AEROSPACE RECOMMENDED PRACTICE	ARP5144™	REV. A
	Issued 2000-03 Revised 2017-04 Reaffirmed 2023-08 Superseding ARP5144	

(R) Heat Application for Thermosetting Resin Curing

RATIONALE

Referenced heating methods and procedures were amended to reflect current technology. Thermal profile and mapping procedures were added. Multiple technical clarifications and figure updates/additions were also included.

ARP5144A has been reaffirmed to comply with the SAE Five-Year Review policy.

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) describes standard methods of heat application to cure thermosetting resins for commercial aircraft composite repairs.

The methods described in this document shall only be used when specified in an approved repair document or with the agreement of the Original Equipment Manufacturer (OEM) or regulatory authority.

1.1 Purpose

The purpose of this document is to provide a number of standard heat application methods that may be referenced in repair documents produced by airlines or airframe and engine manufacturers.

This document is one of several in support of other procedures required to perform composite repairs, intended for use throughout the commercial aircraft industry. These include AIR4844, AIR4938, AIR5278, ARP4916, ARP4991 and others incorporated herein.

2. APPLICABLE DOCUMENTS

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AMS2750 Pyrometry

AIR4844 Composites and Metal Bonding Glossary

ARP4916 Masking and Cleaning of Epoxy and Polyester Matrix Thermosetting Composite Materials

AIR4938 Composite and Bonded Structure Technician/Specialist: Training Document

ARP4977 Drying of Thermosetting Composite Materials

ARP4991 Core Restoration of Thermosetting Composite Components

ARP5143 Vacuum Bagging of Thermosetting Composite Repairs

AIR5278 Composite and Bonded Structure Engineers: Training Document

AIR5367 Machining of Composite Materials, Components and Structures

AIR5431 Repair Tooling

2.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM D2471 Gel Time and Peak Exothermic Temperature of Reacting Thermosetting Resins

ASTM E220 Calibration of Thermocouples by Comparison Techniques

ASTM E230 Temperature - Electromotive Force (EMF) Tables for Standardized Thermocouples

ASTM Manual Series MNL12-Manual on The Use of Thermocouples in Temperature Measurement

2.3 IEC Publications

Available from International Electrotechnical Commission, 3, rue de Varembe, P.O. Box 131, 1211 Geneva 20, Switzerland, Tel: +44-22-919-02-11, www.iec.ch.

IEC 60584-1 Thermocouples Part 1: EMF specifications and tolerances

2.4 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

Original Equipment Manufacturers (OEM) Manuals

3. GENERAL

a. Heat application to thermosetting resins accelerates the curing process and must be applied in accordance with the manufacturer's instructions and the repair design.

b. Several heating devices such as heat blankets, hot air generators, heating lamps, ovens and autoclaves are available for repairs.

c. The choice of heating devices for the curing of a repair depends on the pressure required, equipment available, the geometry of the component, the restrictions of the repair environment, and the required cure accuracy.

d. Composite repairs requiring elevated temperature curing need to be controlled, in accordance with the cure schedule. This will ensure that proper thermal conditions needed to cure and bond materials are obtained. See 8.1 and 8.2 for requirements on recording of cure data.

e. Throughout this document rounding up or down of values has been performed when converting units of measurement. In instances where it would not be appropriate to do this, then a precise conversion is applied.

   Examples:

   212 °F (100 °C) i.e., exact conversion used

   250 °F (120 °C) rounded up from 248 °F

   350 °F (180 °C) rounded down from 356 °F

   12 inch (300 mm) rounded up from 11.8 inch

f. To avoid risk of electric shock, electrical equipment must be handled in accordance with manufacturer instructions. Inspect electrical equipment and power cords for damage before each use. Refer to local electrical codes when using equipment to ensure compliance.

g. The possibility of fire and/or serious damage to the aircraft structure may result from improperly placing thermocouples in relation to the location of the electrical heating device.

4. CURING CYCLE

4.1 Definition

Curing of thermosetting resins is by chemical reaction. For some resin systems the curing may take place at 68 to 79 °F (20 to 26 °C) over a time span of between 8 hours to 7 days depending on the resin. The curing process for these room temperature curing systems can be accelerated by the application of heat, typically 100 to 180 °F (40 to 80 °C). This reduces the curing time which has obvious commercial advantages and improves mechanical and chemical properties. The actual temperature used will be governed by the specific resin chosen. Curing for these systems should not be attempted below 68 °F (20 °C) because of the risk of undercure. It should be noted that once mixed, resins will continue to cure even below 68 °F (20 °C).

Other resin systems will not cure satisfactorily at room temperature but require elevated temperature, typically 200 °F (93 °C), 250 °F (120 °C), or 350 °F (180 °C) to achieve full cure.

During the curing process, compaction is necessary, in order to reduce the porosity level and facilitate vertical bleeding when required. Refer to ARP5143.

The major process parameters which define a repair cure cycle are:

a. Temperature

b. Pressure

c. Time

These process parameters, particularly time/temperature cycles, are defined during resin qualification. They shall be applied within stated tolerances.

Depending on the resin and/or the repair instructions, stepped curing may be necessary. In this procedure curing takes place in a series of steps where the temperature is held at a defined value for a specified time and then raised to a higher value for a further period of time, until the final cure temperature is achieved.

4.2 Curing Profile

Typical curing cycles involve three major phases:

a. Heating Phase: Heat-up at the defined rate to the required curing temperature.

b. Curing Phase (Dwell or Hold Phase): Stabilized temperature period for minimum time to achieve the required cure.

c. Cooling Phase: Cool down at the defined rate.

Each phase of the curing cycle must stay within defined temperature and time tolerances to obtain uniform curing.

The resin cure cycle is stated in the repair instructions.

4.2.1 Heating Phase

The heat-up rate is generally defined in degrees/minute with maximum and minimum values. A fast heat-up rate is desirable to reduce processing times which from a repair standpoint is a benefit if rapid turnaround times are needed. But it shall be slow enough so that gross temperature differences do not cause uneven curing, and related part warpage.

Typical heat-up rates for epoxy curing are 1 to 8 °F (0.5 to 4.5 °C) per minute. Refer to the repair document for specific heat-up rates. Parts with large or complex thermal mass will require a slower heat–up rate. See 5.1 and 6.6 for further explanation of thermally complex parts.

The resin behavior will determine the maximum heat-up rate, to take into consideration the following points:

a. Exothermic Reaction: An exothermic chemical reaction is one in which heat is generated during the reaction. The heat can be considerable and must be contained within acceptable limits.

b. Resin Viscosity Changes: In the early stages of cure the resin reaches a low viscosity. During this period, it can wet the surfaces to be bonded, will fully wet out the fibers, and flow into crevices or surface variations. As the curing process takes place, cross linking of the resin will occur. At the gel point, the resin changes from a fluid to a solid state. On completion of curing, the material is a hard solid.

c. Volatile Extraction: This is an important phase in the cure cycle. It is essential to vent/extract volatiles, which are a by-product of the chemical reaction, or an unacceptable porous structure could result.

d. Gelation: This is an important stage in the cure of the resin. It is the point in a resin cure when the viscosity has increased to a point such that it barely moves when probed with a sharp instrument. At this stage, the cure is well advanced.

The minimum heating rate is defined to avoid excess bleeding before gelation.

To avoid over-heating the repair, close monitoring is necessary. Consideration should be given to reducing the heat-up rate as the temperature of the part nears the cure (hold) temperature. This will assist in preventing overshoot of the cure temperature.

Equipment capability and heat sinks are factors that can affect the heat-up rate, resulting in thermal gradients across the repair. To determine whether thermal gradients may occur, a thermal map should be conducted prior to curing the repair (see 9.1).

4.2.2 Curing Phase (Dwell or Hold Phase)

Measurement of cure time (curing phase) commences when all repair thermocouples are within the required temperature band. During the cure phase all thermocouples shall remain within this temperature band. It is important to bring the temperature within this band as quickly as is practical. Consideration may have to be given to scrapping the repair if this cannot be achieved within an acceptable time. An alternative repair route may then have to be considered.

The cure time (hold time) is stated in the repair instruction.

It may be necessary to extend the curing phase due to “lag time” as determined during pre repair thermal mapping (see 9.1).

4.2.3 Cooling Phase

Cooling may start when the curing phase (dwell or hold) is complete. The cooling rate is stated in the repair instructions.

High cooling rates should be avoided because they increase the thermal gradient and may induce transverse micro-cracking in the repair.

Typical maximum cooling rates for epoxy curing are 3 to 8 °F (2 to 4.5 °C) per minute. Refer to the repair document for specific maximum cooling rates. Parts with large or complex thermal mass will require a slower cooling rate. See 5.1 and 6.6 for further explanation of thermally complex parts.

4.3 Examples of Curing Cycles

4.3.1 Cure Cycle

In this example (see Figure 1) heat and vacuum are applied simultaneously. Temperature is increased during the heat-up phase (ramp), then temperature is held during the curing phase (hold or dwell). During the cooling phase the temperature is decreased to a level which allows release of vacuum, safe handling, and avoids microcracking.

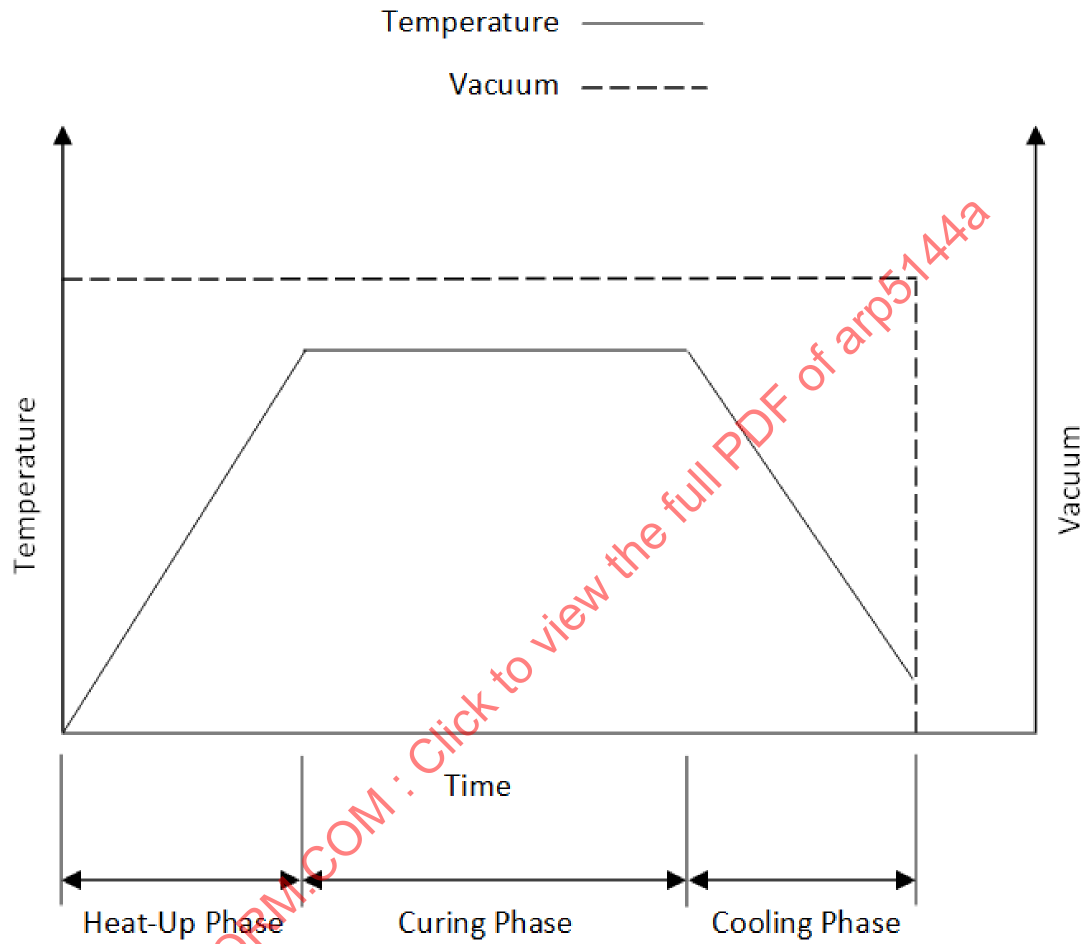


Figure 1 - Cure cycle

4.3.2 Step Cure Cycle

In this example (see Figure 2) heat and vacuum are applied simultaneously. Temperature is increased during the heat-up phase (ramp), then temperature is held during the hold phase (intermediate hold or dwell). The primary purpose of the hold phase is to prevent excess resin flow during heat-up phase. The duration of the step is timed to allow resin gelation to occur. The hold phase can also help avoid exothermic reactions. Temperature is again increased during the heat-up phase (ramp), then temperature is held during the curing phase (hold or dwell). During the cooling phase the temperature is decreased to a level which allows release of vacuum, safe handling, and avoids microcracking.

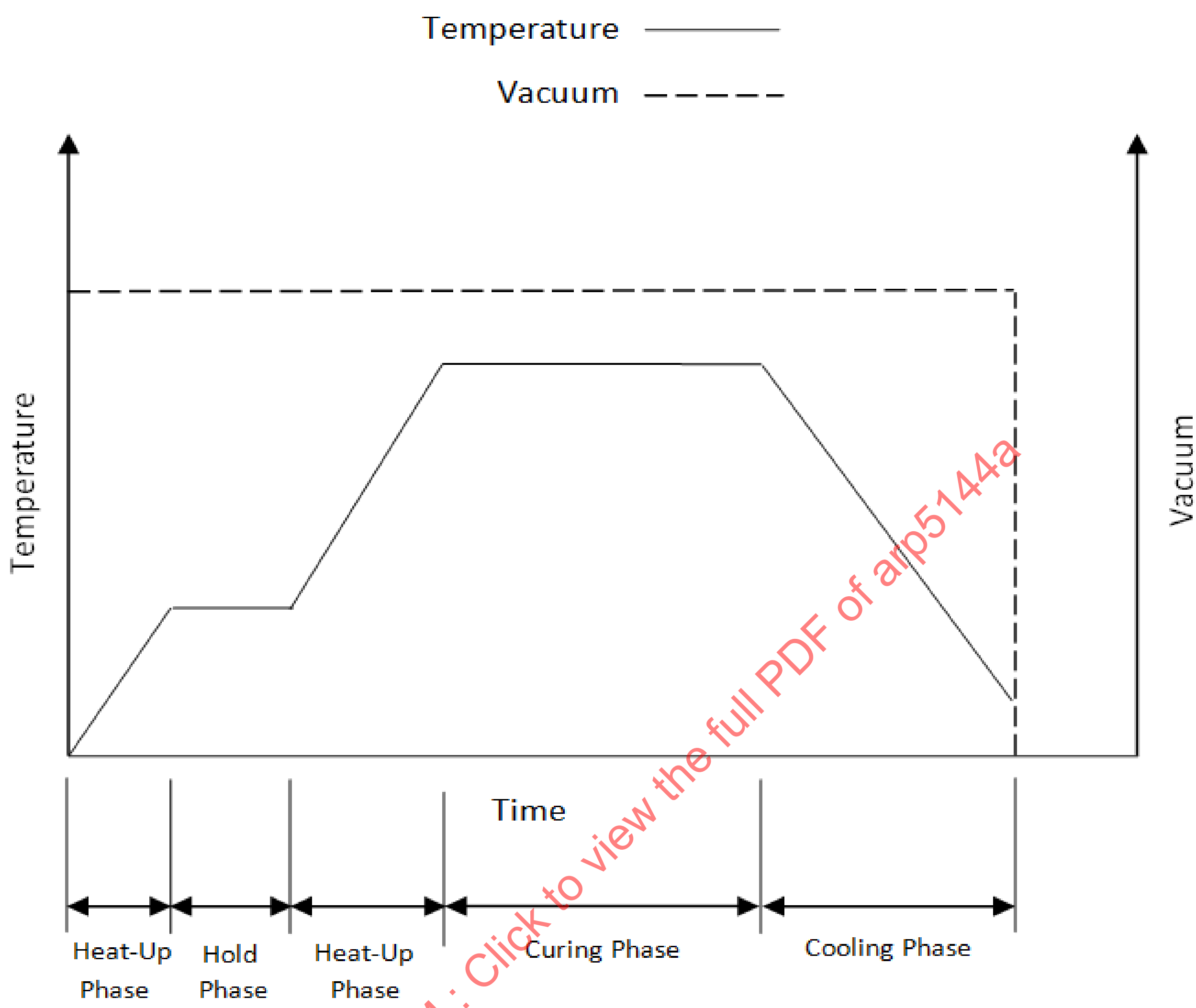
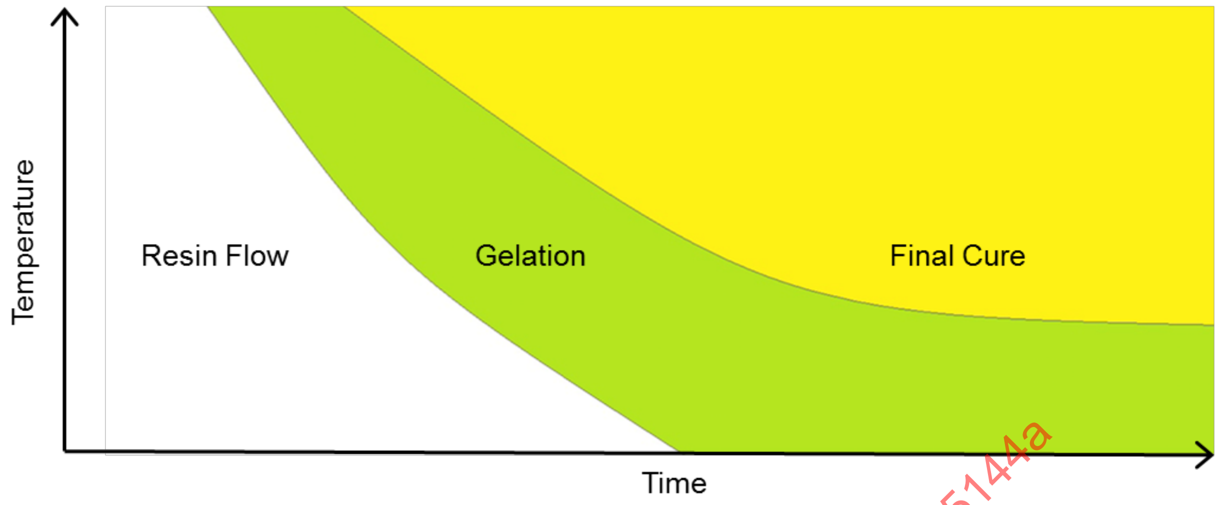


Figure 2 - Step cure cycle

4.4 Repair Actions Following Equipment Failure

Equipment failure prior to full completion of the cure cycle can result in voids and areas of compromised bond. Equipment failure can take many forms. Some failures, such as a momentary power or vacuum interruption, may be able to be fixed immediately with no effect on the cure. Other failures, such as a vacuum bag rupture or heat blanket failure, may require the cure to be stopped to diagnose the problem. When a failure occurs, the technician must assess whether the failure requires stopping the cure. If the cure is stopped, the repair document or OEM documentation may have information to help assess whether the cure may be restarted, or whether the repair must be removed. If a repair requires removal, refer to AIR5367 for guidance.

