



AEROSPACE RECOMMENDED PRACTICE

ARP5144™**REV. A**

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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.

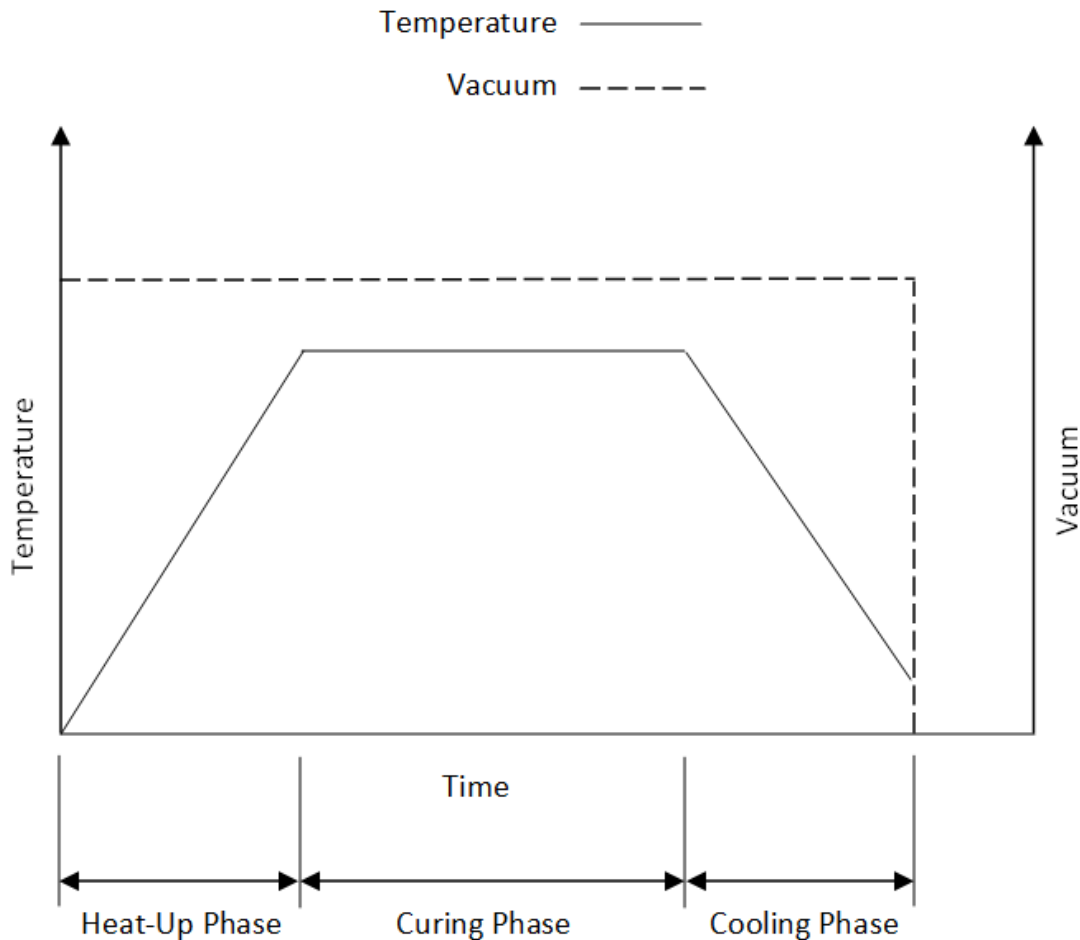


Figure 1 - Cure cycle

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.

