CHAPTER 3 QUALITY CONTROL OF PRODUCTION MATERIALS AND PROCESSES

3.1 INTRODUCTION

Quality conformance tests are needed to assure the continued integrity of a previously characterized material system. The tests performed must be able to characterize each batch/lot of material so a proper assessment of critical properties of a material system can be made. These critical properties provide information on the integrity of a material system with regard to material properties, fabrication capability, and usage. Additionally, the test matrix must be designed to economically and quickly evaluate a material system.

Quality control in a production environment involves inspection and testing of composites in all stages of prepreg manufacture and part fabrication. Tests must be performed by the material supplier on the fiber and resin as separate materials, as well as on the composite prepreg material. The user of the prepreg must perform receiving inspection and revalidation tests, in-process control tests, and nondestructive inspection tests on finished parts. These tests are described in the following sections and normal industry practice is discussed.

3.2 MATERIAL PROCUREMENT QUALITY ASSURANCE PROCEDURES

3.2.1 Specifications and documentation

The specification for materials, fabrication processes, and material testing techniques must ensure compliance with the engineering requirements.

Chapters 3, 4, and 6 in Volume 1 of this handbook describe acceptance test methods for characterizing fiber, matrix, and resin-impregnated fiber materials by their chemical, physical, and mechanical properties. Sections 3.3 and 3.4 of this volume provide information on variable statistical sampling plans that are based on MIL-STD-414 (Reference 3.2.1(a)). These plans control the frequency and extent of material property verification testing to achieve targeted quality levels.

The specifications for destructive and nondestructive test equipment and test methods should contain test and evaluation procedures. These procedures need to describe the means by which the equipment will be calibrated to maintain the required accuracy and repeatability; they should also establish the calibration frequency. Information on the standards to be used in the calibration of chemical analysis equipment will be found in preceding sections of this handbook which deal with the particular test technique.

The standards for quality control documentation requirements are found in military and federal specifications such as the Federal Aviation Regulation Part 21 "Certification Procedures for Products and Parts" used by the Federal Aviation Administration production approval holders (Reference 3.2.1(b)).

3.2.2 Receiving inspection

The composite material user typically prepares material specifications which define incoming material inspection procedures and supplier controls that ensure the materials used in composite construction will meet the engineering requirements. These specifications are based on material allowables generated by allowables development programs. The acceptance criteria for mechanical tests must be specified to assure that production parts will be fabricated with materials that have properties equivalent to the materials used to develop the allowables.

The user material specifications typically require the suppliers to provide evidence that each production lot of material in each shipment meets the material specification requirements. This evidence will in-

clude test data, certification, affidavits, etc., depending upon the user quality assurance plan and purchase contract requirements for a particular material. The test reports contain data to verify the conformance of material properties to user specifications and acceptance standards.

Acceptance test requirements may vary from user to user. However, the tests must be sufficient to assure the material will meet or exceed the engineering requirements. A typical example of acceptance tests required for carbon/epoxy unidirectional tape is shown in Table 3.2.2. Note that Table 3.2.2 is divided into two parts. The first part concerns uncured prepreg properties. The purpose of these tests is to assure that the resin and fibers materials are within acceptable limits. The second part involves tests on cured laminates or laminae. The mechanical property tests should be selected to reflect important design properties. They can be direct tests of a property or a basic test that correlates with critical design properties. The 90°/0° tension test evaluates the fiber strength and modulus. The 90°/0° compression test evaluates the reinforced fiber/resin combination. The compression testing also includes hot dry tests since one resin-dependent mechanical property should include elevated temperature tests to ensure the material's temperature capability . A shear test should be run as a resin evaluation. The short beam shear test or the ±45° tension test should be used depending on the end product's emphasis on interlaminar or in-plane properties.

Receiving inspection test requirements should address test frequency and, in the event of initial failure to satisfy these requirements, retest criteria. Test frequency is a function of the quantity of material (weight and rolls) in a batch. Typical testing may include specimens from first, last and random rolls. A retest criteria should be included for the cured lamina tests so that the material is not rejected because of testing anomalies. If a material fails a test, a new panel from the same suspect roll of material should be fabricated and used to rerun that specific test. If a batch has multiple rolls, that test should run on material from the roll before and after the suspect roll in order to isolate the potential problem. If the material fails the retest, the entire batch should be reviewed by material engineering. As use and confidence increase, the receiving inspection procedure can be modified. For example, the test frequency can be decreased or certain tests can be phased out.

3.3 PART FABRICATION VERIFICATION

3.3.1 Process verification

The quality assurance department for the user generally has the responsibility for verifying that the fabrication processes are carried out according to engineering process specification requirements. The wide range of activities to control the fabrication process are described below.

Material Control: The user process specifications must set the material control for the following items as a minimum.

1. Materials are properly identified by name and specification.
2. Materials are stored and packaged to preclude damage and contamination.
3. Perishable materials, prepregs and adhesives, are within the allowable storage life at the time of release from storage and the allowed work life at time of cure.
4. Prepackaged kits are properly identified and inspected.
5. Acceptance and reverification tests are identified.

Materials Storage and Handling: The user material and process specifications set procedures and requirements for storage of prepregs, resin systems and adhesives to maintain acceptable material quality. Storing these materials at low temperatures, usually 0°F or below, retards the reaction of the resin materials and extends their useful life. Negotiations between the supplier and user result in an agreement on how long the supplier will guarantee the use of these perishable materials when stored under these conditions. This agreed to time is incorporated as one of the requirements in the user material specification.

