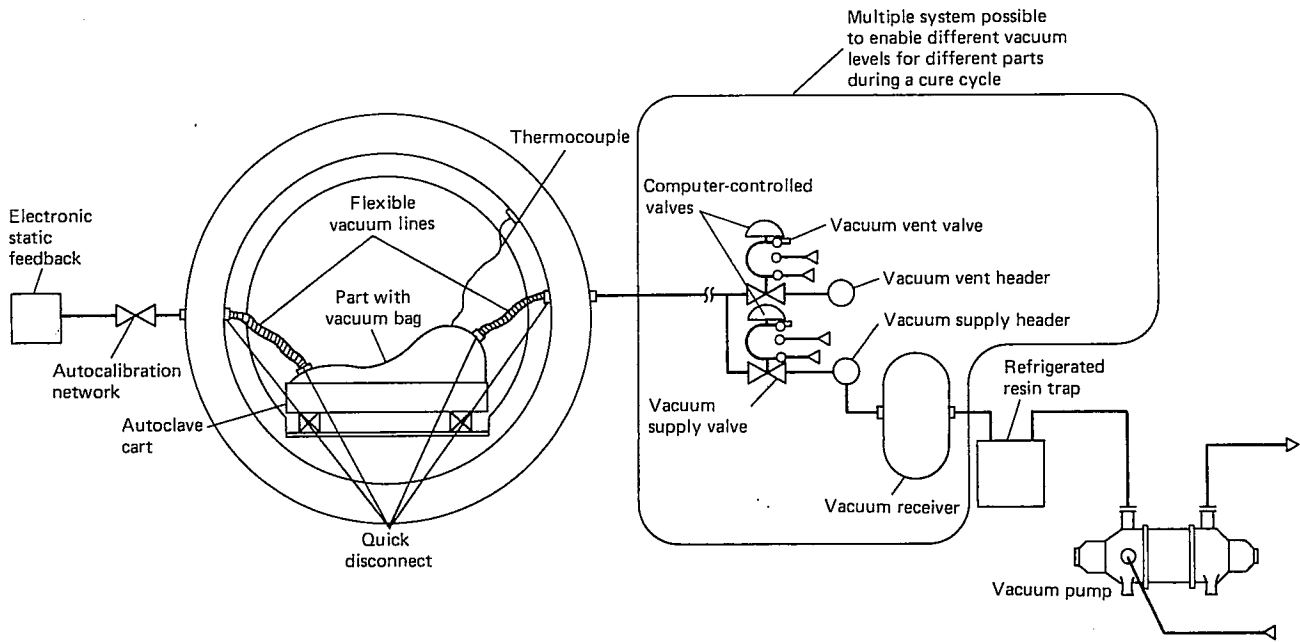


Fig. 3 Advanced vacuum system

nation of the bonding area by PCB, MCB, or silicone-based oils. Area contamination can be disastrous to materials in process. All available heat-transfer oils are combustible and have a maximum operating bulk temperature of 425 °C (800 °F) for silicones and 400 °C (750 °F) for phenyl-based fluids. The potential for fire is significant, and appropriate safeguards must be provided.

Steam heating is often used for autoclaves operating in the 150 to 175 °C (300 to 350 °F) range. The superheated steam is passed through a coil in the autoclave to heat circulating gas. Few steam-heated autoclaves are currently manufactured for composite bonding because of their low operating temperatures.

Most small autoclaves (under 2 m, or 6 ft in diameter) are electrically heated. Electric heating elements are mounted in the circulating gas stream and configured not to radiate onto the workload in the autoclave. Heater elements are made either from open nichrome wire or alloy tubes. Heaters can be either contactor (on-off controlled) or SCR controlled. The major drawback of electrically heating the autoclave is the operating and demand costs, which can be prohibitive for large autoclave systems.

Gas circulation within the autoclave is essential to provide mass flow for temperature uniformity and heat transfer to the part load. This is accomplished with a blower mounted in

the rear of the autoclave. The gas is drawn into the blower through the cooling coil and heater, then returned down the length of the autoclave through the annular duct to the door, where it is then directed through the work space. In the modern autoclave system, the fan motor is mounted in a pressurized housing at the rear. This eliminates the need for pressure seals and external bearings, which have caused maintenance and reliability problems on external motors.

The air circulation should be from 1 to 3 m/s (250 to 500 ft/min) in the work space. Circulation any higher than 3 m/s (500 ft/min) may cause problems with the vacuum bags over the parts if they are not properly attached. Vari-

able-speed fan systems are available for improved part heating performance.