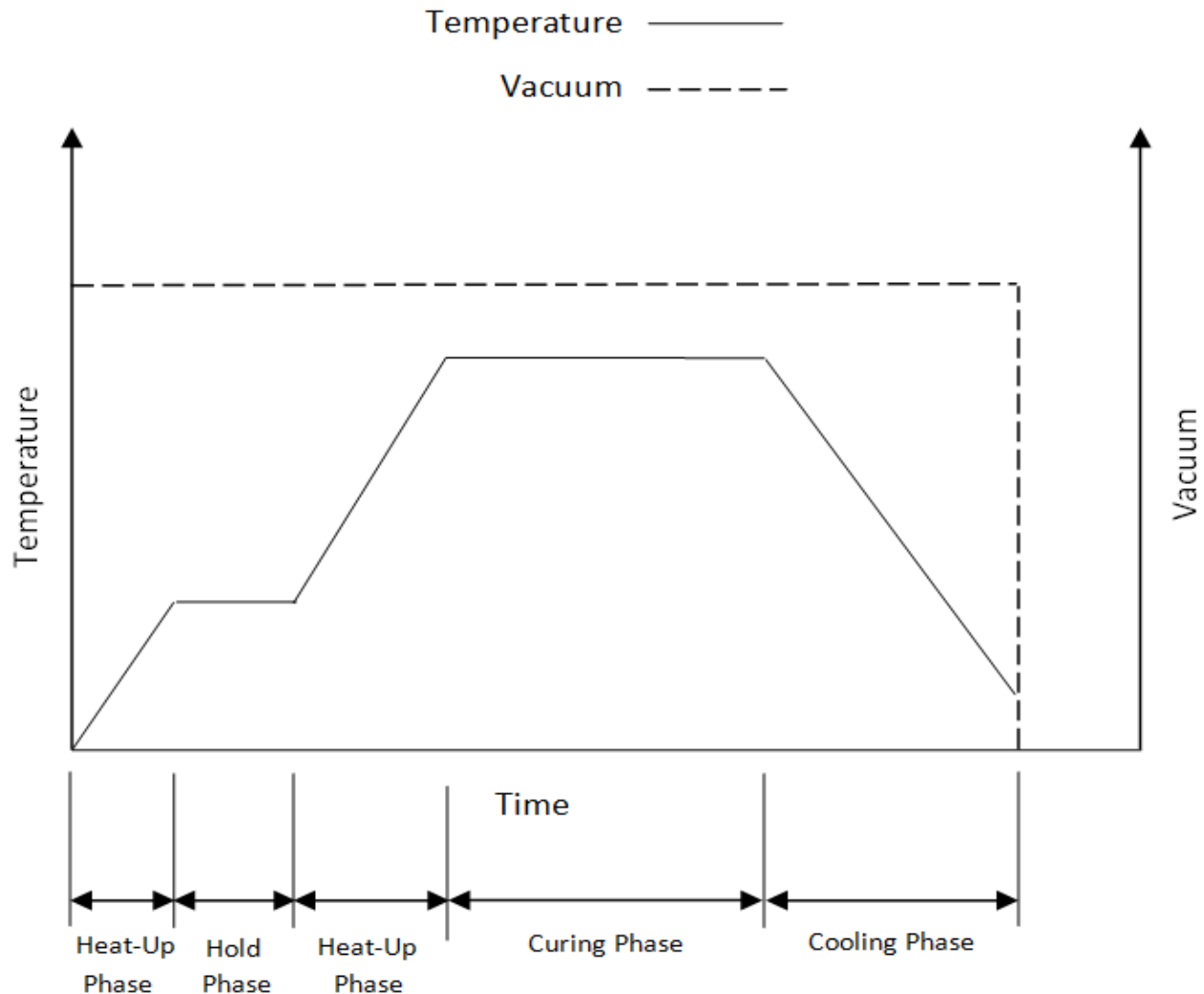


Figure 2 - Step cure cycle

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.