Figure 3 depicts the different cure stages that a resin goes through during cure. Resin viscosity and the degree of cure change throughout the entire cure cycle. Even after full gelation has occurred, crosslinking will continue throughout the final stage of the cure. Generally, if a cure can be continued following equipment failure, it will be within the resin flow stage.



Resin Flow: For wet layup systems after mixing, the resin/hardener mixture remains a liquid. For prepreg systems, as the temperature increases the viscosity will go to minimum.

Gelation: The mix passes into a preliminary cure state when it begins to gel and the mix is only partially cured.

Final cure: The adhesive mix has cured to a solid state and can be dry sanded and shaped.

Figure 3 - Cure stages

5. HEAT (THERMAL) TRANSFER

Heat travels from a hot body (or fluid) to a cold body (or fluid) as a result of a temperature difference or gradient. This temperature difference is considered as the driving force that causes heat to flow.

The term heat will be used to include not only heating but also cooling, as it is the same process, but the flow is in the opposite direction.

Heat is transferred by three basic processes or mechanisms, which can operate together or separately. These processes are referred to as Conduction, Convection, and Radiation.

Heat (thermal) transfer is required in the curing process and whether this is by conduction, convection, or radiation will depend upon the choice of heating method employed.

When required, a thermal map prior to curing will measure the thermal response of the structure and will identify heat sinks. See Section 9 for further details.

5.1 Conduction

Thermal conduction describes the transfer of heat in a medium essentially by the molecular activity within the material. The thermal conductivity of materials differs widely, and the ability to conduct heat is characterized by a quantity known as the thermal conductivity. Substances with high thermal conductivity values conduct heat well. Those materials with low values are poor conductors.

Table 1 illustrates the differences in approximate thermal conductivity among metals and composite materials, from which the superiority of metals as heat conductors can clearly be seen. High conductivity metals such as aluminium are, therefore, used as caul plates to assist in distributing the heat over the repair area. Refer to ARP5143.

Table 1 - Thermal conductivity coefficients

MATERIALS	THERMAL CONDUCTIVITY BTU.FT/H/FT^2/°F	THERMAL CONDUCTIVITY W/M/°C
SILVER	240	420
COPPER	226	390
ALUMINUM	116	200
CARBON & ALLOY STEELS	25	44
S.S. STANDARD AUSTENITIC GRADE	12	21
CARBON EPOXY[1]	2.0-3.43	3.5-6.0
GLASS/EPOXY[1]	1.82-2.46	3.2-4.3
[1]QUASI-ISOTROPIC LAMINATES AT 50% F.V.V.		

Gases like still air are poor conductors.

NOTE: When using heat blankets, conduction is the main thermal transfer mode.

The differences in thermal conductivity and thermal mass of the structure have important implications when carrying out repairs in areas of "heat sink". Consider for example, a composite panel damaged close to a rib or spar. Large temperature gradients can occur in the panel skin in close proximity to a rib or spar. The heat sink is created by the additional mass compared to the panel surface away from the rib or spar which has a much lower mass effect. Therefore, for a uniform heat input the heat sink area could lag behind the rest of the area under repair, leading to possible undercure. The heat sink effect is worse if the rib (of equal cross section) is metallic which conducts the heat away faster because of its higher thermal conductivity. See Figure 4 for examples of areas with different thermal mass.

Honeycomb is a poor conductor of heat because the air trapped in the cells acts as insulation. Therefore, care must be taken with single sided heating repairs on sandwich structures, because of the temperature gradients that will occur between the heated skin and the backside (lower) unheated skin. Undercure may occur on the part of the repair on the unheated skin.

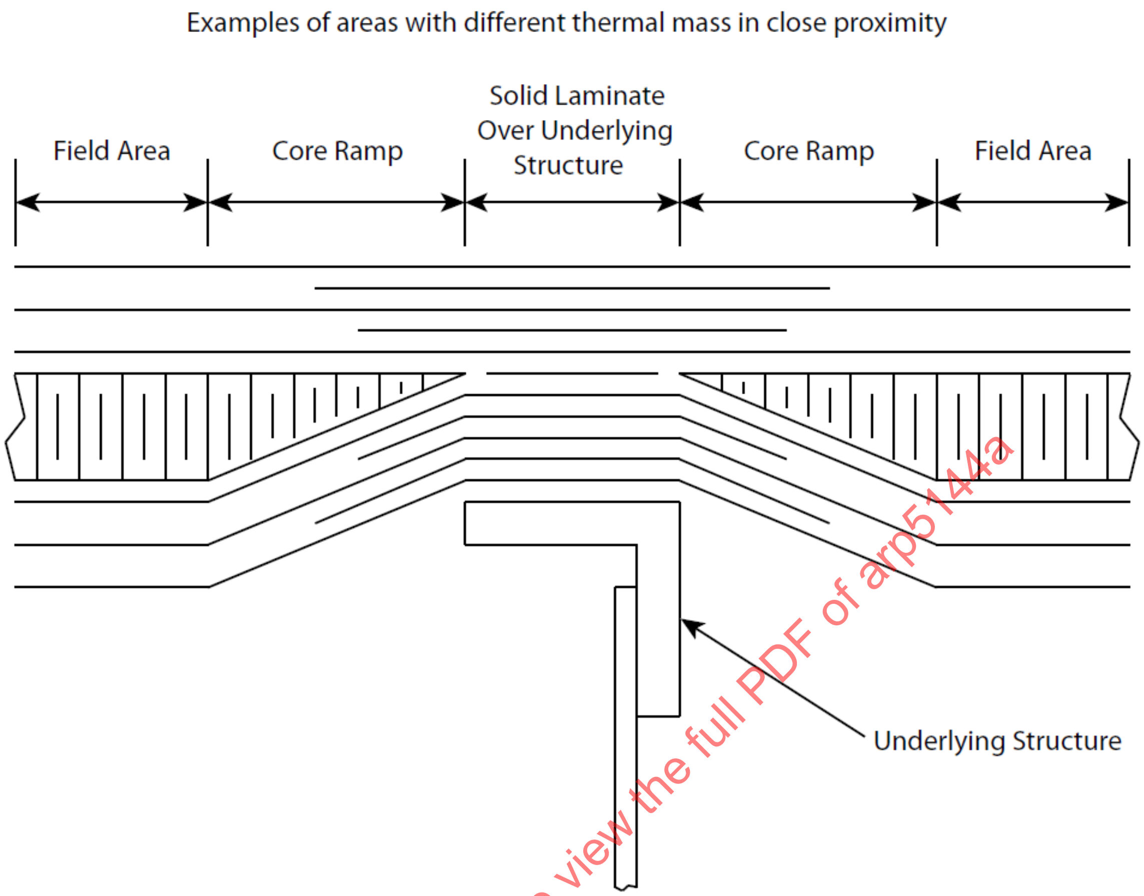


Figure 4 - Example of variations of thermal mass

There are other factors which can affect the thermal uniformity of the repair including part geometry, convection due to part orientation, vacuum bagging and insulation locations, and specific hot bonder settings.

5.2 Convection

Convection is the mode of heat transfer between a body and a moving liquid or gas.

Forced convection occurs when a fluid or gas is forced past a surface by an external force such as a pump or a fan, whereas with natural convection the fluid or gas flow is generated by the heat transfer process itself, making the moving fluid less dense causing it to rise and be displaced by cooler denser fluid.

NOTES:

a. When using a hot air gun, forced convection is the main thermal transfer mode.

b. When curing by convection heating, the thermocouple junction must be shielded, otherwise the temperature measured will read between the true surface temperature and the local airflow temperature. This may be achieved by holding the thermocouple in place with flashbreaker tape covering the welded end of the thermocouple. A caul plate made from thin sheet metal or metal foil tape may also be applied covering but not touching the thermocouple.

5.3 Radiation

Radiant heating utilizes external heat sources (such as heat lamps and infared heaters) located away from the part to heat the repair area.

NOTE: When using radiant heaters care shall be taken to protect thermocouples from direct radiation, so that the surface temperature and not the radiated temperature is measured. See 5.2.b for method of thermocouple shielding.

5.4 Heat Diffusion

Heat diffusion in a structure depends on the material properties (specific heat, density, thermal conductivity), the thickness, and design (monolithic or sandwich structure). Heat diffusion also depends on the environment and is affected by:

a. Surrounding components in contact with the structure

b. Thermal exchanges

c. Air flow

Heat sinks are local areas within the heated area with different heat diffusion characteristics, such as fittings, edgebands, and potted areas. To avoid problems with heat sinks, it may be necessary to use a second heat blanket and controller and different amounts of insulation. Additional heating on the repair underside may be required (assuming access is available) to reduce the severity of heat sinks.

Heat-up rates should be adjusted to minimize temperature gradients while ensuring that the minimum heating rate is achieved.

6. TEMPERATURE MEASUREMENT WITH THERMOCOUPLES

6.1 Definition

A thermocouple (T/C) is a device which uses a circuit of two wires of dissimilar metals or alloys welded together at one end, referred to as the measuring or hot junction. The other ends of the wires are connected to the terminals of the temperature measuring device, referred to as the reference or cold junction. Thermocouples utilize insulation around each wire to ensure the wires do not contact each other. There are multiple types of insulation available. It is recommended to choose an insulation type that minimizes vacuum leaks. Do not remove insulation locally at the vacuum bag sealant tape, which could cause an incorrect temperature reading.

When the two junctions are at different temperatures, a net electromotive force (emf) occurs between the hot and cold junctions. The resulting emf is then converted to temperature by various measuring methods (see 6.2.1 to 6.2.4). Refer to IEC 60584-1 and ASTM E230 for temperature/emf conversion tables.

All thermocouples have a finite response time. The ideal fast response thermocouple would be made of high conductive materials, have a low specific heat, and a low density. Many constraints affect the choice and construction of thermocouples, and what would be practical in a laboratory environment might be totally unsuitable in an airline repair shop, where robustness in handling is a prime consideration. Refer to ASTM Manual Series MNL12.

6.2 Temperature Measurement

CAUTION: It is mandatory that the thermocouple type is matched to the temperature controller and the controller is calibrated to the type of thermocouple being used. It is necessary to install the plugs with the correct polarity into the controller, therefore plugs are designed with different sized pins to avoid reversal. Further, when assembling a thermocouople, the thermocouple wires must be attached to the correct terminals on the plug to ensure correct polarity is maintained.

6.2.1 Direct Methods

Since a thermocouple is an electrical generator, the current it develops can be used to energize a suitable galvanometer (see Figure 5).

In such an arrangement the galvanometer traverses a scale that is graduated in temperature units. As the energy available from a thermocouple is small, such systems are usually confined to indicating wide spans of temperature, often calibrated in 10 °F (5 °C) or 20 °F (10 °C) increments, and are not well suited for work requiring high accuracy.

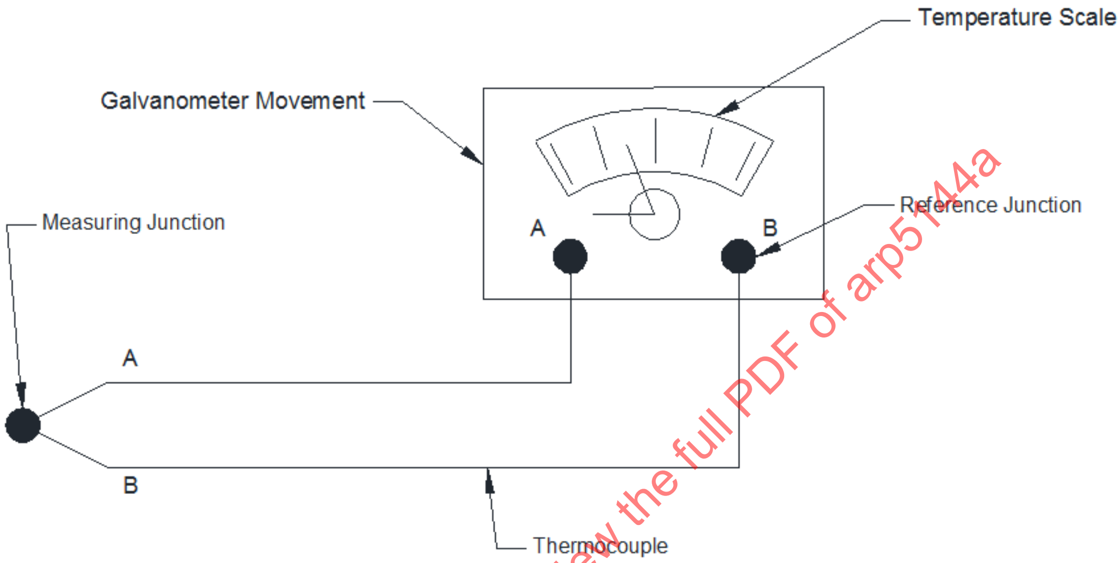


Figure 5 - Thermocouple circuit using galvanometer

6.2.2 Potentiometer Methods

The measuring potentiometer is the classical method for determining voltage. It is shown in simplified form in the following diagram (see Figure 6). In operation, the voltage from the thermocouple is balanced precisely by adjusting the variable resistance, R, until the indicator, I, shows zero current. The variable resistance is calibrated to a suitable voltage value. Each measured voltage is converted to temperature using the standard reference tables for the thermocouple being measured. The method is accurate, reliable, simple to set up, and use.

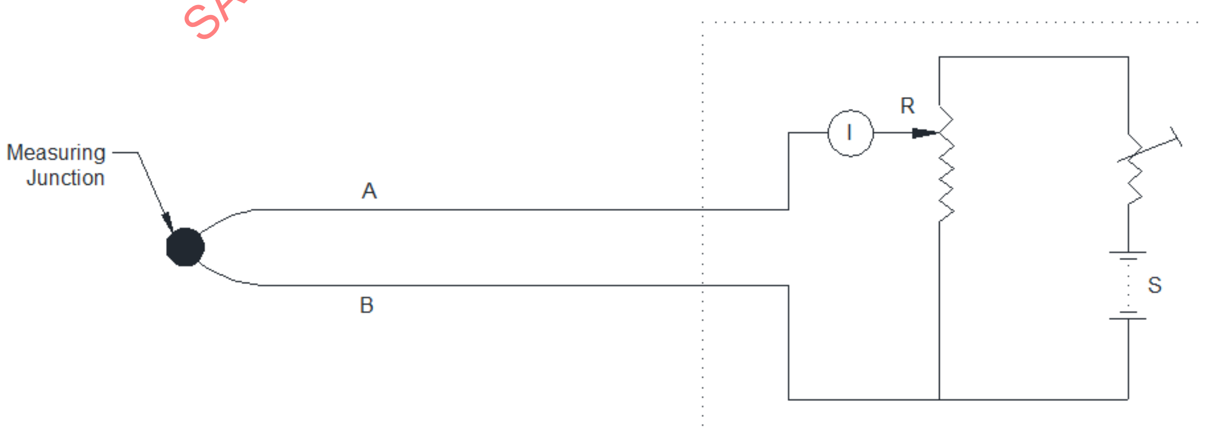


Figure 6 - Thermocouple circuit using potentiometer

6.2.3 Digital Voltmeters

Advantage has been taken of advances in electronics to produce voltmeters that automatically display the applied voltage in digital form. They are well suited to thermocouple measurement and can indicate a voltage change in steps as low as 1 microvolt. For a Type K thermocouple, approximately 40 microvolts is equivalent to a step of 1.8 °F (1 °C).