TABLE 3.2.2 *Typical acceptance and revalidation tests required for suppliers and users.*

PROPERTY	TESTING REQUIRED			SPECIMENS REQUIRED PER SAMPLE
	PRODUCTION ACCEPTANCE (SUPPLIER)(3)	PRODUCTION ACCEPTANCE (USER)(3)	REVALIDATION (USER)(3)	
Prepreg Properties				
Visual & Dimensional	X	X		-
Volatile Content	X	X		3
Moisture Content	X	X	X	3
Gel Time	X	X	X	3
Resin Flow	X	X	X	2
Tack	X	X	X	1
Resin Content	X	X		3
Fiber Areal Weight	X	X		3
Infrared Analysis	X			1
Liquid Chromatograph	X	X	X	2
Differential Scanning Calorimetry	X	X	X	2
Lamina Properties				
Density	X			3
Fiber Volume	X			3
Resin Volume	X			3
Void Content	X			3
Per Ply Thickness	X	X	X	1
Glass Transition Temp	X	X	X	3
SBS or ±45° Tension	X(2)	X(2)	X(2)	6
90°/0° Compression Strength	X(1)	X(1)	X(2)	6
90°/0° Tension Strength & Modulus	X(2)	X(2)	X(2)	6

(1) Tests should be conducted at RT/Ambient and Maximum Temperature/Ambient (See Volume I, Section 2.2.2).
(2) Tests should be conducted RT/Ambient.
(3) Supplier is defined as the prepreg supplier. User is defined as the composite part fabricator. Production acceptance tests are defined as tests to be performed by the supplier or user for initial acceptance. Revalidation tests are tests performed by the user at the end of guaranteed storage life or room temperature out time to provide for additional use of the material after expiration of the normal storage or out time life.

Materials are generally stored in sealed plastic bags or containers to prevent moisture from condensing on the cold material and migrating into the polymer when it is removed from the freezer and allowed to warm up to ambient temperature. The time interval between material removal from the freezer and when the material bag or container may be opened is generally empirically determined. Physical characteristics such as material roll, stacking height thickness, or material type (e.g., tape vs broadgoods) are considered when determining this time interval. Therefore, the user should have procedures that prevent premature removal of materials from storage bags or containers before material temperature stabilization occurs.

Tooling: The tooling (molds) to be used for lay-up are subject to tool proofing/qualification procedures. This demonstrates that the tooling is capable of producing parts that conform to drawing and specification requirements, when used with the specified materials, lay-up and bagging methods, and cure profile. Also, cured material specimens made from the tool should be tested to ensure they meet specified mechanical and physical properties. Tool surfaces must be inspected before each use to ensure the tool surface is clean and free of conditions which could contaminate or damage a part.

Facilities and Equipment: The user will establish requirements to control the composite work area environment. These requirements are a part of the user's process specifications. The requirements should be commensurate with the susceptibility of materials to contamination by the shop environment. Inspection and calibration requirements for autoclaves and ovens must be defined.

Contamination restrictions in environmentally-controlled areas typically prohibit the use of uncontrolled sprays (e.g., silicon contamination), exposure to dust, handling contamination, fumes, oily vapors, and the presence of other particulate or chemical matter which may affect the manufacturing process. Conditions under which operators may handle materials should also be defined. Lay-up and clean room air filtrations and pressurization systems should be capable of providing a slight positive overpressure.

In-Process Control: During lay-up of composite parts, certain critical steps or operations must be closely controlled. Requirements and limits for these critical items are stated in the user process specifications. Some of the steps and operations to be controlled are listed below:

1. Verification that the release agent has been applied and cured on a clean tool surface.

2. Verification that perishable materials incorporated into the part comply with the applicable material specifications.

3. Inspection of prepreg lay-ups to assure engineering drawing requirements for number of plies and orientation are met.

4. Inspection of honeycomb core installation, if applicable, and verification that positioning meets the engineering drawing requirements.

5. The user paperwork should contain the following information.

    a. Material supplier, date of manufacturer, batch number, roll number, and total accumulated hours of working life.

    b. Autoclave or oven pressure, part temperatures, and times.

    c. Autoclave or oven load number.

    d. Part and serial number.

Part Cure: Requirements must be defined in user process specifications for the operating parameters for autoclaves and ovens used for curing parts. These include heat rise rates, times at temperature,

cool-down rates, temperature and pressure tolerances, and temperature uniformity surveys in the autoclave or ovens.

Process Control Specimens: Many manufacturers require special test panels to be laid up and cured along with production parts. After cure, these panels are tested for physical and mechanical properties to verify the parts they represent meet the engineering properties.

The requirements for physical and mechanical testing are frequently defined by drawing notes which designates a type or class for each part. Non-critical or secondary structure may require no test specimens and no testing. Critical or safety-of-flight parts may require complete physical and mechanical testing.

During early composite material production, most users required tests for 0° flexure strength and modulus and short beam shear strength. However, in recent years these tests have been changed by many manufacturers to require glass transition temperature, per ply thickness, fiber volume, void content, and ply count on samples taken from designated areas on the production part.

3.3.2 Nondestructive inspection

Having assured in-process control, the detail composite parts must also be inspected for conformance to dimensional and workmanship requirements and nondestructively inspected for processing-induced defects and damage.