Gas Stream Pressurizing Systems

Three pressurization gases are typically used for autoclaves: air, nitrogen, and carbon dioxide. Gases are introduced into the vessel through solenoids or proportional control valves, the latter being far superior. Proportional inlet and vent valves allow autoclave pressures to be controlled and varied precisely. It is important that this very hot gas being introduced into the pressure vessel not impinge on the part load, as the gas stream could cause part damage due to thermal or mechanical shock. The vessel is vented through similar valves, by means of a silencer to the atmosphere.

Air is relatively inexpensive when supplied in the 690 to 1030 kPa (100 to 150 psi) range, and is acceptable for most 120 °C (250 °F) cures. The main disadvantage of air is that it sustains combustion, and thus may be hazardous at temperatures above 150 °C (300 °F). Nitrogen is the gas most commonly used in autoclaves. The liquid nitrogen is stored in cryogenic form and then vaporized at approximately 1400 to 1550 kPa (200 to 225 psi). Higher pressure tanks and systems are available. Nitrogen suppresses combustion and diffuses well into the air when the autoclave is opened. However, nitrogen costs can be significant if many autoclaves in a plant are using nitrogen and if the autoclaves are large and operating at high pressure. Carbon dioxide is the second most commonly used gas. It is stored as refrigerated liquid at approximately 2050 kPa (300 psi). Its primary disadvantages are high density, hazards to personnel, and physical flow related problems. When using any nonlife-sustaining gas, care should be taken not to enter any vessel without ensuring that adequate oxygen is present.

Vacuum Systems

A very important subsystem is the part vacuum supply. Most parts processed in autoclaves are covered with a vacuum bag, which is used primarily for compaction of laminates (hydrostatic pressure will not compact) and to provide vacuum for removal of volatiles. The bag allows the part to be subjected to differential pressure in the autoclave without being directly exposed to the autoclave atmosphere. The vacuum bag is also used to apply varying levels of vacuum to the part.

New production methods have brought increasing complexity to autoclave vacuum systems. Originally the vacuum systems consisted of a three-way valve which allowed application of vacuum to the part bag or venting of the bag to the atmosphere after pressure application. A gage read the supply, which was nonvariable. This proved to be adequate for simple laminates

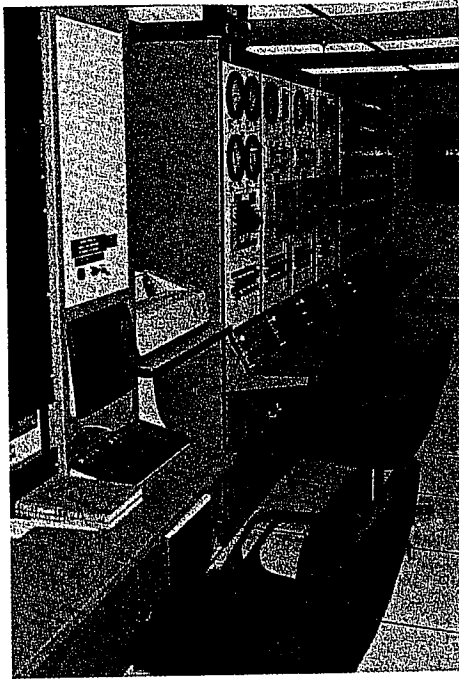


Fig. 4 Computer-controlled autoclave system console. Courtesy of Naval Air Rework Facility, San Diego

and metal bonding, but as the resin systems became more sensitive and quality control became more stringent, advanced vacuum systems were developed (see Fig. 2 and 3).

The purpose of these systems is to provide fully computer-controlled manipulation and monitoring of part pressure, not just supply pressure. The ability to provide pressure on the part under the bag by means of vacuum has reduced void content by keeping the dissolved volatiles and water in solution in the resin system itself. This capability is being included in newer systems.

The modern vacuum system can manipulate vacuum levels from the two independently modulated supply headers to the parts. The transfers between controllable vacuum supply levels are computer-controlled as functions of the autoclave pressure or part temperature. These systems are essential in processing advanced high-temperature resin systems.

Vacuum pumps should, as a rule, be located approximately 0.00045 m³/s (1 ft³/min) for every 0.23 m² (2.5 ft²) of bag area. The water-seal-type pumps have proved to be the most reliable, as they are not damaged by volatile by-products of the curing reaction, unlike oil-flooded pumps. Refrigerated or water-cooled condensing systems are installed on many systems to trap toxic volatiles produced by some resin systems.

Control Systems

Recent developments in computer technology have greatly increased the ability to monitor and control cure cycles. Progress in the past

5 years rivals that in the preceding 20 years. The objectives have been to increase the reproducibility of repetitive cycles, improve throughput by optimizing process parameters, and reduce labor costs associated with manual control. Currently, microprocessor-based autoclave controls are being replaced in favor of interactive computer systems. A computer-controlled autoclave console is shown in Fig. 4.