6.2.4 Temperature Indicators

The digital principle has been extended to more sophisticated instruments that indicate temperature directly. Such instruments are essentially digital voltmeters. These instruments can be powered electrically, or be battery driven, and are frequently matched to Type J or K thermocouples. Modern hot bonders use this same principle to measure and display process temperatures.

6.3 Standard Thermocouples

Thermocouples are generally divided into two main categories - rare metal types typically platinum versus platinum rhodium, and base metal types such as nickel chromium versus nickel aluminium and iron versus copper nickel. Although platinum based thermocouples tend to be more stable, they are also very expensive. The thermocouple alloys used for repairs in the aerospace industry are the base metal types, most commonly type J or K.

Thermocouples are available in three quality grades: extension, standard, and special tolerance. Special tolerance grade designates a higher purity alloy and will increase thermocouple accuracy.

Thermocouples are made to conform to an emf/temperature relationship specified in the form of tabulated values of emfs resolved normally to 1 microvolt against temperature in 1 °C intervals. Refer to IEC 60584-1 and ASTM E230.

Internationally the reference tables are published as IEC (International Electro-Chemical Commission) 60584-1. The standards cover the most commonly used base metal and rare metal type thermocouples, and are referred to by their internationally recognized alpha character type designations.

The two most commonly used thermocouples for composite repairs are Type J and Type K. Industry has established insulation color codes for the standardized letter designated thermocouple and extension wire types. It should be noted that the colors of thermocouple conductors referred to in Table 2 are applicable to the IEC codes only. Other standards may be used for other regions. For example, in North America it is common for Type J thermocouple wire to use a red color code for the positive wire. Refer to IEC 60584-1 and ASTM E230.

Table 2 - Standard thermocouple characteristics

THERMOCOUPLE CODE	Conductor Combinations Positive Wire	Conductor Combinations Negative Wire	Continuous Temperature Range (IEC 60584-1)
Type K (Generally Referred To As Chromel-Alumel)	Nickel-Chrome (Color Code Green, IEC)	Nickel-Aluminum (Color Code White)	-40 to 2192 °F (-40 to 1200 °C)
Type J (Generally Referred To As Iron-Constantan)	Iron (Color Code Black)	Copper-Nickel (Color Code White)	-40 to 1382 °F (-40 to 750 °C)

6.4 Manufacturing of Thermocouples

Welded joints are commonly used for thermocouples (see Figures 7 and 8). It is important when manufacturing or utilizing thermocouples to minimize any bare sections of wire. Bare wire touching metallic structures or conductive materials will cause the thermocouples to give inaccurate readings. Insulation should be kept as close as possible to the thermocouple welded joint (thermojunction).

6.4.1 Thermocouple with Welded Joint

A thermojunction (Figure 7) can be produced using several methods including electrical resistance welding, TIG welding, brazing, and soldering. Electrical resistance welding is the most common method of producing thermocouples.

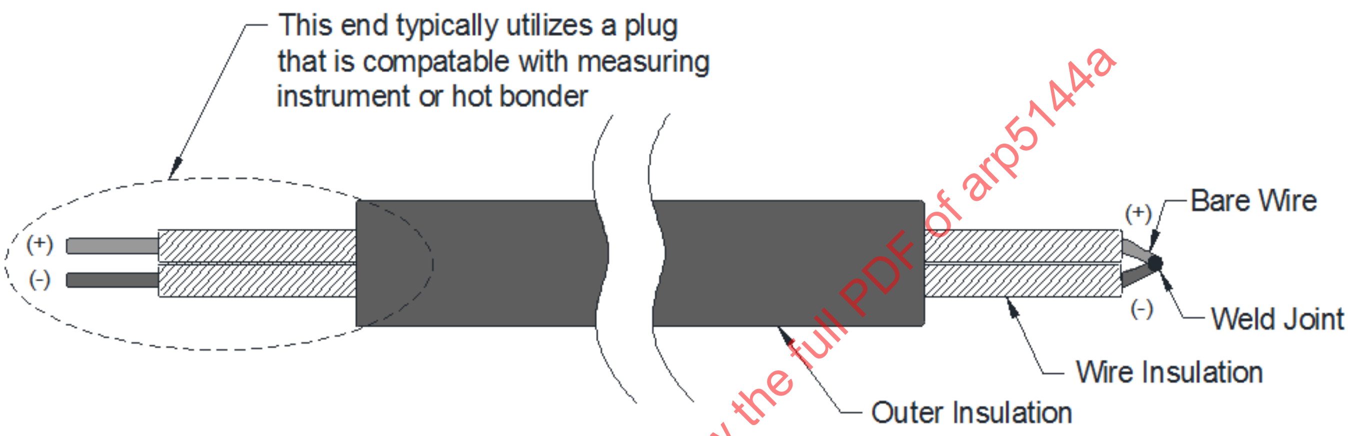


Figure 7 - Thermocouple with welded joint

6.4.2 Thermocouple with Welded Joint Produced by Electrical Resistance Welding

A common method for producing thermocouples is with electrical resistance welding (also referred to as Powder Resistance Welding). This method requires removal of insulation where the thermojunction will be welded. Following removal of insulation, the exposed wires are typically twisted to ensure good contact during the welding process (Figure 8). When welding is complete, excess wire is trimmed from the thermojunction and the sharp edges are removed to produce an acceptable result. Sharp edges can be removed by filing or hammering the weld flat.

CAUTION: When the two metal wires are manually twisted before welding, the temperature indication on the thermocouple controller will be the one recorded at the first twist. Contact between the wires prior to the weld should be avoided.

CAUTION: Do not use thermocouples that have not been properly welded. Twisting the ends of the wire without welding can result in fluctuating or inaccurate temperature readings.

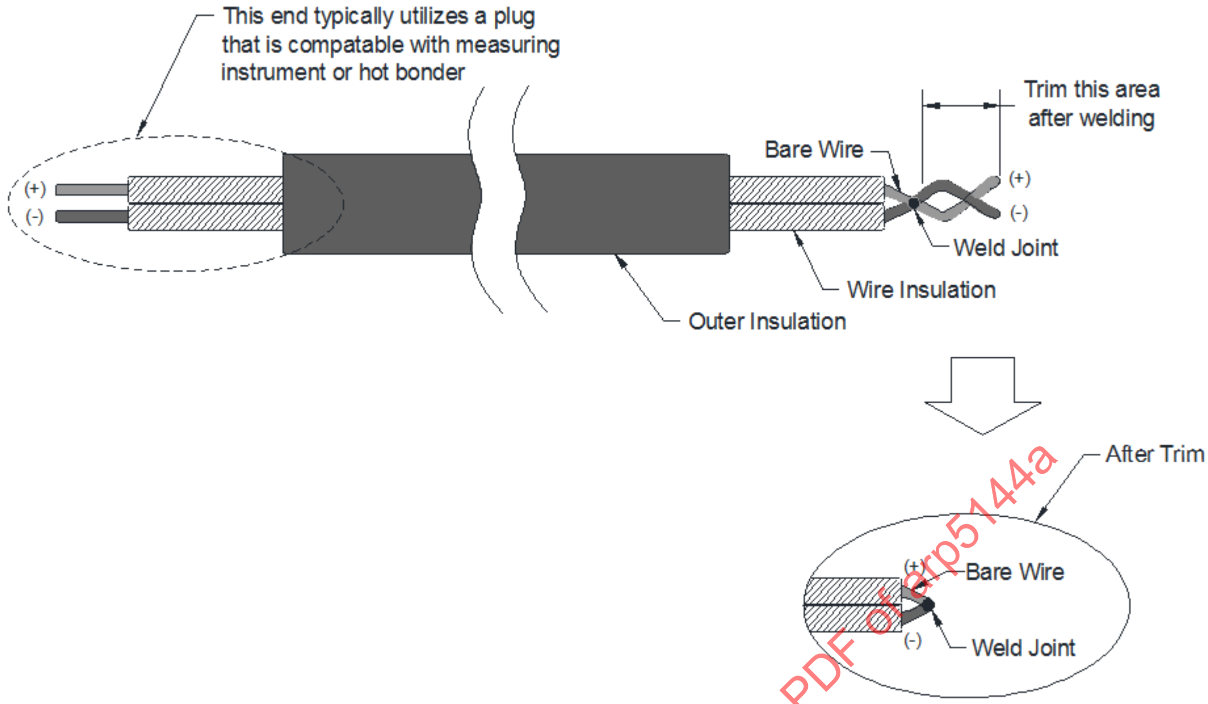


Figure 8 - Thermocouple manually twisted before resistance welding

6.4.3 Thermocouple with Plate Connection

Thermocouple With Plate Connection: This type of connection is mainly used for surface temperature measurements which have poor thermal conductivity. It is not recommended to use this type of thermocouple for repair applications.

6.4.4 Extension Cables

Extension cables provide convenient and economic solutions to extending thermocouple circuits from the sensor to the reference or measuring unit. They take the form of wiring cables with similar conductor materials to those of the corresponding thermocouple.

Care must also be taken to ensure reversed polarity does not occur at the thermocouple/extension wire junction or at the extension wire/instrument junction. Although a single reversal of polarity in the assembly would be noticeable, an inadvertent double reversal likewise may produce errors that could escape immediate attention.

Extension cables are designated by the letter "X" following the thermocouple designation, for example "JX".

6.5 Verification of Thermocouples

Thermocouples are essential for controlling the repair temperature. For accurate application each thermocouple should be checked against known reference standards. This can be accomplished by placing the working thermocouple immediately alongside a calibrated standard temperature sensor and positioning these, for example, in a specially designed heated oil filled vessel, with automatic impeller agitation to reduce temperature gradients. The vessel can then be set to a range of temperatures and the corresponding outputs compared. Refer to ASTM E220.

In the absence of such standards, a simple and effective check is to immerse the thermocouple in a slush of melting ice and confirm that 32 °F (0 °C) is being read from the recording device. A further check would be to immerse the thermocouple in boiling water to confirm 212 °F (100 °C) is being recorded. Refer to AMS2750.

Maintenance and condition of thermocouples is often overlooked. Thermocouples can appear to work at room temperature and then fail to work properly under repair conditions (i.e., high temperature and pressure).

Each thermocouple should be visually inspected prior to being used and then plugged into a recording device for verification. All thermocouples have to read similar temperatures at room temperature. A further check is to hold each junction between thumb and finger and observe temperature change.

CAUTION: During use, thermocouples are exposed to resins and physical abuse. Thermocouples that have the junction area covered in resin may not work properly under repair conditions. Clean off the resin if possible and closely inspect the welded junction to make sure it is intact. If there is any doubt, the thermocouple should be completely discarded or should not be used until it has a new welded junction.

CAUTION: Kinks will sometimes occur in the thermocouple wire resulting in a junction prior to the end of the thermocouple. This could yield inaccurate readings. If in doubt, confirmation of the thermocouple performance can be checked using the ice water or boiling water tests (see 6.5).

6.6 Installation of Thermocouples

The installation of thermocouples for a bonded repair is to monitor and control the cure temperatures and to give warning of high and low temperature deviation. The number of thermocouples is based upon the size of the repair and anticipated hot and cold areas. Thermocouples should be evenly spaced around the repair area, and should be located inside the heat blanket area, near the repair area. Care should be taken to place the thermocouples in the heated area of the heat blanket to avoid a low temperature reading.

A maximum spacing between individual thermocouples of 12 inches (300 mm) is considered satisfactory for temperature monitoring of a repair. Extra thermocouples should be taken into account for a larger area to ensure that proper spacing is maintained.

Any areas that are expected to be hotter or colder due to the thermal characteristics of the component should have a thermocouple to allow for proper cure control. This is particularly important in areas with a higher or lower thermal mass than other areas of the structure within the repair area. Areas with a high thermal mass (heat sinks) will typically result in a lower temperature reading during the cure and will respond to heating more slowly than other areas in the repair area. Areas with a low thermal mass will typically result in a higher temperature reading and quick response to heating. Figure 9 is an example of thermocouple placement in heat sink areas.

Heat sinks such as aluminum sub-structure and fittings should have a monitoring thermocouple installed to ensure these areas do not get overheated. Refer to the repair document for maximum temperature limits for these areas.

Refer also to ARP5143.

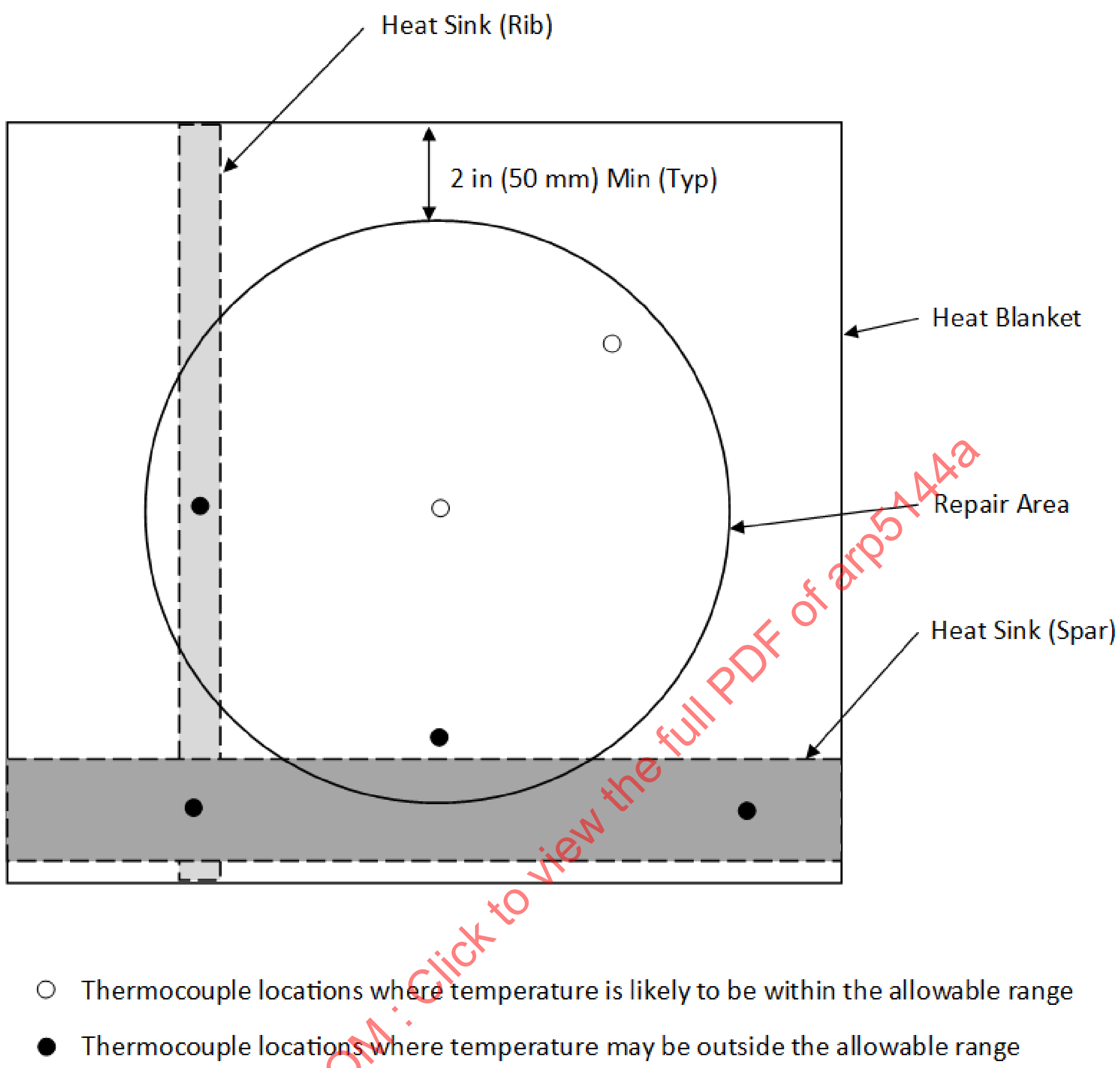


Figure 9 - Example of thermocouple placement on heat sinks

CAUTION: With any repair a minimum of three thermocouples should be used, spread evenly around the repair.

Although the primary use of a caul plate is to provide a more uniform distribution of heat to the repair area, it does prevent thermocouples from imprinting into the repair if they are placed between the heat blanket and the caul plate.

Refer to repair document for additional thermocouple placement requirements. Some experiments will be essential to confirm that undercure will not occur because of the higher temperatures that will be measured on the heat blanket side of the caul plate compared to the repair side.

If thermocouples are in contact with a caul plate or a conductive material such as carbon fiber, the ends should be electrically insulated with high temperature flash breaker tape. This is because the small voltages generated by the thermocouple junctions may cause interference or "cross talk" between thermocouples and give false readings.

6.6.1 Installation of Thermocouples for Skin Repair

Figure 10 depicts typical installation of thermocouples for skin repair.

CAUTION: To avoid cooling from the vacuum, the vacuum probe must be installed away from thermocouples. Refer to ARP5143.

CAUTION: The positioning of thermocouples over a repair should be made with caution because of the risk of imprinting into the repair. As such the optional thermocouple is typically located on top of the heat blanket to monitor the temperature of the heat blanket. Use of a caul plate under the heat blanket will also reduce the risk of imprinting to the repair.