Assembly Inspection: Laminates are prone to particular types of defects unless they are machined and drilled properly. Workmanship standards, required by manufacturer's process specifications, are needed to control the quality of trimmed edges and drilled holes. These standards establish visual acceptance/rejection limits for the following typical defects: splintering, delamination, loose surface fibers, overheating, surface finish, off-axis holes, and surface cratering. Typical defects in the drilling operations are delaminations and broken fibers which start at the hole boundary. Since these defects are internal in nature, an evaluation of the seriousness of the flaws is not possible by visual inspection alone. It should be backed up by nondestructive inspection techniques. Internal defect acceptance and rejection limits must be established for nondestructive inspection.

The extent of nondestructive (NDI) inspection on composite parts is dependent on whether the parts are primary structure, safety-of-flight or secondary structure, non-safety-of-flight. The type or class of part is usually defined on the engineering drawing. The engineering drawing also references a process specification which defines the NDI tests and the accept/reject criteria. The NDI tests are used to find flaws and damage such as voids, delaminations, inclusions, and micro-cracks in the matrix.

NDI techniques commonly used in production include visual, ultrasonic and X-ray inspection. Other methods, such as infrared, holographic, and acoustic inspection are being developed and may be used in production applications in the future.

Visual inspection is an NDI technique involving checks to assure the parts meet drawing requirements and to evaluate the surface and appearance of the part. The inspection includes examination for blisters, depressions, foreign material inclusions, ply distortions and folds, surface roughness, surface porosity, and wrinkles. Accept/reject criteria for such defects are given in the manufacturer's process specifications.

The most widely used nondestructive inspection technique for composites production is ultrasonic thru-transmission C-scan inspection, followed by ultrasonic pulse echo A-scan inspection. Since the subject is so broad, the engineering requirements and criteria are usually contained in a document that is referenced in the user's process specification. The principal defects evaluated by ultrasonics are internal voids, delaminations, and porosity. These inspections require fabrication of standards with built-in known defects. The output is in the form of charts which shows the sound attenuation variations over the entire part. The charts are compared to the part to show the locations of the sound attenuation variations. If defects are found outside the limits allowed by the specification, the parts are rejected and dispositioned

by Engineering. Parts may be dispositioned 1) acceptable as is, 2) subjected to further rework or repair to make the part acceptable or 3), scrapped.

X-ray inspection is frequently used in NDI testing to evaluate bonding of inserts in laminate panels and honeycomb core to facesheet bonds in sandwich panels. The extent of testing required is designated on the engineering drawing by type or class of inspection. The type or class is usually defined in a separate document that is referenced in the manufacturer's process specification. As with ultrasonic inspection, standards with built-in defects are usually required to evaluate the radiographic film properly.

3.3.3 Destructive tests

3.3.3.1 Background

Destructive tests are often used to ensure the structural integrity of a component whenever assurance cannot be gained by nondestructive techniques alone. These tests include periodic dissection of the part to examine the interior of complex structures and mechanical testing of specimens cut from excess parts of the component (Figure 3.3.3.1).

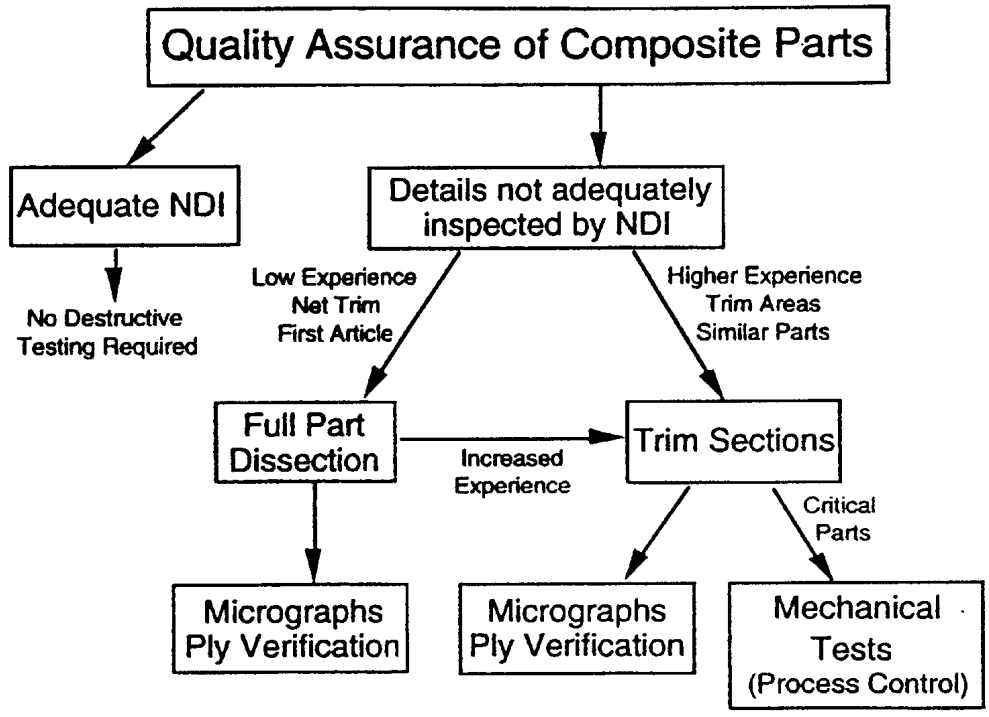


FIGURE 3.3.3.1 *Use of destructive tests.*

3.3.3.2 Usage

Destructive tests are often used to ensure the structural integrity of a component whenever assurance cannot be gained by nondestructive techniques alone. These tests include periodic dissection of the part to examine the interior of complex structures and mechanical testing of coupons cut from excess parts of the component.