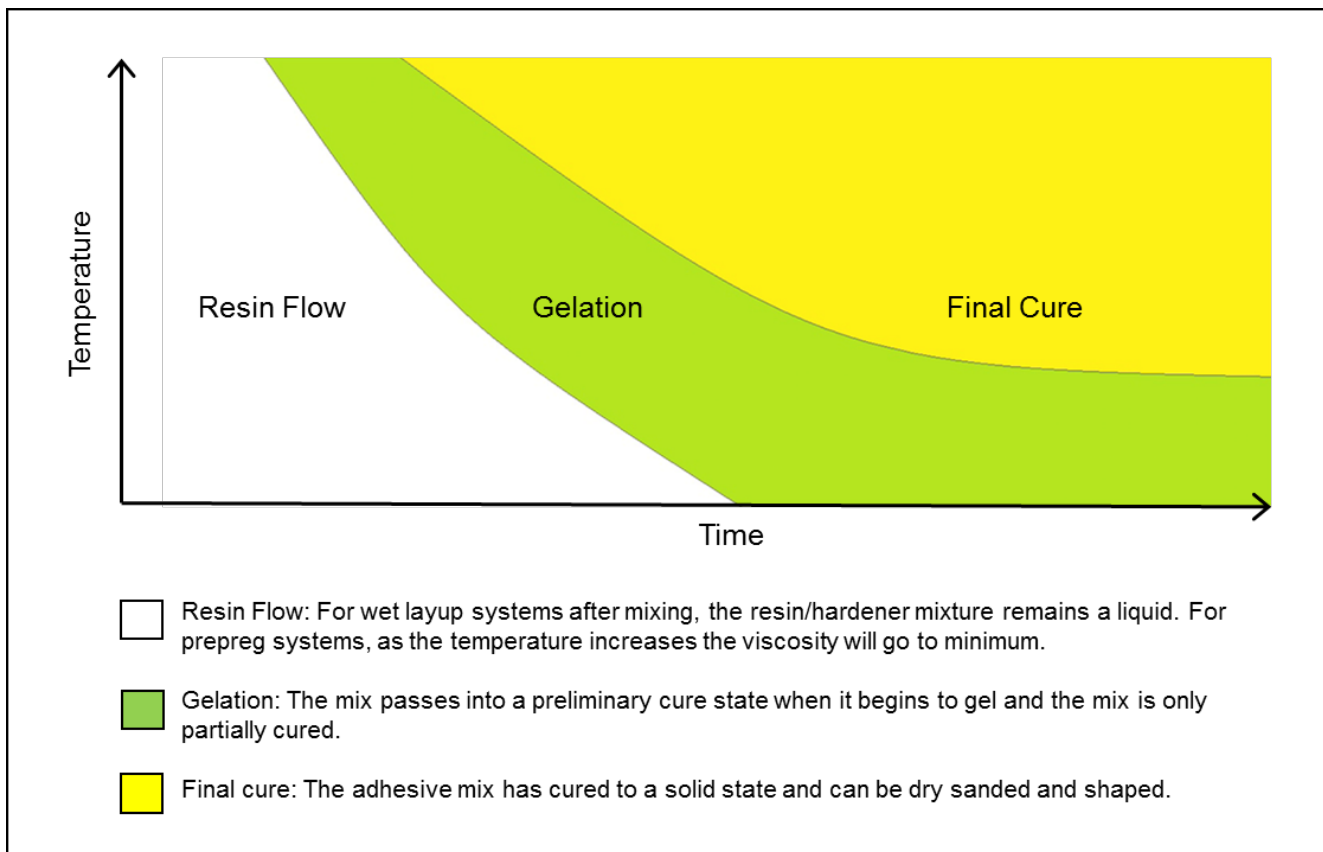


Figure 3 - Cure stages

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.		