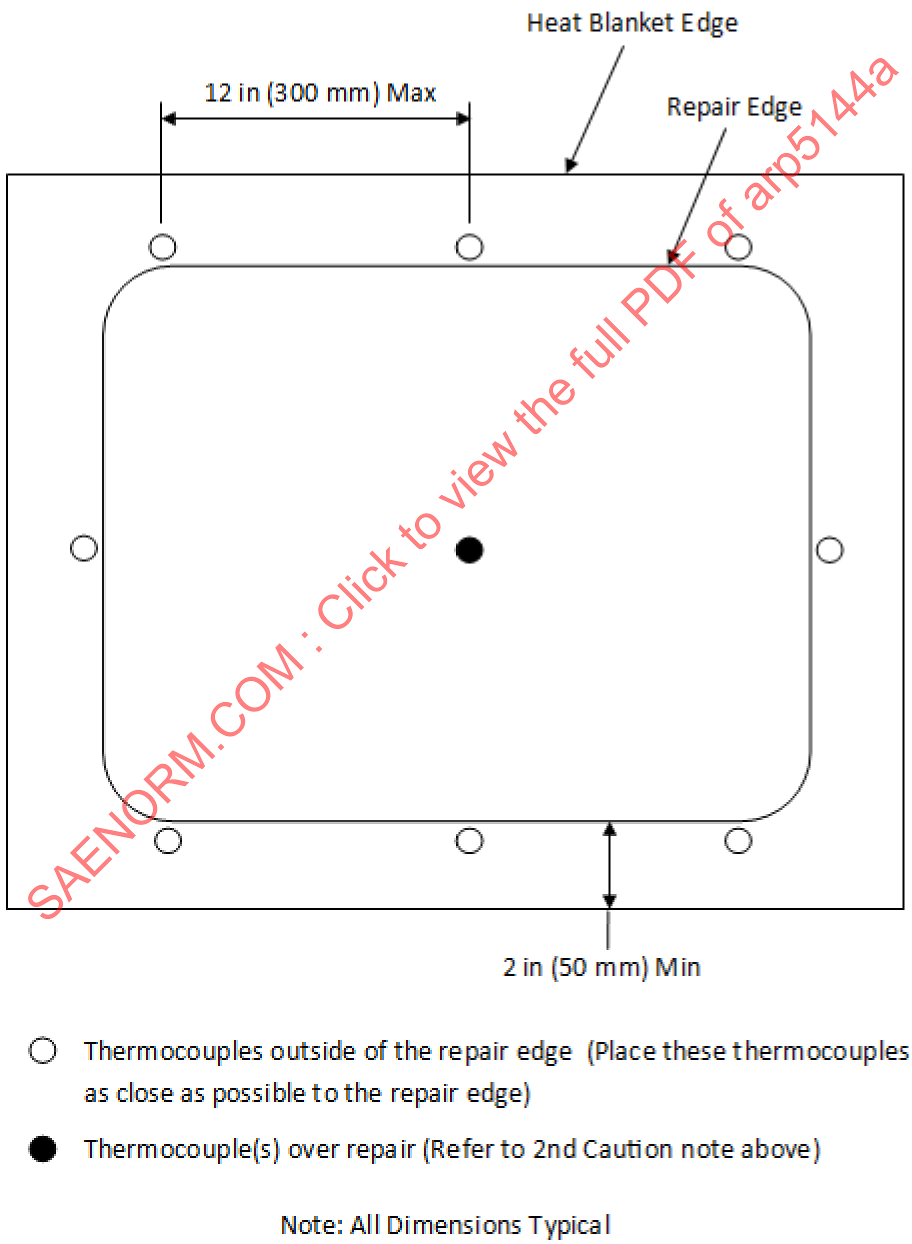


Figure 10 - Installation of thermocouples for skin repair

6.6.2 Installation of Thermocouples for Core Bonding with Single Sided Access

The setup in Figure 11 covers the situation where only single sided access is available for heat application. In this situation heat transfer is challenging since placement of the heat blanket near the bond line is not possible. As such the skin and bond line nearest to the heat blanket (top skin) can potentially be degraded due to overheating when trying to bring the bond line at bottom skin to the required cure temperature.

CAUTION: The positioning of the controlling thermocouple(s) for core bonding is important and the accepted practice of putting the thermocouple down the cell wall to make contact with the adhesive will give erroneously high, hence false, temperature readings at the thermojunction due to heat conduction along the wire. It has been demonstrated by test, that a “turnover” of at least 0.75 inch (20 mm) of the thermocouple prior to the thermojunction is necessary to give true temperature readings at the core/adhesive bond line. The turnover must make intimate contact with the bottom skin thus ensuring that any heat picked up in the wires will be dissipated through the heat sink effect of the bottom skin.

CAUTION: Insulation must be used to protect the top skin from heat damage. The amount of insulation selected is to ensure that cure is achieved at the bottom of the cavity. This is particularly important with any thickness of honeycomb where access is limited to the one side.

If the hot bonder does not have a specific control thermocouple but instead uses hottest thermocouple or average thermocouple control, proceed as follows:

a. Use the thermocouple installation shown in Figure 11.

b. Select the hottest thermocouple control method.

c. Assume that thermocouples monitoring the top of core will be the hottest and, therefore, controlling. Select a control set point temperature consistent with these thermocouples not overheating the top skin but hot enough to ensure that thermocouples monitoring core adhesive will reach the minimum cure temperature.

d. For example, if the minimum cure temperature is 250 °F (120 °C) choose a set point of 270 °F (132 °C) along with a low deviation limit of 20 °F (12 °C). The deviation limit will ensure that the hot bonder does not consider that the cure has commenced until the minimum temperature has been reached.

As pointed out in 4.2.2., if the minimum cure temperature cannot be achieved within a specified time then consideration will have to be given to an alternative repair route.

NOTE: After cure the thermocouples will be bonded in place. Cut thermocouple close to the top of core taking care not to damage core cell surfaces.

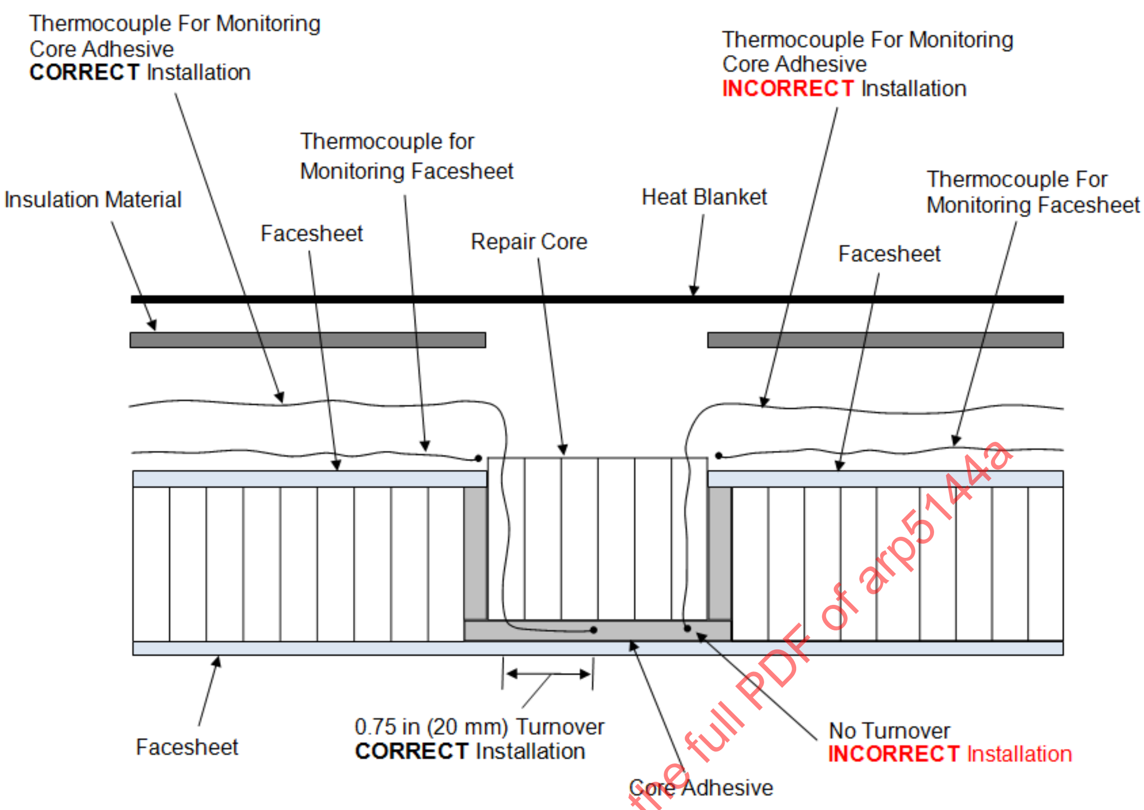


Figure 11 - Installation of thermocouples for core bonding

6.6.3 Installation of Thermocouples for Co-Curing of Skin/Core Assemblies

CAUTION: The standard practice of positioning thermocouples around the edge of the top skin repair plies when carrying out hot bonding skin/core co-curing repairs and assuming that the skin temperatures obtained are applicable to the bottom skin/core bond line is incorrect. This is the case when single sided heating is used, even on honeycomb as thin as 1/4 inch (6.25 mm). It has been determined from tests that for a repair ply skin temperature of 250 °F (120 °C), temperatures at the bottom skin/core bondline lagged by 45 °F (25 °C) even when insulation was applied. Without insulation the temperature gradient would be more severe. An undercure could, therefore, result if 250 °F (120 °C) materials were being used to bond the core to the bottom skin. At 350 °F (180 °C) the temperature differential across the repair would be even more severe. This effect occurs due to low thermal heat transfer through the core material.

It is recommended that for any planned elevated temperature co-cured skin/core repairs involving single sided heating, that thermal mapping is conducted according to 9.1 to determine temperature distribution over the whole repair area.

7. HEATING DEVICES

Several heating devices are available for repair curing. Depending on the repair conditions they can be used in-situ, in the hangar, or in the repair shop.

Depending on the type and structural classification of the component there may be a restriction on the damage size repaired by either heat blanket, or radiant heater, or hot air blower, when used in conjunction with low pressure vacuum bags. Refer to the OEM's Manuals.

Whatever heating device is used, the temperature obtained on the repair must be known and controllable in order to comply with the curing instructions (time/temperature). Cure parameters should be recorded (see 8.1 and 8.2).

Thermocouple location should be as indicated in 6.6. To avoid heat damage outside of the repair area, it is recommended to monitor temperatures where heat damage may occur.

7.1 Heat Blankets

Heat blankets are the most widely accepted form of applying heat to a composite part to be repaired and for in-situ repairs are recommended by the OEM's. Heat blankets apply heat to the repair by thermal conduction.

Heat blankets are made from flexible fiberglass reinforced silicone rubber sheets encapsulating evenly-spaced heating resistance wire which is connected to external power leads. Common configurations are rectangular or round, although a range of sizes including two and three dimensional shapes are available (see Figure 12). Heat blankets are connected to a hot bonder to provide controlled power and regulate the heat output from the blanket. Heat blankets must be designed to provide uniform heat with no significant hot or cold spots during the curing process. Some heat blankets are not flexible and are designed for use on flat structures only. Using these on a curved surface could result in breaking the wires in the blanket. If the part is sharply contoured, stretchable heat blankets without fiberglass reinforcement, or contoured heat blankets conforming to the shape of the part can be used.

Figure 12 - Typical heat blankets

Heat blankets must be in good condition. Care in handling and storage are important for a long and trouble free life. If a heat blanket is shipped and stored rolled, ensure that the blanket is not creased or folded. If a heat blanket is shipped and stored flat, provide support beneath the blanket to prevent bending. Heat blankets should preferably be stored flat in a dry area. During storage avoid placing heavy and sharp objects on the blankets which could damage the heating circuits and rupture the silicone rubber fabric. Another practical form of storage is to "hang" the blanket thus avoiding possible contact damage. Care is also needed to avoid damaging the electrical connections to the blanket. Do not hang the blanket by the electrical leads. Always inspect the heat blanket and electrical leads prior to use. If any bare wire is exposed, the blanket will need to be repaired or replaced for safe operation. Reject all blankets containing foreign bodies, showing torn areas, creases, or other damage.

CAUTION: The heat blanket must be rated at the same class voltage as the line voltage.

To ensure traceability, each heat blanket should be given an identification tag with the following minimum information.

a. An identifying Serial No.

b. Initial electrical resistance value.

The electrical resistance value should be provided by the supplier, or measured and recorded immediately upon receipt of the blanket (see 7.1.3, Method 3). This information is used to verify the condition of the heat blanket circuit.

NOTE: The electrical resistance measurement does not take the place of initial thermal uniformity test. It is recommended that heat blankets are initially tested for thermal uniformity using one of the procedures contained in 7.1.1 (Method 1) or 7.1.2 (Method 2).

When using heat blankets, a uniform temperature over the whole blanket surface must be obtained. The temperature distribution over the blanket and the ability to achieve the required cure temperature can be confirmed via an Infrared (IR) Sensor test (Method 1) or a Thermal Imaging test (Method 2). Tests should be carried out in a draft-free area in a uniform temperature environment. There shall be no forced air blowing on or near the test area that could affect the test.

7.1.1 Verification of Heat Blankets with Infrared (IR) Sensor: Method 1

a. Position the blanket on a flat surface of uniform absorption with low heat diffusion properties, for example a glass/epoxy molded sheet, and vacuum bag into position (see Figure 13). Multiple layers of low heat diffusion materials may be used to thermally isolate the heat blanket.

   CAUTION: High heat diffusion material such as aluminum or steel will mask the effects of uneven spots.

b. Connect the blanket to the appropriate power source controller, select a particular heat setting to achieve 250 °F (120 °C) or 350 °F (180 °C), and wait for temperature equilibrium. If equilibrium is not achieved in a reasonable time then the blanket may be damaged. Investigate further for confirmation.

c. Make temperature measurements at a pitch of 2 inches (50 mm) both in length and width of the blanket using the IR sensor.

   Verification with an infrared sensor can also be done on the repair part. The record of hot and cold points will be useful for the installation of thermocouples for the curing process.

   NOTE: The following measurements can be performed using thermocouples, but this may only be practical on very small blankets, due to the number of thermocouples that would be required.

d. Record all temperature readings. A tolerance of ±10 °F (±5 °C) for an average value of 250 °F (120 °C) or 350 °F (180 °C) can be accepted. Reject heat blankets which exceed this temperature requirement.

   NOTE: Thermal uniformity requirements do not apply to the 2 inch (50 mm) wide heat blanket edge band.

   If some points are out of tolerance, the area must be identified.

   Extreme caution must be used when using a heat blanket with cold or hot spots due to a risk of over/under cure. Reject blanket if in doubt.

   Repeat verification will be dependent on the blanket resistance checks (see 7.1.3). Should the heat blanket resistance fall outside the stated requirements, then the blanket should be re-tested.

7.1.2 Verification of Heat Blankets by Thermal Imaging: Method 2

a. Refer to and use technique in 7.1.1a

b. Refer to and use technique in 7.1.1b

c. Refer to and use technique in 7.1.1c but use a thermal imaging camera

d. Refer to and use technique in 7.1.1d

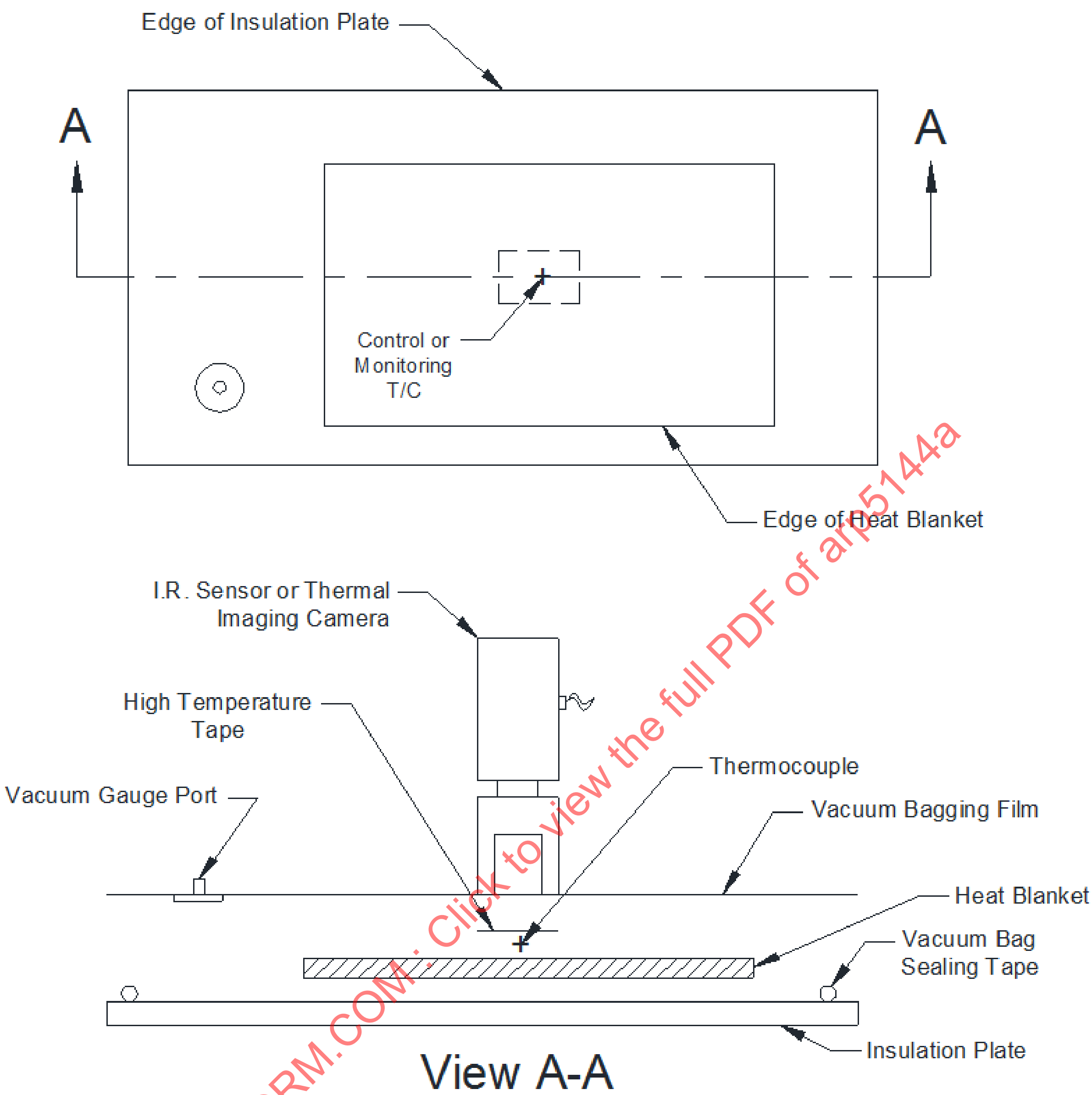


Figure 13 - Setup for temperature verification test of heat blanket

Suspect broken wires within the blanket can be located by X-ray. A broken heating circuit usually requires replacement of the heat blanket.