3.3.3.3 Destructive test approaches

There are two primary categories of destructive tests: dissection of the full part or examination of trim sections of the part. Full dissection, generally done for the first part from a new tool, gives a complete examination of the part, but is expensive to perform. Examination of excess trim sections is the preferable approach whenever possible. The part is not destroyed, structural details can still be examined and mechanical test specimens can be obtained.

Full Part Dissection: Full part dissection is the approach often envisioned when the term "destructive testing" is mentioned. Since it prevents future use of the part, full part dissection should be reserved for parts that meet the following criteria:

- Areas cannot be adequately inspected by NDI
- Part is complex *and* there is a low experience level for working with the structural configuration or fabrication process
- Part is net trim; detail areas of interest cannot be examined using excess trim areas or part extensions.

Trim Sections: Examination and testing of trim sections offers a balance of quality assurance and cost. Trim sections can be part extensions that are intentionally designed to go beyond the trim line or can be taken from cutout areas inside the part. Section cuts from detail areas can be examined for discrepancies. Test coupons can be machined from the sections and mechanically tested to ensure the structural capability of the part and verify the quality of the fabrication process. Using coupons in this way can satisfy destructive testing requirements and process control requirements (Ref. Section 3.2.2).

3.3.3.4 Implementation guidelines

The frequency of destructive tests are dependent on part type and experience. If the producer has significant fabrication experience, complex parts may not require periodic destructive testing, but only a first article dissection. For low experience with complex parts, periodic inspection with increasing intervals may be preferable. Critical (safety of flight) parts warrant consideration for destructive testing.

Examination and testing of trim sections can be carried out on a more frequent basis and at less cost than full part dissection. Quality assurance can be enhanced by using more frequent and less elaborate trim section examinations.

Destructive tests should be conducted before the part leaves the factory. Periodic destructive tests monitor the manufacturing processes to assure the quality of parts. If a problem does occur, the periodic inspections bracket the number of suspect parts. Not every part series needs to be examined. If many parts reflect the same type of configurations and complexity, they can be pooled together for sampling purposes. Parts made on tools fabricated from one master splash can also be grouped together.

Sampling: A typical sampling plan might include first article full part dissection followed by periodic inspections employing dissection of trim sections. The periodic inspection intervals can vary depending on success rate. After a few successful destructive tests, the interval can be increased. If nonconforming areas are found in destructive tests, the inspection interval can be tightened up. If problems are found in service, additional components from the same production series can be dissected to assure that the problem was isolated.

For the trim section approach, periodic destructive tests can be conducted at smaller intervals since the cost is much less. Small intervals may be especially desirable in the case of critical parts.

For first article inspection, one of the first few articles may be chosen to represent first article. Some of the reasons for not stipulating the very first structure built are: (1) it may not be as representative of the production run because of lessons learned and special handling; and (2) another part with processing problems or discrepancies may reveal far more information.

Potential areas: Potential areas and items to examine include:

Primary load paths within the part,
Areas that showed indications from non-destructive inspection,
Tool markoff near cocured details,
Ply drop offs at a taper,
Ply wrinkles,
Resin starved and resin rich areas,
Corner radii and cocured details,
Core to face sheet fillets,
Tapered core areas.

3.3.3.5 Test types

Both full part dissection and trim sections involve examination of detail areas. After machining the detail areas, photomicrographs can be obtained to examine the microstructure. Another type of destructive testing is ply verification. Only a small section is need to perform a deply or grind down to verify that the plies are laid up in the correct stacking sequence and orientation. For machine lay-up, this procedure should not be necessary after initial validation. To investigate items such as ply lay-up, potential ply wrinkles and porosity, initial core plugs can be taken at fastener hole locations and photomicrographs can be developed.

When mechanically testing specimens that were machined from trim sections, the coupons should be tested for the critical failure mode for that part or that area of the part. Tests addressing typical failure modes are unnotched compression, open hole compression and interlaminar tension and shear.

3.4 STATISTICAL PROCESS CONTROL

3.4.1 Introduction

Since composites exhibit a strong capacity for variability, the tools used to identify, assess, and hopefully control variability become critical. Statistical process control is a term used to tie together several different aspects of statistical and other quality methods.

3.4.2 Quality tools

There are several methods which form the bulk of SPC efforts. They range from fairly simple methodologies for gathering and evaluating data, to sophisticated statistical techniques for answering very specific questions. What is described in the following sections should not be construed as a comprehensive evaluation. There are many other techniques, or variants on the techniques discussed, which can be reviewed in the literature.

3.4.3 Gathering and plotting data

One of the first concepts in evaluating data is to collect them in a rigorous manner. Once the data have been gathered, the data should almost always be plotted in some fashion. It can be very difficult to discern even moderate trends in tabular data. This can be true with even just a handful of data points. In many cases, the same data can and should be plotted in several different manners, looking for patterns and relationships between factors, or trends over time.