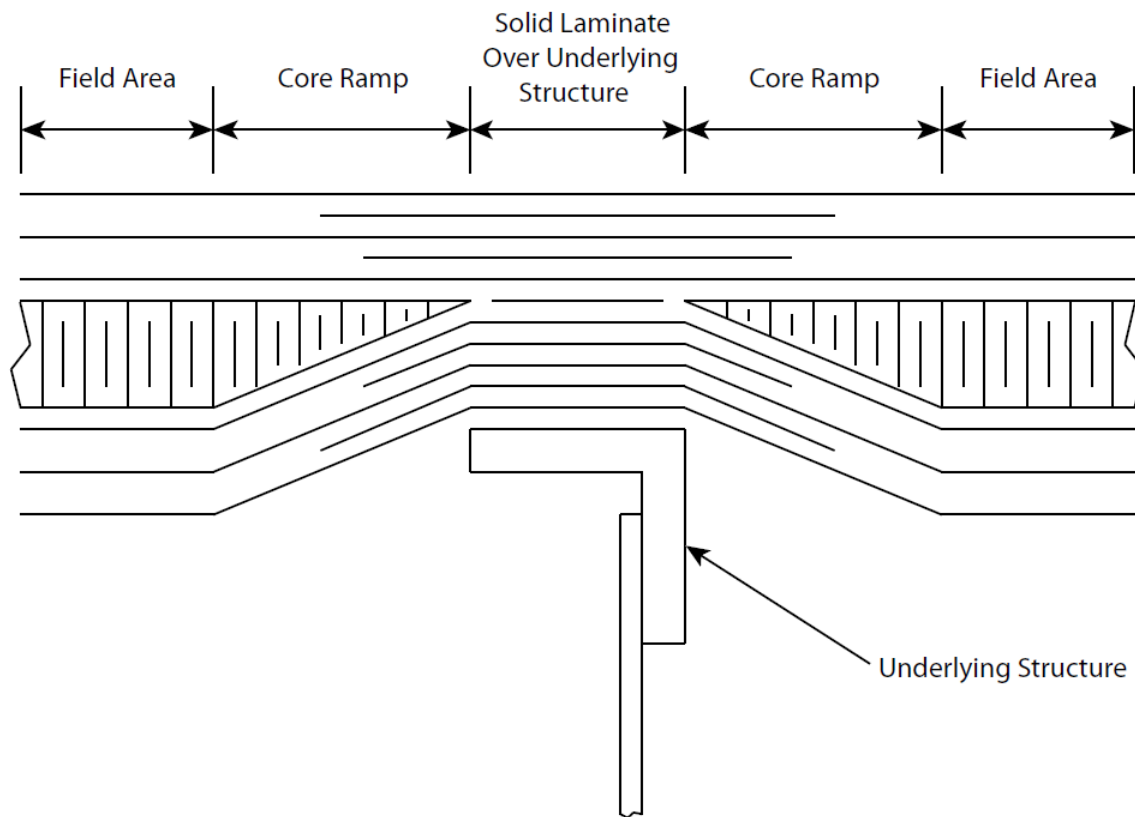
Gases like still air are poor conductors.

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.