The cure cycle is controlled by feedback from thermocouples, transducers, and advanced dielectric and ultrasonic sensors. The software is growing in complexity, with features varying between suppliers of computer systems. When selecting a computer-controlled system, process engineers and users should test it to determine its appropriateness for the application. Computer-controlled systems should always be installed with backup conventional microprocessor controllers to serve as a fail-safe means in case of computer failure.

When a computer system is being considered for existing equipment, the user should realize that a new computer does not solve existing mechanical and electrical problems in an autoclave system. Existing system problems should be remedied before computerization.

Loading Systems

Loading systems are probably the most perplexing aspect of production confronting the autoclave user. Because of the circular configuration of the vessel and the relatively small size of the components, carts must be designed to distribute parts horizontally and vertically in the autoclave. Other considerations are:

- The loaded parts should be accessible to enable repair of bag leaks
- All vacuum source and vacuum sensor lines must be connected to the part when loaded on the cart, and vacuum must be maintained as the parts are introduced into the autoclave
- The cart must be easily rolled or transported into the autoclave

Designing a cart system to meet all the desired criteria is a challenge. The essential loading-system requirements must be determined, because including one feature will often preclude the inclusion of another. Typically, carts of various configurations are used, based on mold size and shape.

Modified Autoclaves for Specialized Applications

The development of thermoplastic matrix composites has necessitated the design of specialized equipment for use within autoclaves to form thermoplastic materials. This need has been met with retrofittable processing fixtures that enable the processing of high-temperature materials in existing low-temperature autoclaves. Often, electrically heated molds are

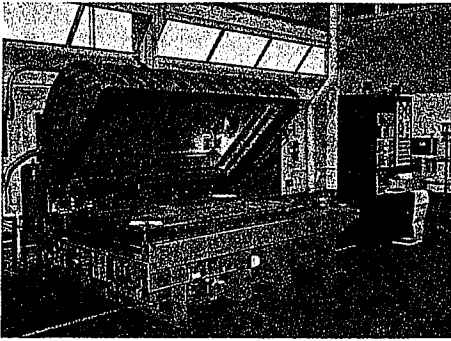


Fig. 5 Vacuum pressure chamber. Courtesy of Naval Air Rework Facility, San Diego

used. Autoclaves should be manufactured to incorporate design features that make transitions to new materials relatively simple.

The polyimides and related resin matrix systems have created a new set of problems in the design of autoclave systems. Primarily, the vacuum control systems have had to be reengineered to accept the large amount of volatiles (resin solvent) released during cure. Also, additional computer interaction is required to process these materials properly.

Metal matrix composites have been in service for many years and require systems operating from 480 to 700 °C (900 to 1300 °F) at 6900 to 69 000 kPa (1000 to 10 000 psi) to

diffusion-bond the matrix into a homogeneous mass. Because of the high-pressure requirement, autoclave systems for curing these composites are usually smaller than others.

Modified autoclaves are currently being used for processing carbon-carbon composites, both for impregnation and carbonization. These complex autoclaves operate at temperatures up to 815 °C (1500 °F).

Phenolic parts have been processed as exit cones and throats for rocket motors in hydroclaves for many years. A hydroclave is similar to an autoclave, except that it is water flooded and pressurized. Hydroclaves are typically run at 6900 kPa (1000 psi) and 150 to 175 °C (300 to 350 °F).

The vacuum pressure chamber (Fig. 5) is a dedicated flexible process center designed for field repair and remanufacturing of composite parts. Future advances will necessitate more dedicated equipment that is directed to specific applications, yet functionally similar to the autoclave. These machines will take the form of bladder presses, versatile process centers, and cavity presses, among others.

Safety and Installation

It is usually standard to have redundant safety features on any autoclave because of the potential seriousness of any malfunction. Overpressure conditions are usually prevented by

three different methods: a separate overpressure sensor and shutdown control, rupture disks designed to rupture at pressures above the operating pressure of the autoclave, and pop-off safety valves with the same function. A standard production autoclave has all three. Vessels are usually proof tested to high margins of safety, but the danger posed by the possibility of a burst vessel cannot be overemphasized.

Overtemperature protection is not as critical an issue from an injury standpoint, but overtemperature conditions could damage the interior systems of the autoclave; therefore, overtemperature controls are usually provided. The vessel shell, because of the internal insulation, may not be rated to the maximum operating temperature of the autoclave. As previously noted, the external surface of the autoclave should not exceed 60 °C (140 °F), except at penetrations.

Installation is also an important consideration. Even small autoclaves are not designed to just plug in and run. It is important to consider site preparation before or during design of the system. Important considerations include foundation, cooling water supply, electrical supply, gas (if used for heating), and pressurization medium supply and exhaust arrangements. Even though installation may be provided by the manufacturer (and this is quite valuable), careful site preparation by the user can prevent many future problems.