3.4.4 Control charts

One of the specific ways that data can be plotted is as a part of a control chart. With control charts, variability in a process output is measured. The sources of variation are partitioned into chance or com-

mon cause, and assignable variation. Data are plotted as it is generated by a process, and a simple set of rules can be used to determine if an assignable cause should be pursued. With proper application, issues can be identified and addressed prior to reaching rejectable levels.

3.4.5 Process capability

A fundamental question for a manufacturing process is given the variability present, what percentage of product would meet specification requirements. Numbers representing this concept are termed measures of process capability. The process variability, represented by the standard deviation, is used to establish tolerance limits which describe where almost all of the product should fall. For one measure of process capability the range between these limits is compared to the specification range.

The lower the quantity of product produced outside the specification limits, the more capable the process. Various ratios can be used to assess process capability. An important issue is whether the process mean is centered between the specification limits, and the implications if it is not.

3.4.6 Troubleshooting and improvement

Many times a new process requires characterization and development, or improvements become necessary for an established process. A process that was once in control may not be any longer for reasons which are not well understood. In situations such as these, tools for troubleshooting established processes, and making improvements to new or established process become valuable. Three common methods are described below.

3.4.6.1 Process feedback adjustment

Introduction

Process control is achieved through both process monitoring and adjustment. Process monitoring is accomplished through Statistical Process Control (SPC), including tools such as process control (or Shewhart) charts and cumulative sum (Cusum) charts. These are used to interrogate the process or system to determine its stability. Process adjustment is used to bring a process back from drifting and is usually termed Engineering Process Control (EPC). SPC and EPC do not compete but can work together.

They can be adapted for environments where an appreciable cost is associated with making a change to the system or taking the measurement. These look at minimizing the overall cost of controlling the system using also the cost of being off the process target. EPC can also implement bounded adjustment charts that will dictate both the necessity and magnitude for an adjustment to the process. Finally, the monitoring of a process that is undergoing feedback control is covered.

The stable, stationary state, which is the environment under which traditional Statistical Process Control (SPC) is supposed to take place, is actually very difficult to attain and maintain. While the more familiar technique of process monitoring through the use of control charts can help achieve this control, frequently processes require adjustment of parameters to attain the desired output. While some of the tools and procedures are similar to those for process monitoring, the intent and approach is actually quite different.

Process monitoring is defined as the use of control charts that are used to continuously interrogate the stability of the process being investigated. When unusual behavior is detected, assignable causes as the source of the behavior are searched for, and if possible, eliminated. This technique has been widely used in the standard parts industry as SPC.

Process adjustment utilizes feedback control of some variable related to the desired output in order to keep the process as close as possible to a desired target. The origins of this procedure are in the process industry, which is termed Engineering Process Control (EPC).

Control Charts

Control charts that are used to observe frequencies and proportions are covered in the Section 3.4.4.

Different types of charts are used for monitoring of measurement data. These look at a sample average and range and are known as X bar and R charts. Some of the useful simplifications used for frequency and proportion data are not applicable for measurement type data. The same general terminology is used except as noted.

Several rules, some of which are industry or even company specific, can be applied to these control charts. The most widely known set of rules is the Western Electric rules that are applied to the control chart to determine if a deviation warrants the search for an assignable cause to be eliminated.

There are assumptions made for the application of these control charts. While some mild violation of these assumptions is not usually catastrophic, an unstable system can result in inappropriate warning and action limits.

Process Adjustment

In the process regulation the object is not to test hypotheses about the likelihood of a set of data indicating special cause, but rather statistical estimation of a disturbance to the system which is then compensated for in various manners.

As an indication of the differences between the objectives between process monitoring and process adjustment, waiting to implement a process adjustment until the process monitoring indicates a statistically significant deviation as a control strategy would usually lead to excessive process output variation.

For many processes acceptable control may not be achievable without process adjustment at some interval. These adjustments must not be made in an arbitrary fashion for consistent results. Important concepts in implementing process adjustment are the processes resistance to change, termed inertia, and the use of models to predict the future output of the process.

A unit change in the adjustment variable will not most likely result in a unit change of the process output. The relationship between these factors is termed the system gain. In attempting to predict the output of the process, it is useful the split the response in the categories of the white noise, and the system drift.

It is important to note that many processes, if left alone, will continuously drift away from a target value. Because of this drift, a low value is more likely to be followed by another low value, termed autocorrelation. These changes may be in the form of step changes, spikes, or changes in slope. With process adjustment, it is attempted to estimate the direction of the process, and then adjust the process, compensating to keep the process directed toward the target value.

The types of disturbances that induce this drift can be environmental changes such as temperature and humidity, or changes in the composition of the input materials. Whether or not these variable have been identified, some sort of feedback control may be necessary to compensate for their effect, allowing the process output to return to the target value. These feedback adjustment procedures have a direct relation to the types of automatic control methods used in the process industry.

While some sort of alteration of the process based on SPC input is frequently employed, a consistent methodology is seldom implemented. By using some sort of feedback adjustment scheme, the variation in the process output can be reduced several-fold in many applications.

What has allowed feedback adjustment the opportunity for more widespread application outside the traditional chemical process industries is the determination that substantial errors in modeling the system, and even significant errors in applying the feedback adjustment result in minimal effects on the process output variability.

Some processes do not experience the full effect of the process adjustment in one interval. These processes are termed to have inertia. Modified processes are required to adapt to these process characteristics.