CAUTION: Observe National Safety Instructions when carrying out X-ray inspections.

The data from tests performed shall be maintained on file for the life of the blanket. This will enable trends to be established and to give warnings of possible under-performance.

7.1.3 Verification of Heat Blankets with Resistance Measurement: Method 3

A method of checking a blanket for major problems is by measuring its resistance with an ohm meter. While the blanket is still new or in known good condition, confirmed by the procedure set out in 7.1.1 or 7.1.2, measure and record its resistance (not required if this has been provided by the supplier) by applying the ohm meter to the power leads. It is recommended that the operator compares the blanket's resistance every time before use against the established baseline resistance. If it is not greater than 4%, the blanket circuit(s) are in good condition. If this value is exceeded, then the blanket must be investigated using the procedure contained in 7.1.1 or 7.1.2 before further use. If the blanket passes the thermal uniformity test, a new electrical resistance certification value shall be issued.

Suspect broken wires within the blanket can be located by X-ray. A broken heating circuit usually requires replacement of the heat blanket.

CAUTION: Observe National Safety Instructions when carrying out X-ray inspections.

The data from tests carried out (Method 1, 2, or 3) shall be maintained on file for the life of the blanket. This will enable trends to be established and to give warnings of possible under performance.

7.1.4 Requirements for Repaired Heat Blankets

Heat blankets that have had repairs or parts replacement shall be given a unique serial number. Before re-using, the heat blanket shall be tested and shall meet the requirements in accordance with 7.1.1 through 7.1.3.

7.1.5 Installation of Heat Blankets

A typical vacuum bag set-up for repair using a heat blanket is illustrated in Figure 14 derived from ARP5143. Figure 14 depicts a typical bleed cure, however refer to ARP5143 for other vacuum bag arrangements (e.g., no-bleed cure) and further details such as overlap dimensions of the layup materials.

For a number of reasons, temperatures drop off around the perimeter of heat blankets. Heat blankets must, therefore, be installed with a minimum of a 2 inch (50 mm) overlap beyond the repair boundary (see Figures 16 and 17).

If large temperature differences across the part being repaired are evident then additional heat blankets with multiple controlled zones can be applied. All the zones must be controlled with the same curing schedule and regulated in accordance with the temperature response of each zone.

To reduce heat losses, consideration should be given to insulating the area above and around the heat blanket. Blanket temperature will need to be monitored to ensure that it does not overheat. Typical maximum temperature for silicone rubber heat blankets is 450 °F (230 °C). Upper temperature application is usually limited to 350 °F (180 °C).

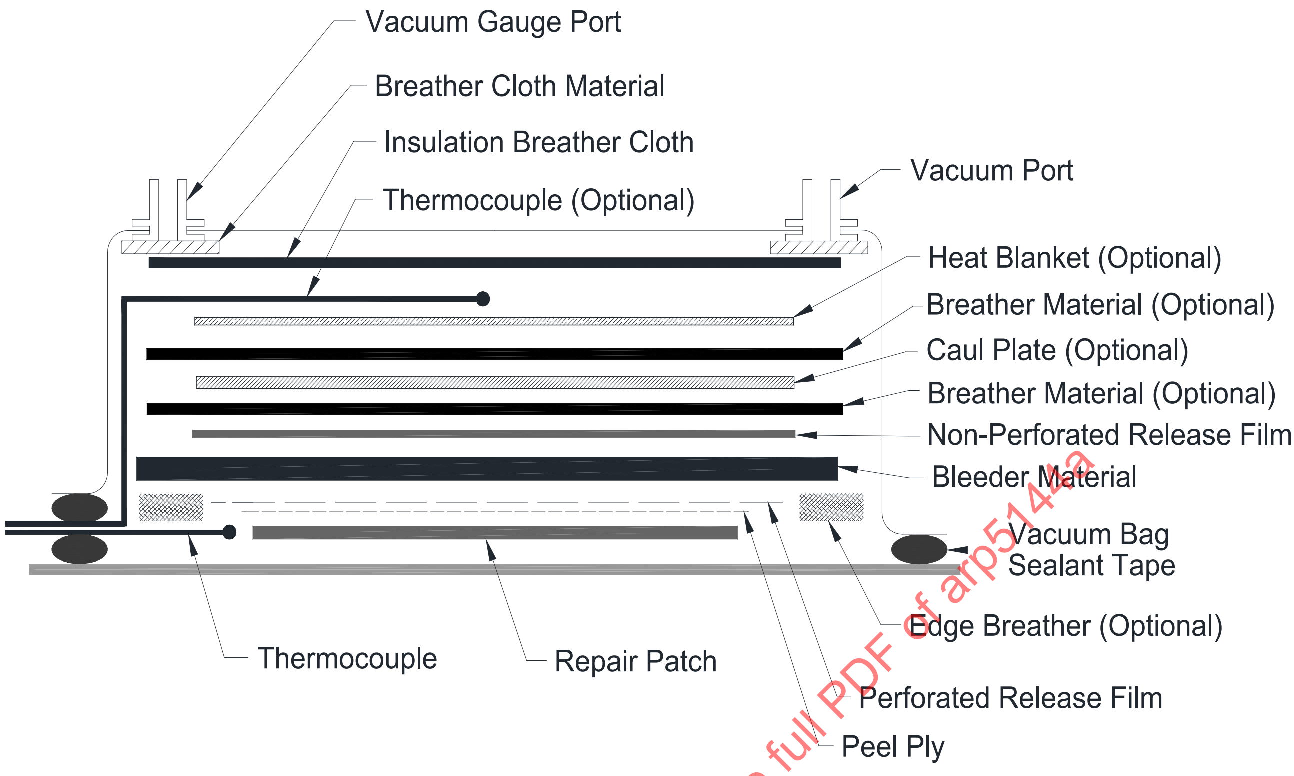


Figure 14 - Typical bleed vacuum bag setup

It is recommended that a single heat blanket be used for most repairs. The use of two or more heat blankets creates significant complexity.

When using multiple heat blankets, care should be taken to ensure the heated areas are not overlapped. Blankets with a very narrow unheated zone may be installed with a butt joint if the temperature survey does not indicate cold areas (see Figure 15). An aluminium caul plate of 0.016 inch (0.4 mm) thickness may be installed under the butt joint unless a full area caul plate is being used. The function of the caul plate is to reduce the temperature gradient across the joint.

Blankets with a wider unheated zone may require an overlapped installation. The temperature survey should be used to ensure no hot or cold areas if an overlap is used.

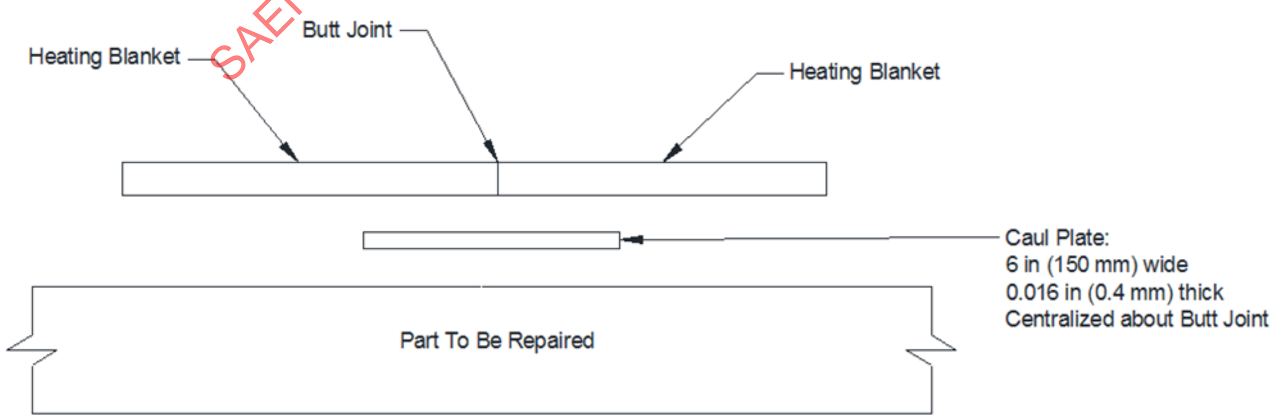


Figure 15 - Multiple heat blanket installation illustrating the blanket join line

CAUTION: Unless a full area caul plate is used, the joint will be over the repair which could lead to a risk of "mark off". This must be considered during the repair planning phase.

The heat blanket is vacuum bagged onto the repair area to ensure intimate contact with the repair. This is important, both on the top side and the underside of a component, and ensures that heat is conducted into the repair. The applied vacuum pressure will ensure that the heat blanket is pulled tight against the repair thus reducing temperature gradients.

7.1.6 Caution for Application

In most cases heat blankets are larger than the minimum area to be heated. Damage may occur to the part or heat blanket if care is not taken to manage excess heat. To reduce the risk of causing thermal damage to the part, the heat affected zone should be the minimum permitted by the repair document.

In situations where the repair is near the edge of the part, it may be appropriate to extend the heat blanket excess off the edge of the part as shown in Figure 16. Additional heat-sink material may be needed to avoid overheating the heat blanket, and to support the heat blanket to avoid bending.

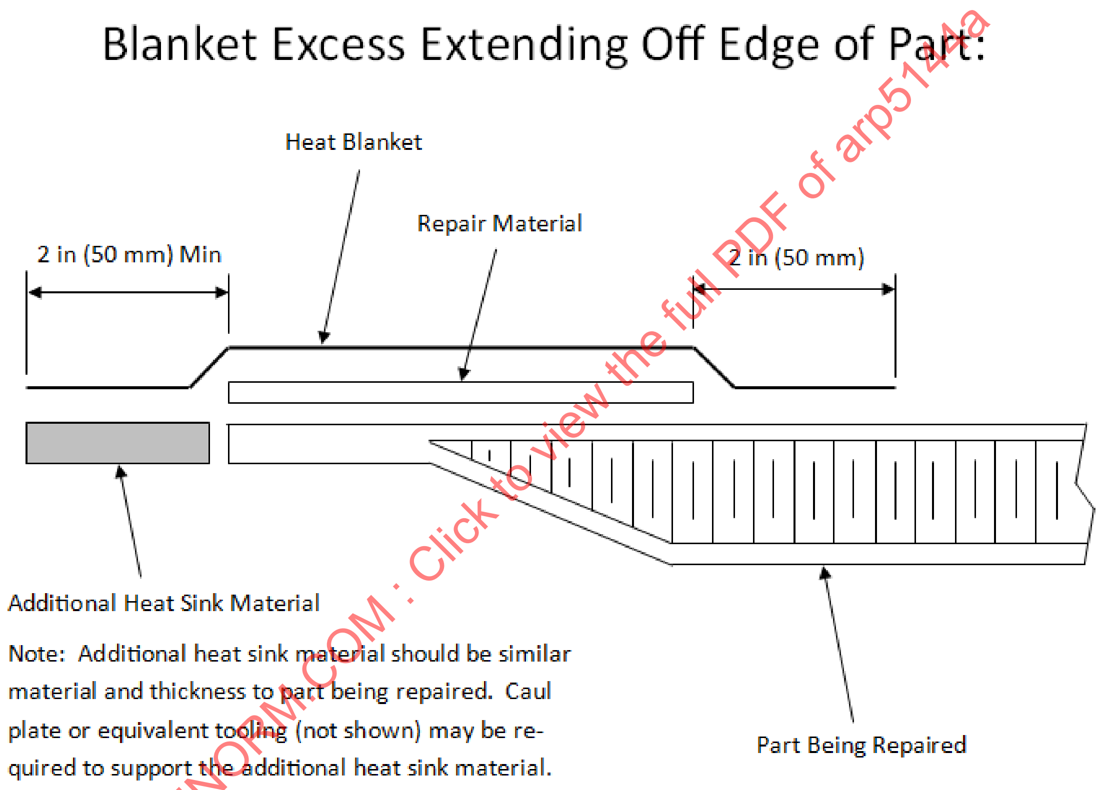


Figure 16 - Heat blanket excess at edge of part

In situations where the heat blanket is not near the edge of the part it may be appropriate to use insulation under the heat blanket excess as shown in Figure 17.

To reduce the risk of causing thermal damage to the part, it is desirable to minimize the heat affected zone beyond repair area. Figure 17 depicts a 2 inch (50 mm) heated zone beyond the repair but this may vary depending on the type of structure and the results of the thermal mapping/survey.

The area surrounding the repair area beyond the required overlap may require the addition of insulation and heat-sink material. Insulation such as standard breather may be used between the heat blanket and thermally sensitive areas of the part. To avoid overheating of the heat blanket, a material with similar thermal characteristics to the part being heated may be used as a heat-sink.

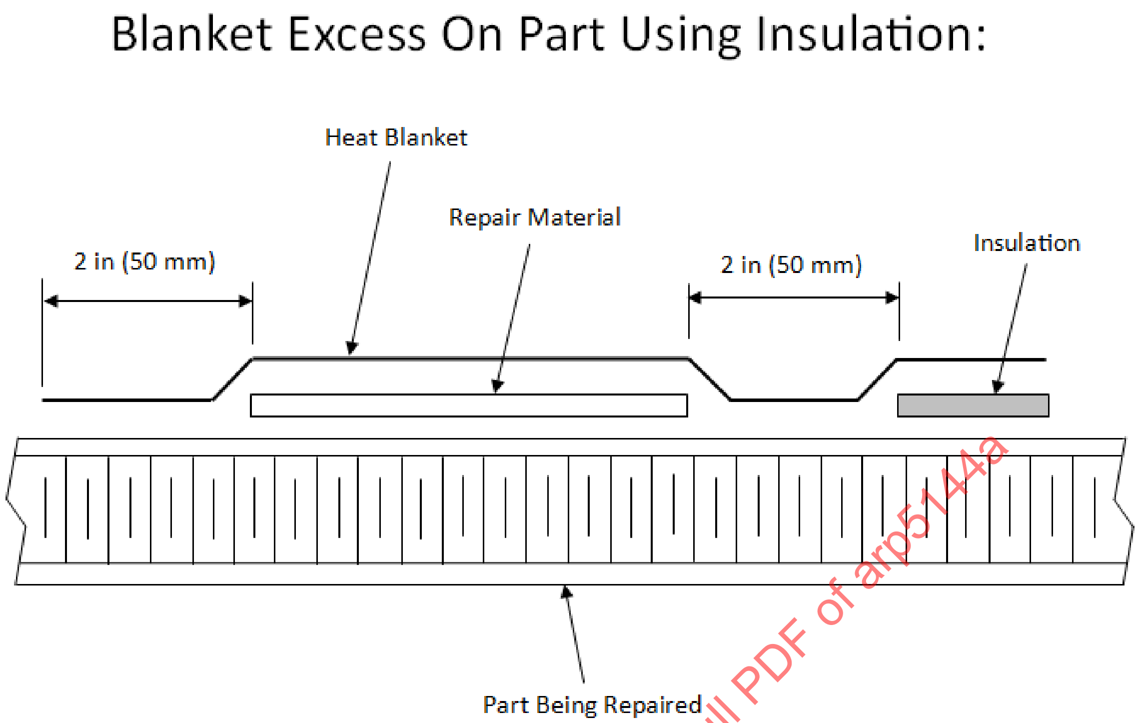


Figure 17 - Heat blanket above thermally sensitive area

The methods referred to in this document may not necessarily apply to complex contoured heat blankets.

The use of a heat blanket that has been verified by the methods described in 7.1.1 and/or 7.1.2 does not eliminate the need for thermocouple placement and monitoring during repair curing.

7.2 Radiant Heaters

The term radiant heater applies for both heating lamps and radiators. Thermal radiation is used to heat the repair area. Common types of radiant heaters include incandescent bulb, quartz bulb, quartz tube, and ceramic.

Calibration of Radiant Heaters: Before curing the repair, calibrate the temperature versus the distance between the repair and the heater (see Figure 18).