Examples of areas with different thermal mass in close proximity

**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:

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

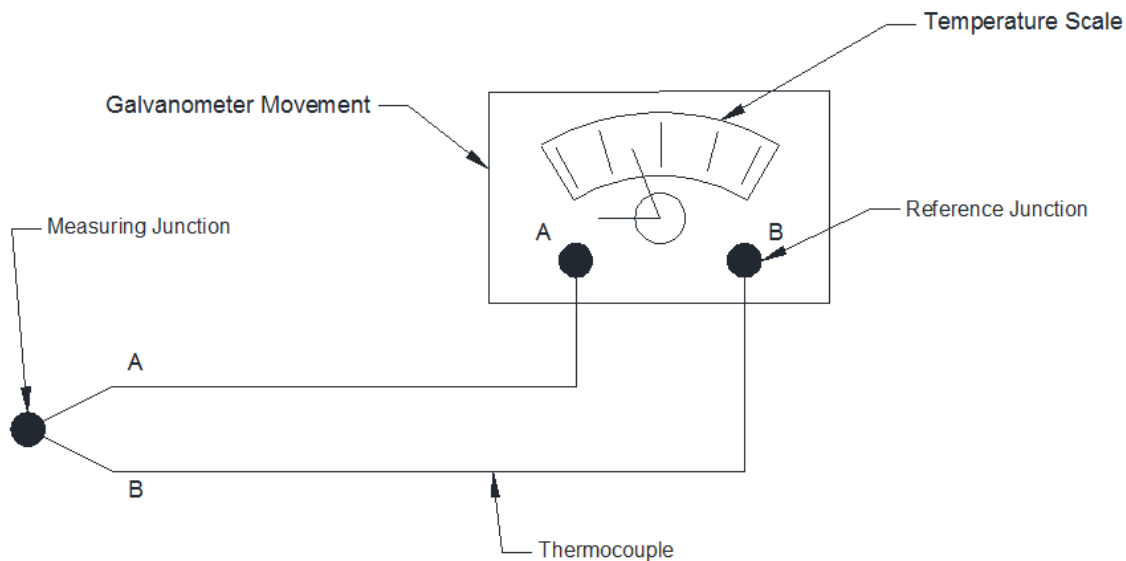


Figure 5 - Thermocouple circuit using galvanometer

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.

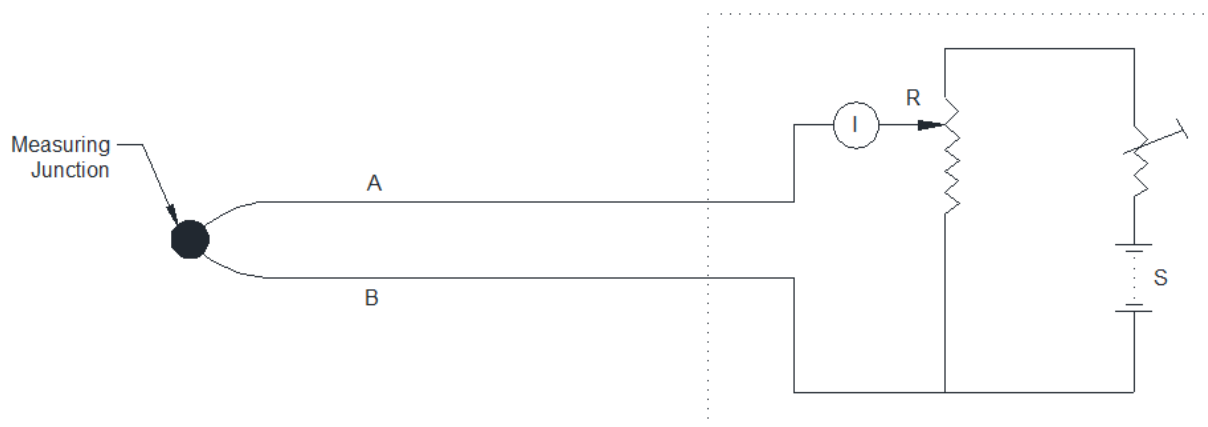


Figure 6 - Thermocouple circuit using potentiometer

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.