Another goal for the process adjustment is to minimize the number of adjustments to the process required. This is especially important when there is an appreciable cost associated with the adjustment process. While constraining the adjustment does have the effect of inflating the process output variability, it has been experienced that dramatic reductions in process adjustment frequency can be implemented with only modest increases in process output variability over the theoretical minimum.

Some of these processes include the use of a dead band about the target value. Process output predictions in this dead band do not result in any process adjustment. Another process is the bounded adjustment.

Another point of concern is the inadvertent use of process adjustment to a process that is already in a state of perfect control. It has been determined that implementation on such a process would only result in an increase of about 5% in the process output variability. Weighed against this potential is the likelihood that most processes violate the assumptions required to achieve a perfect state of control.

Another aspect of concern of feedback adjustment is the potential for costs associated with observing and/or adjusting a process, weighed against the cost of drifting from the target value. Modifications to the feedback adjustment process have been made to minimize the overall cost associated with these areas.

The question of how often a process should be observed is also present, along with the associated costs. Costs associated with reading a process can be weighed against costs from adjusting the process and increased process variability or deviation from the target value.

3.4.6.2 Design of experiments

Background

While the statistical analysis of data generated by manufacturing processes has become commonplace, the layout or structure of the data generated has largely resisted a consistent methodology. Rules of thumb, historical precedent, or simply availability dominate data gathering efforts, although some statistically based analyses of composite bolted joints have been performed. There is a frequent perception that such a methodology would somehow remove control from the technical process expert, or that it has little additional to offer compared with recognized precedents. One of the most established tenets of conventional data layout carried through most programs is that only one data factor is ever intentionally changed at one time in an experimental program. While without an appropriate approach this may be prudent, there is a message that has been lost. With a proper methodology changing more than one variable at a time can be performed efficiently and effectively, providing information that is impossible to obtain when only one factor is changed at a time. Often the uncovered hidden relationships dominate the process results.

The general name for such a methodology is Design of Experiments (DOE). Another term is Designed eXperiments (Dx). Through DOE a great number of factors which could potentially influence an output of interest can be efficiently screened, establishing statistically with a linear model whether they truly influence the process output. Building on this data, interactions between significant factors can be determined, but only by violating the rule about changing only one factor at a time.

Another technique builds upon DOE to form nonlinear models, such as quadratic models, allowing process optimization to be performed. This approach is known as Response Surface Methodology (RSM). As the name implies, the desired output is usually a multi-factor nonlinear relationship.

DOE and RSM are used serially in a process known as sequential experimentation. In this method initial experiments are used to screen for significant factors. If a factor being adjusted is not actually significant, this data is not wasted but becomes replicates or duplicates for other significant factors, providing

additional information on process variance. Additional data can be added to pursue indications of significant interactions. The model also provides signs on whether nonlinear relationships should be further pursued. Additional points added through RSM are used to establish these nonlinear (quadratic) characteristics. The models use all the data generated for one or more purposes, providing for very efficient experimentation.

There are in the literature applications of designed experiments used for determining composite elastic properties, and a few were found used for determining composite mechanical properties such as bolted joint strength. Use of this efficient methodology can allow serious evaluation of processes previously considered too complicated for full experimental investigation. As a result, typically in the past only a few established areas of interest would have been tested, with a pick-the-winner approach. Rarely was it established that there was even a statistical difference between the "winner" and the discarded options, much less that any kind of optimum had been achieved. But application of DOE and RSM experimental methods can provide these tools and options.

One Factor Models – Linear and Quadratic

Fitting a line or linear equation to data is a fairly routine process, as shown in Figure 3.4.6.2(a). The line represents the trend of the data, but rarely do all the data points fall directly on the line. At a given value along the horizontal or X-axis, the data is frequently normally distributed about some average value represented by that point on the line. This can be seen in the figure for one point. The same distribution should hold for all the points on the line.

One of the important considerations in fitting an equation to data is the spacing of the data. If an equation is to be fit for a result as a function of one factor, the data may be closely spaced, as seen in Figures 3.4.6.2(b) and (c). In Figure 3.4.6.2(b), the normal distribution of data at two given points, representing a large sample of data, is shown. In Figure 3.4.6.2(c) a relationship is present, but only a small sampling of data (three points) is indicated. What Figure 3.4.6.2(c) shows is that with a small sample at two closely spaced points a significant relationship can be missed. The farther the data are spread towards the edges of interest or practical experimentation, the more likely to detect a statistically significant relationship with a minimum of data, as seen in Figure 3.4.6.2(d). Frequently only a single data point is gathered at the ends, especially early in a screening program.