The calibration, to be accurate, must be performed under the same conditions as for the repair:

a. Same environment.

b. Same bagging as the one that will be on top of the repair or same repaired surface color and contour.

c. Same number and location of heaters.

d. Ensure the thermocouples are not exposed directly to light source when carrying out the calibration (see 5.2.b).

e. Ensure that additional thermocouples are placed in critical areas as shown in Figure 18 during the calibration to determine the coldest and hottest areas.

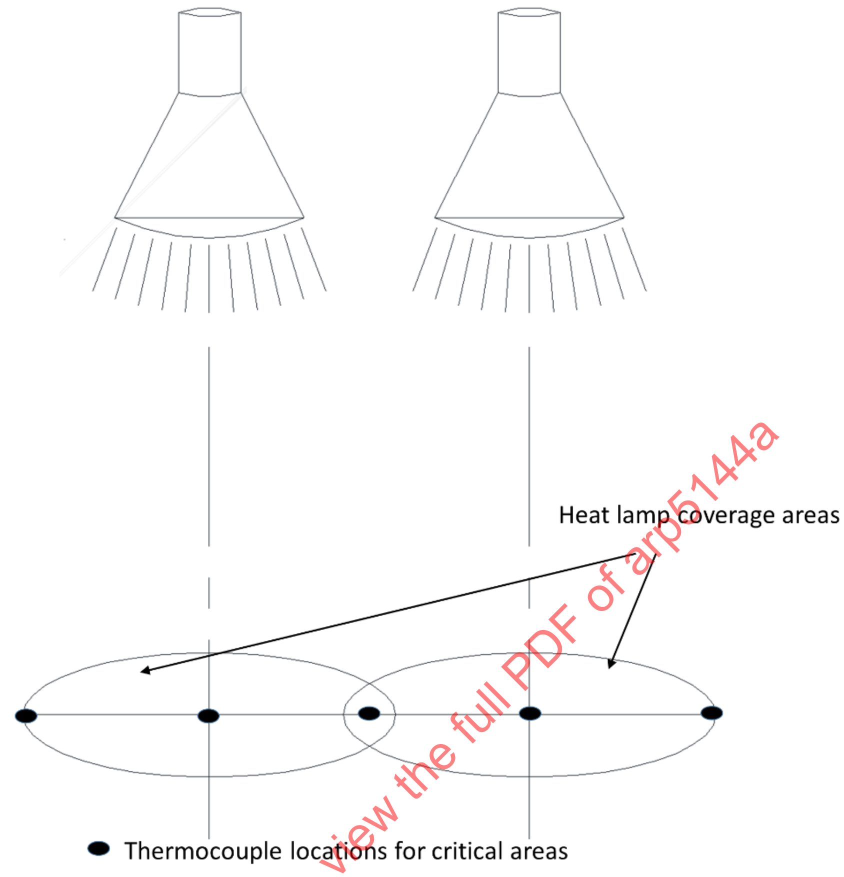


Figure 18 - Thermocouple placement for calibration of radiant heaters

a. Follow the pre-repair thermal mapping procedure (see 9. 1) with no dummy patch.

Calibrate the heater (Option A) as follows (refer also to ARP4977 for additional information).

a. Using Figure 19, construct Graph 1 showing the temperature at the center of the heated area as a function of the distance between the heater and the surface.

b. Use the graph to find the distance from the heater to the part that is required for the cure temperature given in the repair instructions.

c. Construct Graph 2 showing the temperature as a function of the distance from the center of the heated area at the distance chosen in step b.

d. If several heaters are used (Option B) make the previous two graphs for the combined heaters similar to Graphs 1 and 2 in Figure 19.

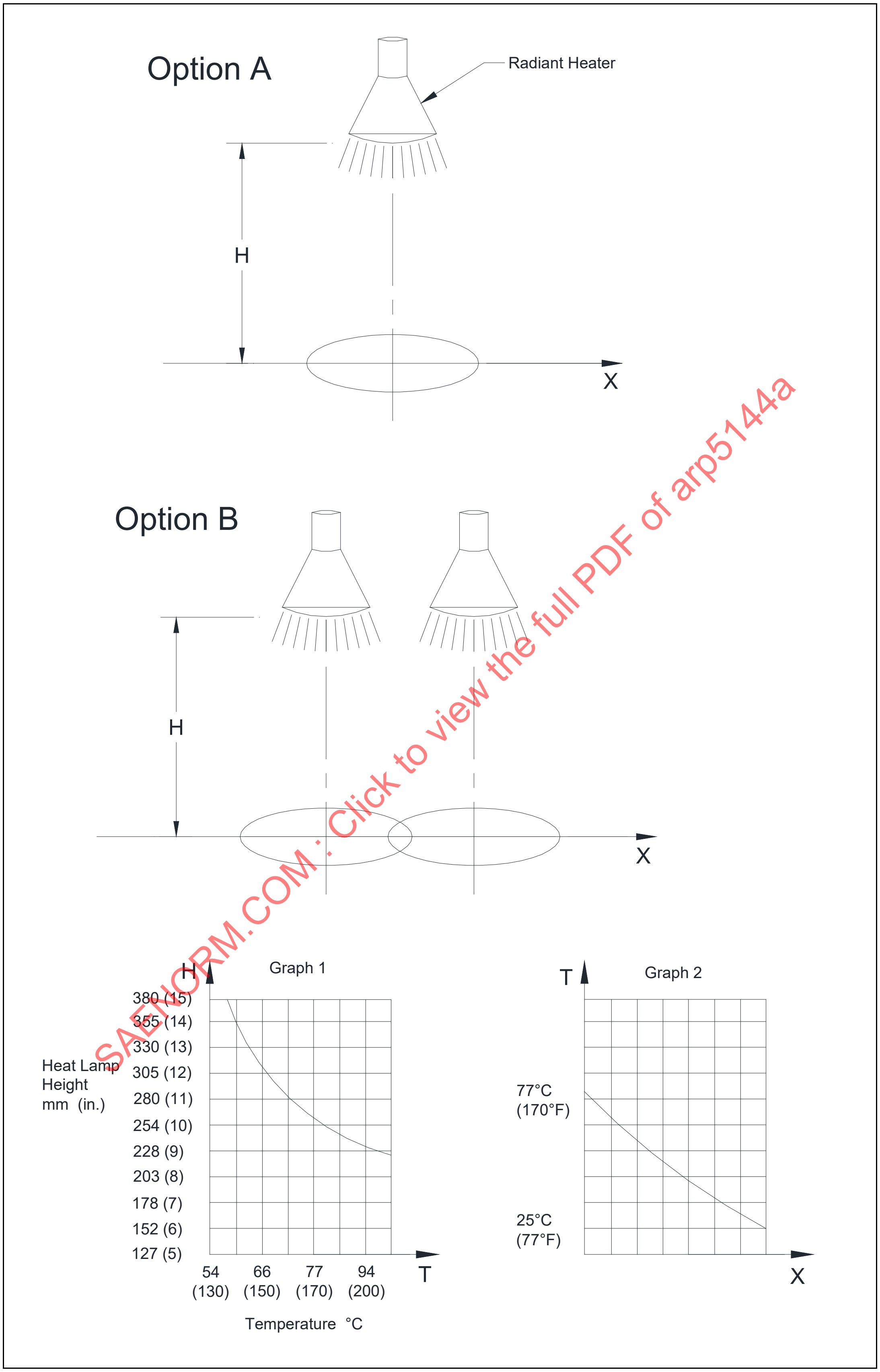


Figure 19 - Calibration of radiant heater

7.2.1 Installation of Radiant Heaters

a. Install one or more heaters to get the required temperature on the area to be repaired. Use the calibration graph to get the distance to the repair surface.

7.2.2 Caution for Application

Radiant heaters should be used with caution for irregular shaped surfaces. The radiant nature of these heaters makes uniform heat application difficult. They are very sensitive to the position relative to the part and can give differences in temperature between the center and the periphery of the infra-red beam.

NOTE: Environmental conditions will affect thermal uniformity during radiant heating. These factors include localized drafts which can be avoided using skirting material around the part.

Radiant heaters do not permit precise heat-up and cool-down rates unless controlled by a hot bonder or equivalent control device. When not controlled by a hot bonder, the repair area must be monitored for proper temperature distribution and cure profile. Except for shop repairs (no air flow), the curing cycle obtained is not generally reproducible.

Radiant heaters should preferably be limited to lower temperature curing and drying applications.

Radiant heaters can be used to provide supplemental heat to alleviate heat sink effects. Other common uses are to accelerate cure times for room temperature curing of potting compounds, coatings, and resins.

7.3 Hot Air Blower

Hot air blowers use thermal convection to heat the repair area.

7.3.1 Hot Air Blower Installation

Hot air blowers must be controlled by a hot bonder or equivalent using thermocouples on the repair part (see 6.6).

In order to improve the heat distribution, a closed support or enclosure around the part may be used. This permits a more uniform temperature over the repair (see Figure 20).

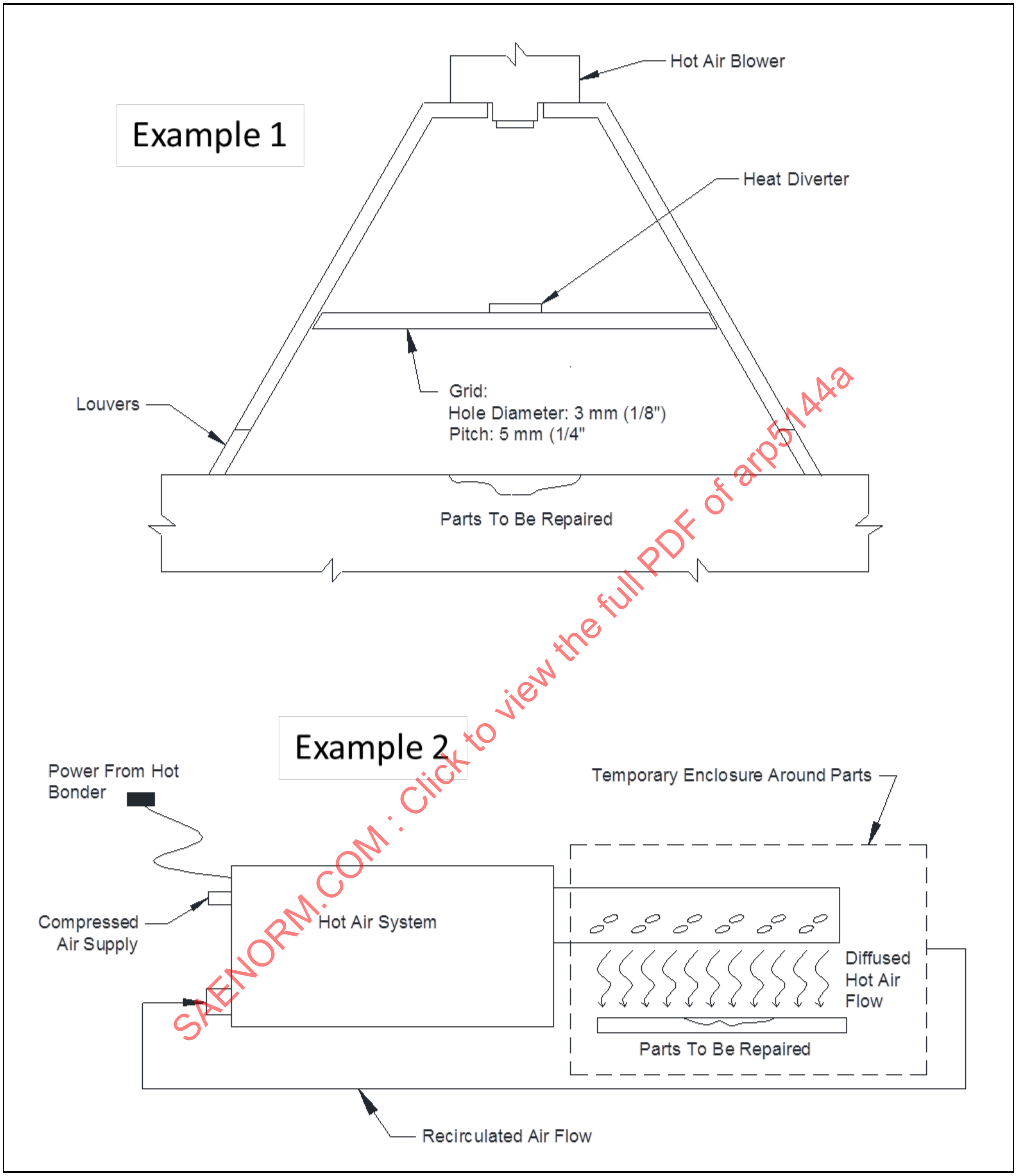


Figure 20 - Hot air blower heating of repair area

7.3.2 Caution for Application

When the hot air blower is controlled by a thermostat, the different curing phases (heat-up, cure period, and cool-down) cannot be followed accurately. If a hot bonder is used to control the hot air blower, then the cure profile can be controlled more readily. The fan of the hot air blower must be independently controlled to allow it to run constantly, varying the input to the heating element to control the temperature. Some hot air blowers do not require the use of a fan, and operate with compressed air to supply constant air flow.

The repair surface must be contained within the hot air enclosure. Special hot air blower support adaptors or enclosures may need to be used for some applications.

7.4 Ovens

Ovens offer controlled temperature (without pressure) environments which are used to cure low pressure or vacuum cured composite components but can only be used if the part being repaired is removed from the aircraft. Ovens are available in a range of sizes from bench type up to very large capacity, with doors at one or both ends, which may provide walk in capability.

A large thermal input is necessary to enable rapid temperature adjustments to be made. The oven should be capable of operating through a temperature range from room temperature up to 400 °F (200 °C). A forced circulating air system is required, with a baffling arrangement such that temperature in the oven can be maintained at ±10 °F (±5 °C). A vacuum system with sufficient capacity to service a number of independent vacuum take off points, together with gauges and valves to maintain a minimum of 22 in Hg (560 mm Hg) on all parts during cure is necessary. Each vacuum gauge or monitor should be connected to indicate the actual pressure on the part being cured. A stand-by vacuum system is recommended that can be immediately brought into operation in the event of failure of the primary system.

The oven should include an automatic recording control system to produce a permanent record of the thermocouple data for each temperature/time cure cycle. Consideration will have to be given to the heat control methodology. Control can be from the air temperature of the oven or from the actual part temperature. When controlling to part temperature, the thermal lag between the air temperature and the time the part temperature equalizes may lead to an overtemperature condition on the surface or bagging material. If control is to the oven air temperature, the cure time must be adequate to ensure the part reaches and is exposed to the required cure temperature per the material specifications to prevent an undercured condition.

7.5 Autoclaves

Autoclaves are used in the manufacture of composite parts. For repairs, autoclaves are typically used for extensive re-build, or when additional pressure beyond vacuum pressure is required. As with oven curing the part must be removed from the aircraft for repair.

In general an autoclave is a heated pressure vessel and its process depends on internal heat transfer from a pressurized gas to cure the repair. The gas is usually air, but for temperatures above 300 °F (150 °C) an inert gas such as nitrogen is recommended. Although more costly than air, in the event of an autoclave fire, the inert gas will not support combustion thus avoiding possible expensive downtime for repairs to plant and tooling. Fan assistance within the autoclave reduces temperature gradients and stagnation points of hot and cold zones by circulating the heated gas, such that the temperature is maintained within ±10 °F (±5 °C) of the set point at any location within the autoclave, when filled with the required number of parts to be repaired.

The pressurization system must be able to pressurize the volume of the autoclave quickly, and the control system be able to control pressures within 5 psi (35 kPa).

An adequate vacuum system is required to maintain vacuum pressure on the components during any part or all of the cure cycle. A vacuum monitoring system is required to display and record the vacuum in each bag.

The thermal input source (gas, electricity, for example) should be adequate to provide the temperature responses required during the cure cycle for the maximum number of components to be repaired in the autoclave. Some autoclaves allow for the use of heat blankets as a heat source within the autoclave. In general the autoclave should be capable of operating through a temperature range of 70 °F (20 °C) to 400 °F (200 °C). This should cover all epoxy repairs on aircraft structures.

Normally parts that are vacuum bagged/oven cured are subject to a pressure of 22 in Hg (560 mm Hg), equivalent to 11 psi (77 kPa). Some autoclaves can apply pressures up to 435 psi (3000 kPa), although a typical range for repairs is 25 to 90 psi (170 to 620 kPa). Autoclaves can thus give greater consolidation to the repair than could be achieved from oven curing.

Large damage sizes usually require the same level of tooling as was used in the original manufacture of the part. The choice of tooling can have an effect on heat-up rate for composite parts. Refer to AIR5431. Thin tools heat faster than thick tools. Tools that have well designed air flow paths, e.g., tools with egg crate support structures, heat-up faster than those without an open support structure. The actual location and orientation of tooling within the autoclave can also affect the heat-up rate.

Materials with a high thermal conductivity such as aluminium will heat-up faster than an equivalent steel or composite tool, which have lower thermal conductivities (see Table 1).

Steel and aluminium tooling have thermal expansions (CTEs) an order of magnitude greater than carbon composite tools. This emphasizes the need for thermal matching in tool design when repairing composite parts. Refer to AIR5431, where this topic is discussed in greater detail.

The autoclave should provide an automatic recording system for a permanent record of pressure and temperature for each cure cycle.