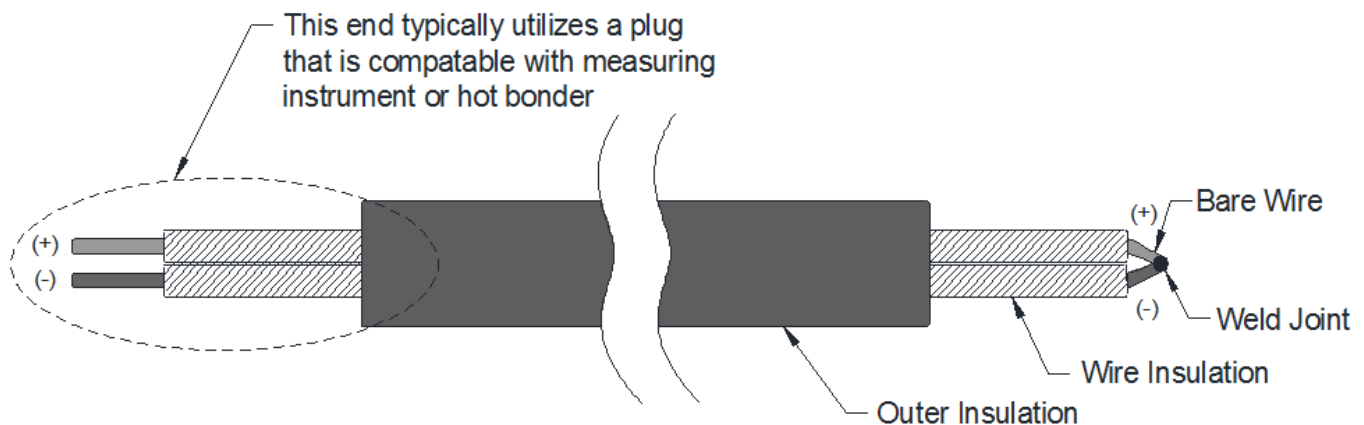


Figure 7 - Thermocouple with welded joint

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.

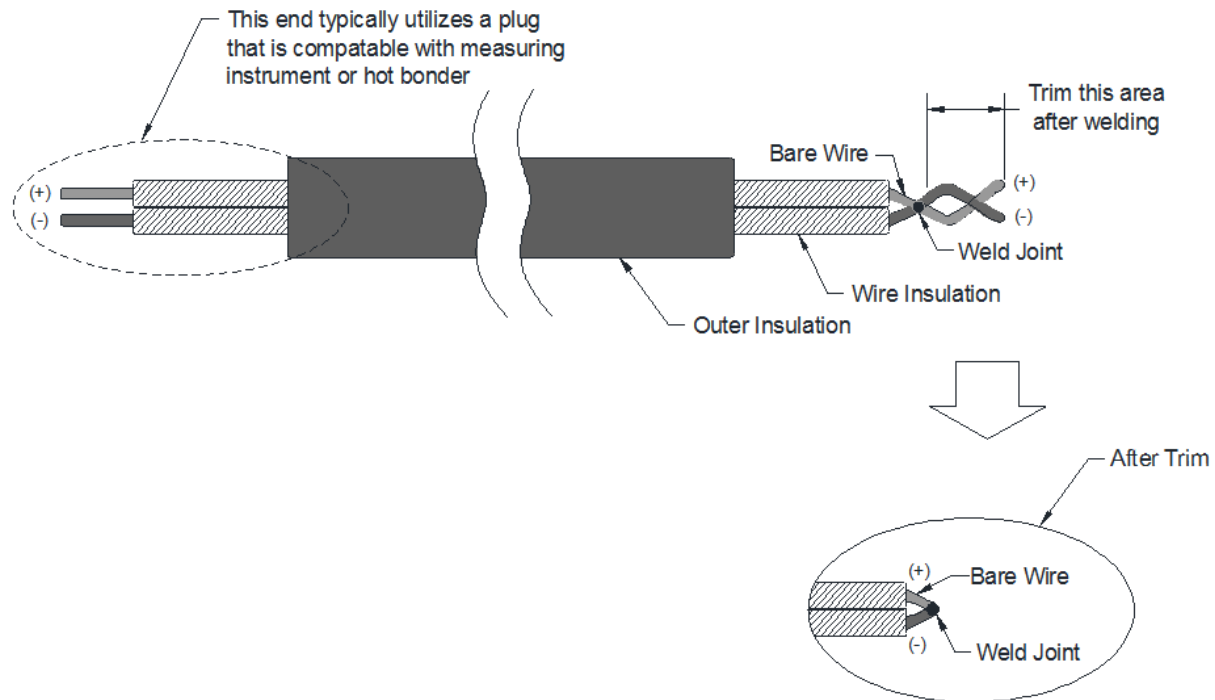


Figure 8 - Thermocouple manually twisted before resistance welding

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.