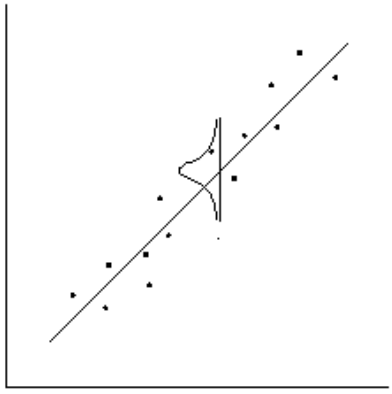


FIGURE 3.4.6.2(a) *Fit of linear equation to data (normal distribution of data about line shown).*

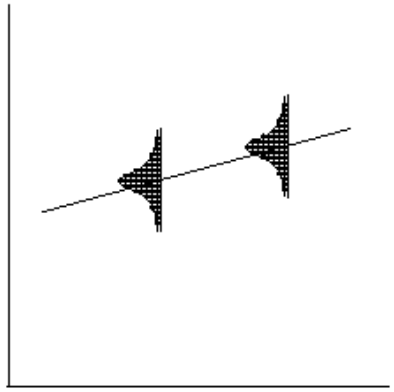


FIGURE 3.4.6.2(b) *True relationship established with large data sample with closely spaced points.*

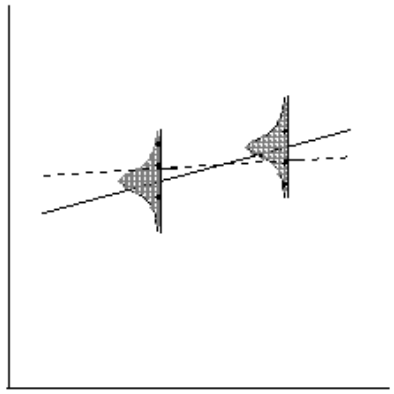


FIGURE 3.4.6.2(c) *True relationship missed with small data sample and closely spaced points.*

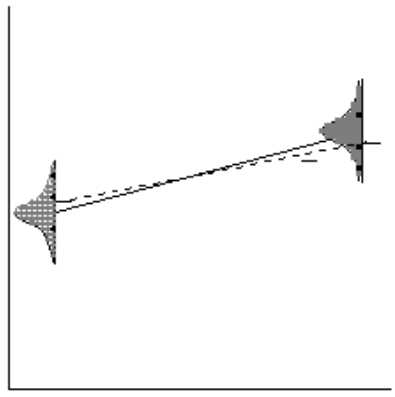


Figure 3.4.6.2(d) *True relationship identified with small sample and widely spread points.*

For linear models, which are typically used for identifying significant factors, this means minimizing the number of points between these edges or end points. Some data points can be used at the midpoint between these edges to replicate data. The estimate of variability derived from the replicate data is used to judge whether differences seen between the ends are statistically significant or not.

The form of a linear equation is the familiar "$y = a + bx$". The "x" represents the independent variable that can be manipulated. The "b" which is multiplied by "x" represents the slope of the line. The "a" is the intercept value of "y" when "$x = 0$". If the equation is nonlinear, for example a quadratic equation, then an additional term is added. The form of the equation then becomes "$y = a + bx + cx^2$". The quadratic term brings the ability to match the curvature seen in the data.

If the relationship is linear, then the average of the data at the center point should be roughly the average between the two end points, as seen in Figure 3.4.6.2(e). If the center point average deviates significantly from this average of the endpoints, it is an indication of a nonlinear relationship.

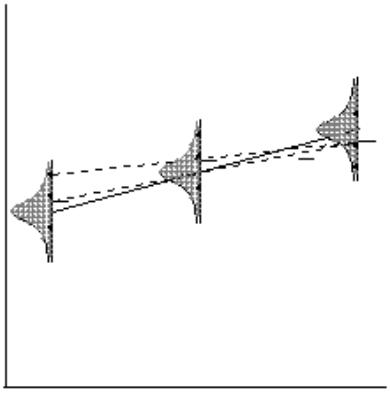


FIGURE 3.4.6.2(e) *Use of center points.*

Certainly one reason for closely spacing the points within the region of interest is that within the spacing the relationship will appear linear, which is much more commonly applied. A nonlinear relationship without proper experimental techniques can be difficult to economically characterize, and typically is avoided if possible. However, if the relationship is truly nonlinear, as shown in Figure 3.4.6.2(f), and there is a reasonable chance that the process may proceed outside the currently established limits, then this is of interest and value, and should not be overlooked.

If the relationship is strong enough and the end points are far enough apart, then a single data point at each of the ends may be sufficient to identify a significant relationship. Some assessment of variability must still be made or assumed. These multiple data points can also be generated at the center point, and much more efficiently than replication at each of the end points. The variability is then assumed to be comparable across the range.

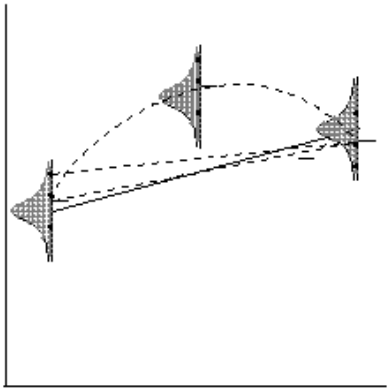


FIGURE 3.4.6.2(f) *Nonlinear relationship identified with center points.*

Two Factor Models – Linear and Quadratic

The same rationale and methodology can then be extended to fitting an equation for some process output as a function of more than one factor. The same ideas about spacing of the data collection levels hold true, as shown in Figure 3.4.6.2(g). The idea is to spread these to the edges as far as possible without changing the basic relationship of the fundamental measurement of interest. Also, the same advantages of center points still hold true, but for continuous factors the center points may serve for both factors. For two factors the equation which is developed can be plotted to create a response surface, a graph with the appearance of a topographical map. This can be looked at as a series of single factor equation lines or curves evenly spaced as a function of the second factor.