7.6 Caution for Application

Oven and autoclave curing overcomes the problem of single sided heating by heating up the whole part, not just the repair area. However, the areas not being repaired are subject to high temperatures which may cause deterioration to existing bonds and finishes. Support tooling and additional pressure above vacuum may be necessary if the oven or autoclave temperature is close to original cure temperature.

Loading parts into the oven or autoclave on a mix of tools with dissimilar thermal characteristics (i.e., tool mass, tool design, tool material) should be taken into consideration at the planning stage of all repairs. Failure to observe the effect of these tool variables could result in tools with low mass reaching cure temperature well in advance of tools with larger mass. The time difference could be significant which could result in overcure on some parts. Thermal capacity of the oven or autoclave is a critical factor with high tool loading and will dictate heat-up rates and final temperature capability.

Differing tool heat-up rates between the various parts to be repaired in a mixed loading could affect the gel point of the resins. The gel point will tend to increase with increasing heat-up rate and decrease with low heat-up rate. An attempt to achieve satisfactory heat-up rates on large mass tools may be different for low mass tools. What may be satisfactory for large mass tools may lead to exotherm and excessive temperature differentials on low mass tools.

Some cure schedules include a dwell period. The dwell allows the material to consolidate, and also allows the heat to dissipate which tends to reduce uncontrolled exotherms.

Unless cure schedules are nominally identical, then the curing of different resin types should not be carried out in the same autoclave or oven loading.

Parts should be spread evenly throughout the oven or autoclave to improve air circulation and to eliminate air stagnation points. This will assist in improving the temperature distribution between the various parts being cured.

If maintaining a uniform temperature distribution is in doubt, a "dry run" (thermal survey) on the tools alone will indicate the probable response from an actual cure.

7.7 Typical Steps in Oven and Autoclave Curing

The following are typical steps used in autoclave or oven curing. It is assumed that lay up and bagging of the component to be repaired has been made in a clean room or other suitably designated repair preparation area, and that vacuum is maintained on the component.

All parts must have their own dedicated thermocouples. These should be re-checked to ensure that they are functioning correctly after the component is positioned in the autoclave or oven and the thermocouples are connected to the recording device.

Include process test coupon panels, as part of the quality control process, if required by the repair document. It is preferable to locate the process test panel on an extension piece on the repair mold tool, in order to shadow the cure cycle being imparted to the part under repair. If this is not possible then the test panel should be positioned on a suitable structure that has similar thermal characteristics to the tooling used to repair the part in order to reproduce the cure conditions of the repaired component.

Computer systems are used on many autoclaves and ovens for monitoring and control of temperature, pressure and vacuum, thus permitting unattended and/or remote supervision of the repair process.

a. All parts that have the same cure cycle are placed in position in the oven or autoclave.

b. Vacuum hoses are re-connected to the oven or autoclave internal connectors so that vacuum pressure is registered on gauges outside the curing chamber.

c. Parts are re-checked to ensure that minimum vacuum has been obtained and there are no leaks. If the vacuum is lost during the transfer period it should be re-applied carefully. The assembly should be checked for bridging, movement, and leaks.

d. Doors are closed and the cure cycle begins.

e. For oven curing the vacuum pressure must be maintained at 22 in Hg (560 mm Hg), or as required by the repair document. The oven temperature is increased at the required rate.

f. For autoclave curing, apply pressure and raise temperature at the specified rates in accordance with the selected cure cycle. When the pre-determined autoclave pressure is reached, vent vacuum to atmosphere. Bag venting reduces porosity at the bond lines and within the laminates. Continue raising autoclave pressure to the required level.

g. It should be noted that any leaks under vacuum could result in back pressures within the vacuum bag during autoclave pressurization, leading to possible porosity, and to reduced cure pressure on the part being repaired.

h. Cure time (cure or hold phase) begins when the lowest reading thermocouple reaches the minimum specified cure temperature. Ensure all parts have reached the cure temperature before timing the start of the cure cycle. Hold parts at cure temperature for a time in accordance with the specified cure cycle. At no time shall any part exceed the specified cure temperature limits.

i. At the end of the cure cycle, cool assemblies at the specified rate in accordance with the cure schedule but maintain full pressure on the assemblies, both in the autoclave and in the oven.

j. When the temperature has fallen to 120 °F (50 °C) as measured by all thermocouples, reduce autoclave pressure. When pressure in the autoclave falls to 10 psi (70 kPa) re-apply full vacuum to the part(s).

k. All parts both in the autoclave and oven should be cooled below 120 °F (50 °C) while still under vacuum pressure to minimize thermal shock and deformation.

l. When pressure reaches 0 psi in the autoclave, unlock lock ring on autoclave door and open.

m. Before removing vacuum lines, confirm that bag is still under vacuum pressure. If it is not, and bag failure is suspected inspect repair carefully.

n. Disconnect vacuum lines and thermocouples and remove assemblies.

o. Remove the charts for the cure cycle just completed. List relevant details.

p. Remove part from tooling and check repair integrity.

q. Pass test pieces to Quality Control (if requested in the repair instruction).

NOTE: Some resin systems require a post cure to enhance the crosslinking density which is carried out at a temperature higher than the initial cure temperature. Post curing can be programmed as an extension of the initial cure and carried out while still in the oven or autoclave.

Alternatively post curing can be undertaken following removal from the oven or autoclave in a separate heating environment immediately or postponed to a later date. Time interval between curing and post cure should be kept to a minimum.

Some post curing is undertaken “free standing”, i.e., after the part has been demolded, usually in order to free the tools for another repair application. The practice of free standing post curing carries a risk of part warping or distortion. Some form of support to the part is recommended to minimize this possibility.

The method/choice of post curing is invariably based on technical/commercial considerations and linked to maximizing scheduling of parts to be manufactured or repaired.

7.8 Hot bonders (Curing Console)

Hot bonders, sometimes referred to as curing consoles, are commercially available to ease the practical application of the curing process (see Figure 21). Hot bonders are portable or fixed units and control the time/vacuum/temperature cycle required for repair curing. Heat blankets and vacuum or pressure hoses are connected to these consoles. Heat-up rate, cooldown rate, cure duration, and temperature are usually computer controlled. Most curing consoles provide a printed or digital record showing all the curing data (duration of each step, temperatures, pressure, alarm message) at time intervals compatible with the repair curing requirements. Records should be maintained to verify compliance with the Repair Document cure cycle requirements and to satisfy regulatory requirements.

Figure 21 - Typical hot bonders

Hot bonders are available with various power ratings, typically capable of up to 7200 W per zone (this example is based on 240 V and 30 A rating). Using a heat blanket with a rating of 5 W/in^2 (0.775 W/cm^2) means that a heat blanket size of up to 38 inch x 38 inches (965 mm x 965 mm) can be used. Heat blankets are typically sized to allow for a 2 inch (50 mm) overlap beyond the repair area. A maximum spacing between individual thermocouples of 12 inches (300 mm) is considered satisfactory for temperature monitoring of a repair. A lower rating heat blanket, i.e., less than 5 W/in^2 (0.775 W/cm^2) will enable a larger area to be repaired but may limit the maximum temperature which the heat blanket is able to achieve. A higher voltage will also allow a larger heat blanket to be used as illustrated in Figure 22. Extra thermocouples should be taken into account for a larger area to ensure that proper spacing is maintained.

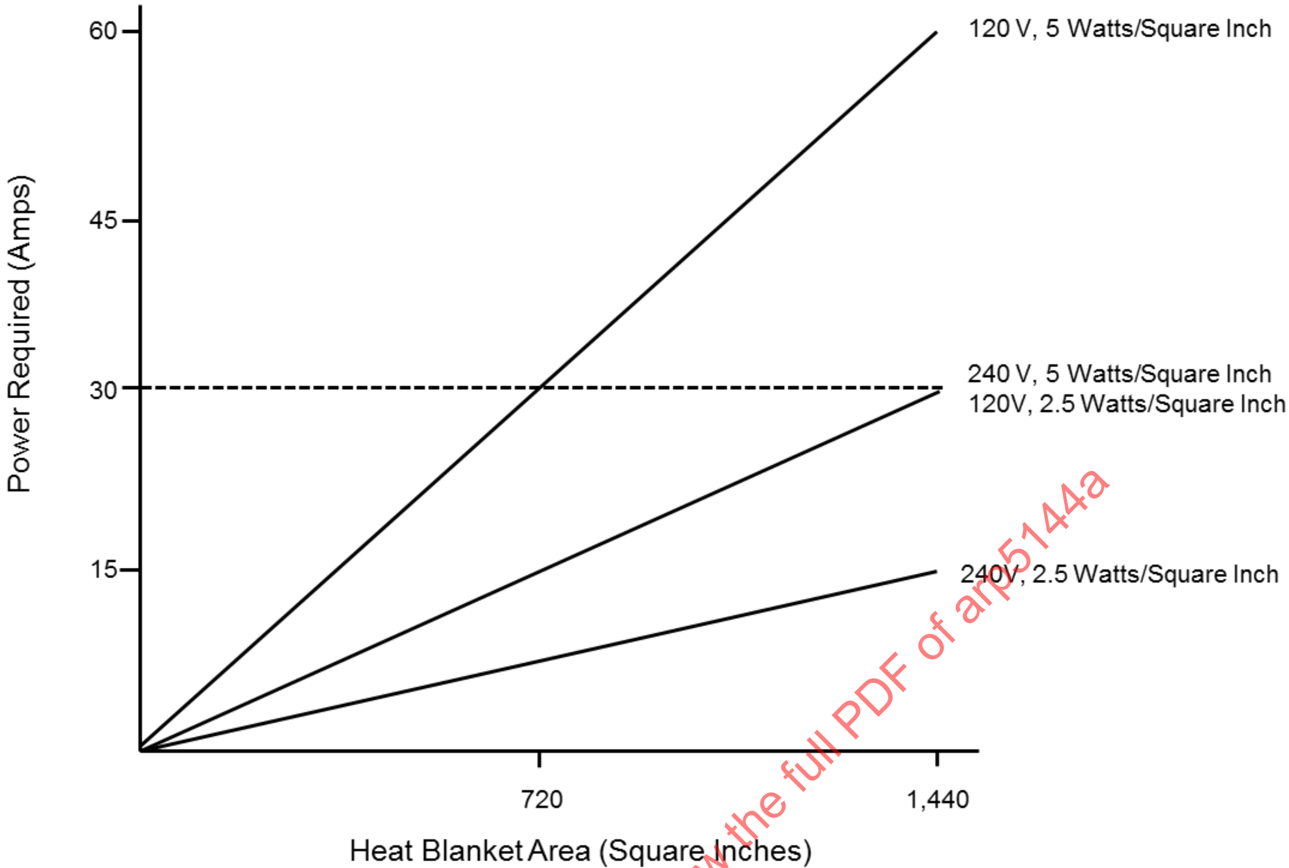


Figure 22 - Power requirement versus repair size

Larger areas will require additional hot bonders or a hot bonder with a higher amperage power rating, based on the assumption that 5 W/in^2 (0.775 W/cm^2) blankets are being used. Equipment is available for increasing the power output from a common hot bonder by using a secondary power system with higher amperage capability. The calculated heat blanket amperage requirement must not exceed the rated amperage of the hot bonder or accessory to which it is connected.

Some hot bonder models may be interconnected to run a common cure profile across multiple hot bonders. Using multiple heat blankets controlled by more than one hot bonder can improve thermal uniformity for larger repair areas and areas with complex thermal characteristics. This approach allows each heat blanket to be cured to a common temperature profile, while controlling temperature for each heat blanket independently.

Common control modes available in hot bonders include average, hottest, coldest, and individual thermocouple control. Various alarm modes are also available in most hot bonders. These alarms include high and low temperature limit alarms, power failure, and vacuum alarms.

NOTE: It is recommended to use a hot bonder that has capability for multiple alarm thermocouples. However, if a hot bonder only has a single alarm thermocouple it is critical that this thermocouple is placed in the hottest area of the repair to avoid heat damage. It is preferable to use a hot bonder that automatically selects and monitors the hottest thermocouple. The coldest (lagging) thermocouple is used to determine the cure time.

Calibration of hot bonders should be performed on a yearly basis in accordance with industry standards.

7.8.1 Caution for Application

Some hot bonders use a thermocouple embedded in the heat blanket to control the cure. The temperature of the repair and the temperature of the heat blanket are different. The temperature of the coolest repair thermocouple should be used for control. Use the thermocouple in the blanket only to make sure that the blanket does not exceed its design temperature. Add extra thermocouples and use those for control.

Electrical overloading of the power supply of a hot bonder carries some risk of blown fuses or tripped circuit breakers which at a critical point of a cure could compromise the repair. This needs to be considered during the equipment planning stage of the repair. Attention should be given to the power requirements of the heat blanket being controlled, power capacity of the hot bonder, electrical plugs and cabling used with the hot bonder, and the electrical power source where the hot bonder is connected.

Some hot bonders use only one thermocouple to control repair temperatures and some hot bonders can monitor several thermocouples but can only control from one thermocouple or the average of all thermocouples. This is not necessarily the trailing thermocouple. The solution is to switch through the thermocouples to find the coolest one when the curing phase, sometimes referred to as the hold phase or hold temperature, is approaching. Use the coolest one to control the hold temperature. The remaining thermocouples should be monitored with a separate recorder.

Some hot bonders have small charts which cannot accurately record the parameters. An external recorder should be used with these devices.

Some hot bonders use venturi type vacuum devices with limited capability. If the vacuum source with the unit is not capable of obtaining a minimum of 22 in Hg (560 mm Hg) on the vacuum gauge, the vacuum pump should be supplemented with an external pump.

8. REPAIR CURING

8.1 Process Control

Ensure that all equipment is calibrated or verified.

Operators must be trained to an approved standard. Refer to AIR4938.

To confirm a satisfactory repair has been made, data on each phase of the curing cycle shall be reviewed and recorded (see 8.2).

8.2 Cure Records

Record keeping and retention periods shall be in accordance with National Aviation requirements. the records must include heating and cooling rates, alarms and warning, cure time, cure temperature, cure temperature deviations, vacuum pressure and vacuum pressure alarms, and a thermocouple location map. Care should be taken to ensure that thermocouple numbering is consistent between all cure records (maps, diagrams, data output from heating devices, etc.).

Examples of typical cure records are given in Figures 23 through 27.

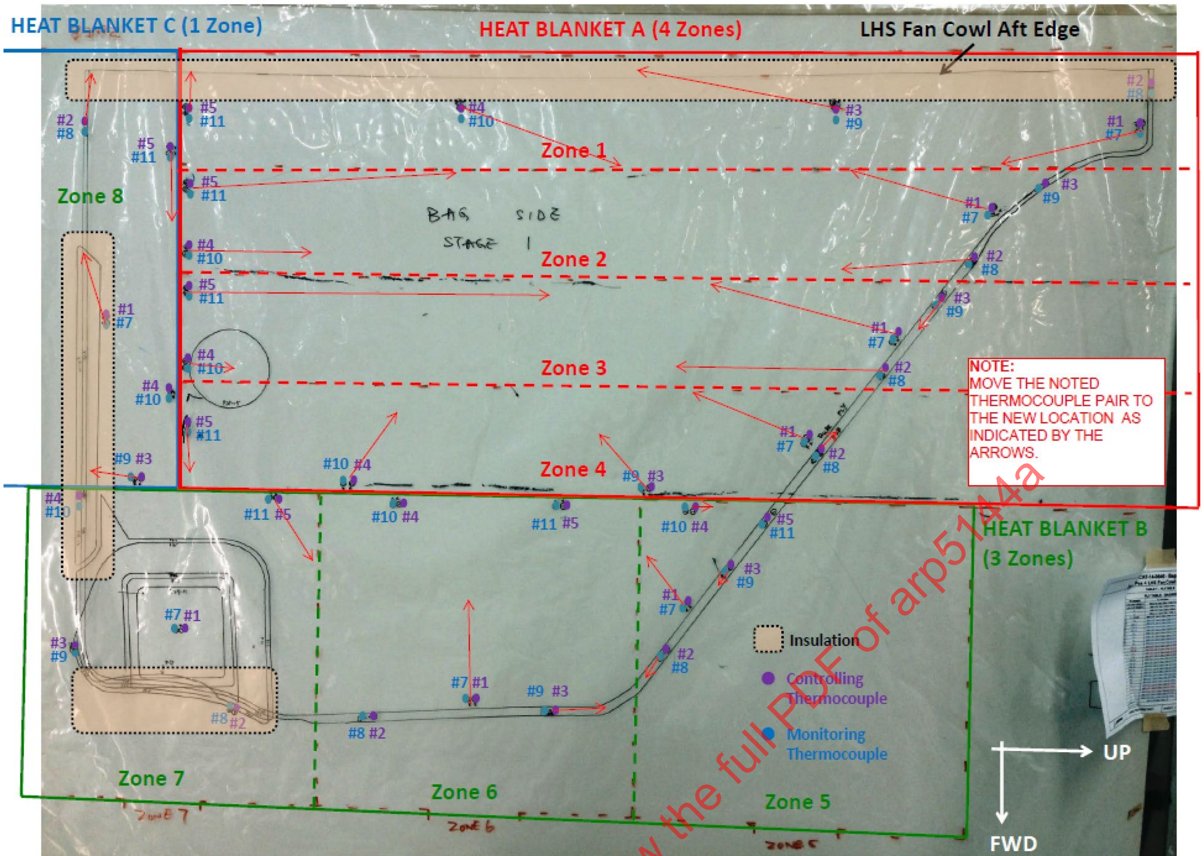


Figure 23 - Example of thermocouple locations for multiple zone repair

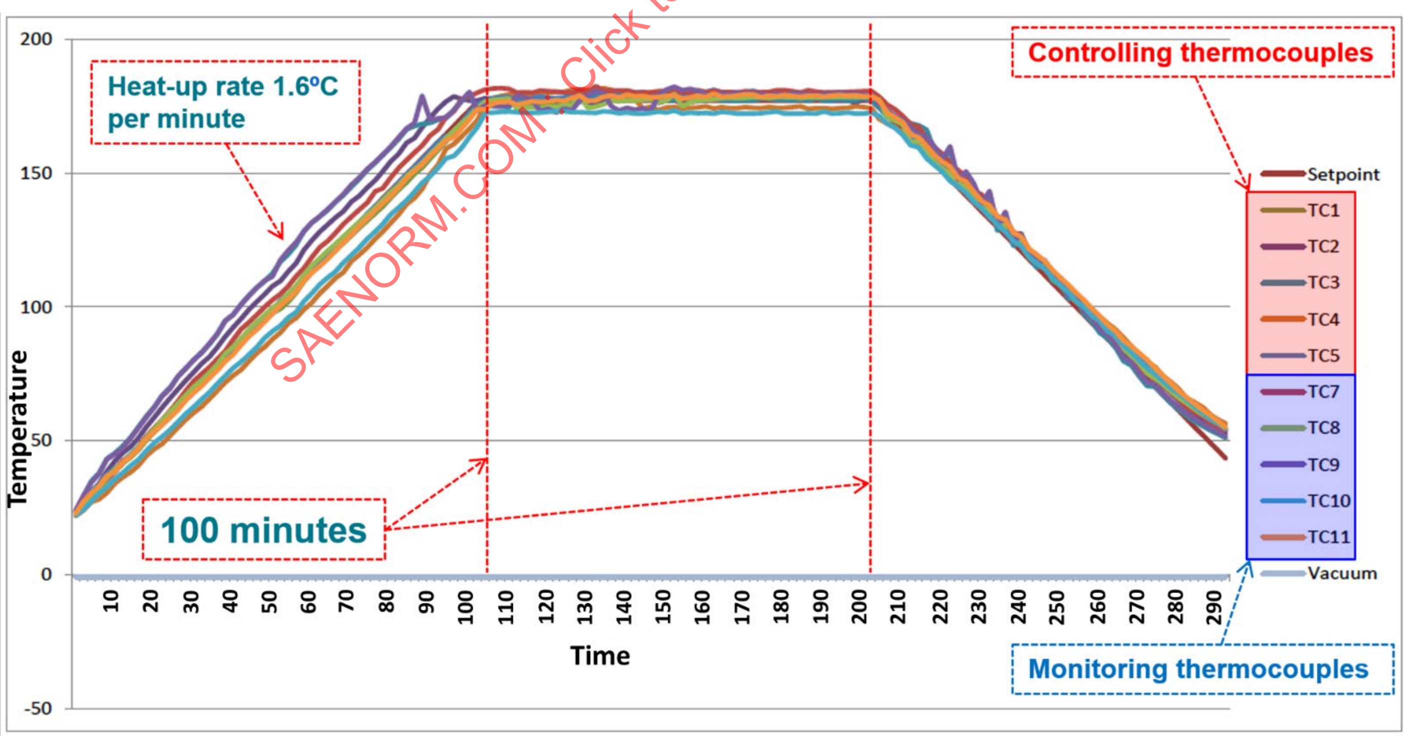


Figure 24 - Example of cure temperature record for one zone

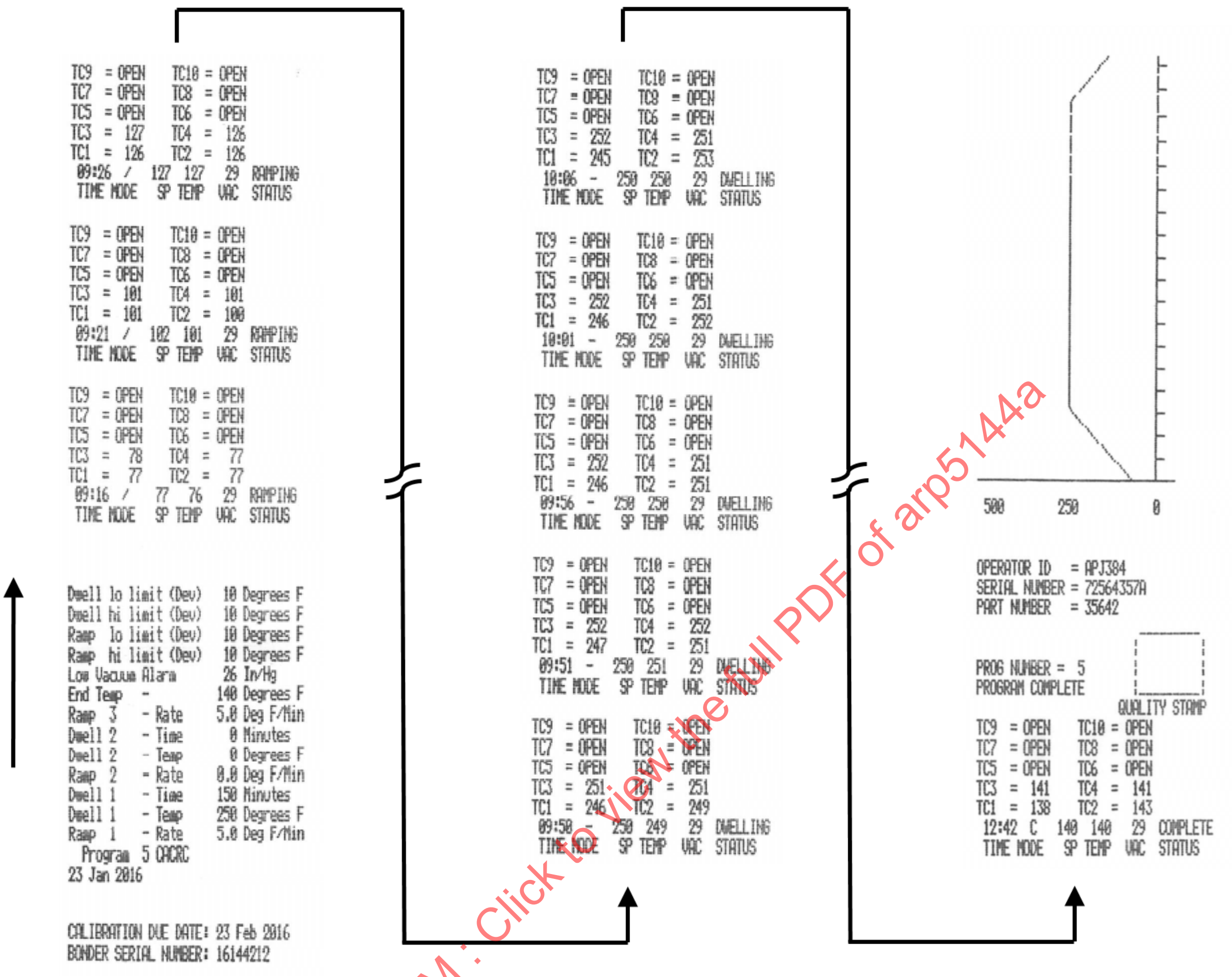


Figure 25 - Example of hot bonder cure record

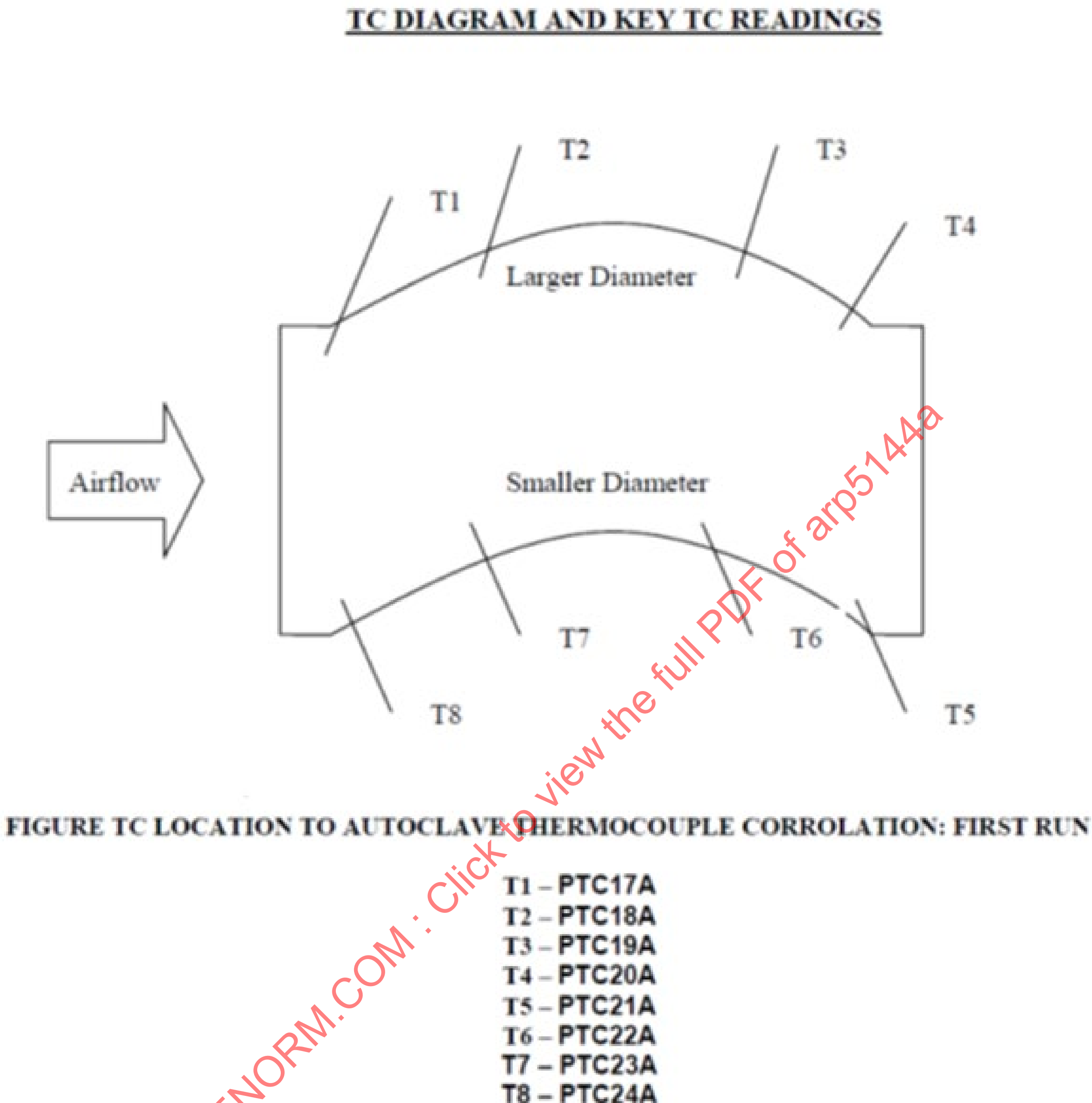


Figure 26 - Example of thermocouple location in autoclave

- Autoclave #1

Numeric Report - Part

LoadNumber:	4288	OperatorName:	
Equipment:	Autoclave	RecipeDesc:	Cure Cycle #6
Recipe Spec:		Recipe Revision:	
Recipe Mod:	4/21/2010 7:57:42 PM	Recipe Audit #:	N/A
DataFile:	AC4-20100421-003.DAT	Report Date:	Monday, July 19, 2010, 11:01:55 AM
Run Start:	Wednesday, April 21, 2010, 8:02:34 PM	Run End:	Thursday, April 22, 2010, 12:32:10 AM

PART & TOOL INFORMATION

#	WITH	FIELD NAME	FIELD VALUE
1	NA	PartNumber	: C192858/002
		SerialNumber	: 1344654-1
		ToolNumber	: 4160
		PartName	: PW2000 NOSE COWL PANEL

ATTACHMENT INFORMATION

PARTTC	PRB	SRC	OTHERS	LEAKAMT/REQ
PTC17A	VPRB4	VPRB1		1.6 / 5.0
PTC18A		VPRB3		
PTC19A				
PTC20A				
PTC21A				
PTC22A				
PTC23A				
PTC24A				

? Indicates a disabled thermocouple.
S Indicates a change of segment record.

Time	Mins.	PRESS Psig	AIRTC Deg.F	PTC17A Deg.F	PTC18A Deg.F	PTC19A Deg.F	PTC20A Deg.F	PTC21A Deg.F	PTC22A Deg.F	PTC23A Deg.F	PTC24A Deg.F
20:02:34	0.0	-1.8	96.4	80.7	83.1	80.8	80.2	81.7	82.0	80.4	81.6
S20:02:34	0.0	-1.8	96.4	80.7	83.1	80.8	80.2	81.7	82.0	80.4	81.6
S20:05:13	2.7	10.0	105.8	86.5	88.8	85.1	85.5	86.2	87.1	87.2	87.3
20:09:36	7.0	27.0	109.0	91.9	93.8	91.6	90.5	92.2	92.3	92.1	92.7
20:14:36	12.0	35.5	125.3	99.0	100.8	99.0	98.2	99.5	99.5	99.4	100.3
20:19:36	17.0	35.6	157.6	114.3	116.0	113.7	113.3	114.3	114.6	115.1	116.2
20:24:36	22.0	35.6	183.3	132.3	133.9	[illegible]	130.8	131.9	132.7	133.3	134.6
20:29:36	27.0	35.5	204.6	151.4	153.2	150.3	148.9	151.0	151.6	151.8	153.6
20:34:36	32.0	36.0	227.1	171.3	173.2	170.1	167.6	170.9	171.0	171.4	173.1
20:39:36	37.0	35.7	247.1	190.6	192.1	189.4	186.3	190.2	190.3	190.4	192.1
20:44:37	42.1	35.7	267.6	210.3	[illegible]	209.4	205.3	210.1	209.9	209.3	211.8
20:49:36	47.0	35.4	288.3	230.4	231.7	229.6	224.6	229.8	229.1	229.1	230.7
20:54:36	52.0	35.5	310.5	250.3	250.7	250.1	244.9	249.6	248.8	248.9	249.5
20:59:36	57.0	36.0	330.8	270.7	270.9	270.6	265.3	269.7	268.6	269.4	269.7
21:04:36	62.0	35.9	350.4	291.1	291.1	290.7	284.8	290.2	288.6	289.9	290.2
21:09:36	67.0	35.9	369.8	311.0	311.1	308.3	304.1	310.0	308.3	310.7	310.7
21:14:36	72.0	35.4	378.1	329.8	330.0	324.3	322.2	328.8	326.5	329.8	329.4
21:19:37	77.1	34.9	367.4	339.1	341.0	335.3	331.3	337.9	335.7	339.0	338.2
21:24:36	82.0	34.7	[illegible]	344.2	346.7	342.2	337.4	343.4	341.2	343.9	343.1
S21:28:31	86.0	34.4	[illegible]	345.7	348.7	344.8	340.0	345.1	343.2	345.1	344.4
21:28:36	86.0	34.3	354.6	345.7	348.7	344.8	339.9	345.1	343.2	345.1	344.4
21:33:36	91.0	34.3	347.8	345.3	348.2	345.6	341.1	345.1	343.2	344.5	343.9
21:38:37	96.0	34.5	346.5	344.9	347.2	345.4	341.9	344.7	343.3	343.9	343.6
21:43:36	101.0	[illegible]	348.5	345.3	346.9	345.6	343.3	345.2	344.1	344.3	344.0
21:48:37	106.1	34.4	350.3	346.2	347.3	346.3	344.7	346.0	345.2	345.2	345.0
21:53:36	111.0	34.7	351.3	347.1	348.0	347.1	345.9	347.0	346.3	346.1	346.1
21:58:36	116.0	34.6	351.3	347.7	348.6	347.8	346.8	347.7	347.1	346.8	346.7
22:03:36	121.0	34.6	351.1	348.1	349.0	348.2	347.4	348.3	347.7	347.2	347.2
22:08:36	126.0	34.6	351.0	348.4	349.1	348.6	347.8	348.6	348.1	347.4	347.6
22:13:37	131.1	34.5	350.9	348.6	349.3	348.8	348.2	349.0	348.4	347.7	347.8
22:18:37	136.1	34.5	350.6	348.7	349.4	348.9	348.4	349.0	348.5	347.8	347.9
22:23:36	141.0	34.6	350.7	348.8	349.4	348.9	348.5	349.2	348.7	347.9	348.0
22:28:36	146.0	34.5	350.6	348.8	349.4	349.1	348.6	349.3	348.8	347.9	348.1
22:33:37	151.1	34.7	350.6	348.9	349.4	349.0	348.7	349.3	348.9	347.9	348.2
22:38:36	156.0	34.6	350.5	348.9	349.5	349.1	348.8	349.4	348.9	347.9	348.2
22:43:36	161.0	34.7	350.6	348.8	349.4	349.1	348.7	349.3	348.9	348.0	348.2
22:48:36	166.0	34.6	350.6	349.0	349.4	349.2	348.8	349.5	349.0	348.0	348.2

Figure 27 - Example of autoclave cure record