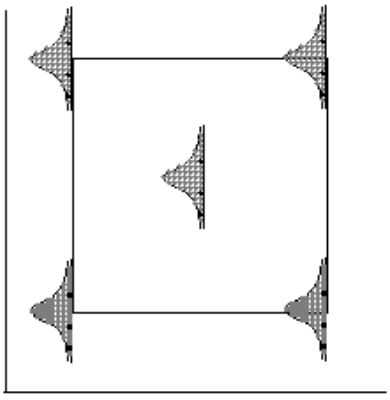


FIGURE 3.4.6.2(g) *Data spacing for two factors.*

If the relationship is strong enough and the end points are far enough apart, then a single data point at each of the ends may be sufficient to identify a significant relationship. Some assessment of variability must still be made or assumed. These multiple data points can also be generated at the center point, and much more efficiently than replication at each of the end points. The variability is then assumed to be comparable across the range.

For a linear model this will create a plane cutting through the four corners of the square. The form of the equation would then be "$y = ax + by + c$". It is a natural extension of the single factor linear equation,

although perhaps more difficult to visualize. An example can be seen in Figure 3.4.6.2(h). If there is an interaction between the two factors there can be a twist to the surface, giving the appearance of a nonlinear equation. The interaction term in the equation is the product of the two independent variables multiplied by a coefficient. The form of the equation would then be "$y = ax + by + cxy + d$".

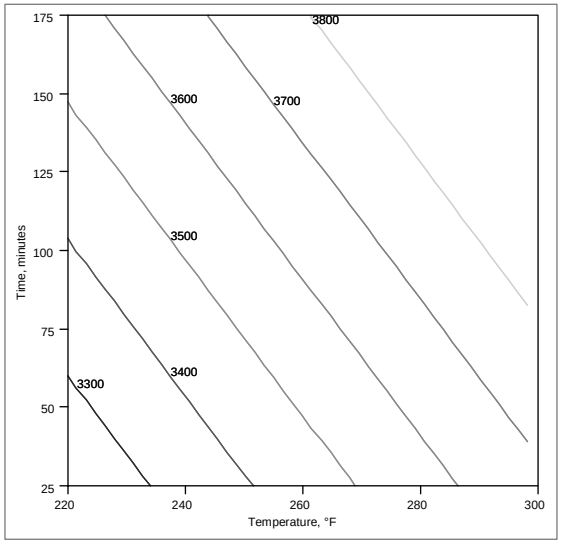


FIGURE 3.4.6.2(h) *Example of linear response surface (adhesive lap shear strength in psi as a function of cure final dwell time and temperature).*

The center points function in the same manner as for the single factor. If the center points fall reasonably close to the surface of the plane, then there is not an indication of a nonlinear relationship. If the center points do not fall reasonably close to the plane, then there is an indication of nonlinearity.

Here Response Surface Methodology can be introduced to complement Design of Experiments. RSM builds on the data and linear model from the DOE, supplementing with some additional data in the optimal manner which allows generation of a nonlinear model to fit the relationship. The form of the equation would then be "$y = ax + by + c + dxy + ex^2 + fy^2$". The data layout can be seen in Figure 3.4.6.2(i).

Here the concept of an interaction comes into play. An interaction means that the level of one factor influences the effect of a second factor. A simple example of this that is a common manufacturing experience is curing a thermosetting plastic. If a plastic is cured at 325°F, then perhaps it takes 100 minutes to optimally cure. If the oven is at 350°F, then perhaps it only takes 50 minutes. The temperature of the oven affects the time it takes to cure; one cannot be optimally set independently from the other. If at 350°F the plastic is left to cure 100 minutes, it may become oxidized, warp, or provide reduced properties. The effect that 50 minutes curing has on the plastic depends on the oven temperature.

The conventional way to handle this type of problem is to attempt to not allow the temperature to change. All but one factor is held fixed. The one factor is varied, and the effect is measured. Without DOE tools this may be the only approach available, but with these tools a more accurate relationship can be developed. These additional RSM points are called "star points", as seen in Figure 3.4.6.2(i). They allow the nonlinearity to be assessed while still using all the data generated in the attempt to create a linear model. The proper placement of these points is the basis of RSM. An example of the response surface generated from a quadratic model can be seen in Figure 3.4.6.2(j).

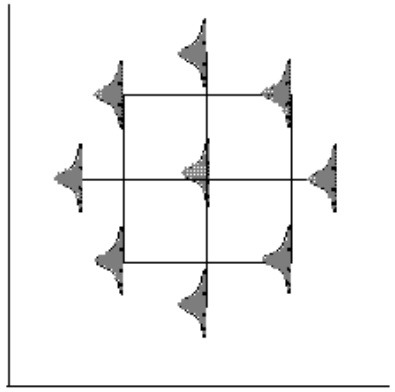


FIGURE 3.4.6.2(i) *Placement of star points outside of square.*

Multiple Factor Models – Linear and Quadratic

Again this method can be extended to three or more factors. Instead of a square the placement of points now extends to a cube, where the vertices of the cube represent the various combinations of high and low values for the three different factors being evaluated, as seen in Figure 3.4.6.2(k).

The fitting of the equation follows the very same methodology, although it is now more difficult to plot the output for all three factors. With one factor fixed, the other two can be plotted in the same manner as seen for two factors above. The center points have also been used in the same manner for all three continuous factors. Because they are being shared for all three factors now, the efficiency of their use has increased even more. The extension to a nonlinear model follows the same basic pattern as well, as shown in Figure 3.4.6.2(l).

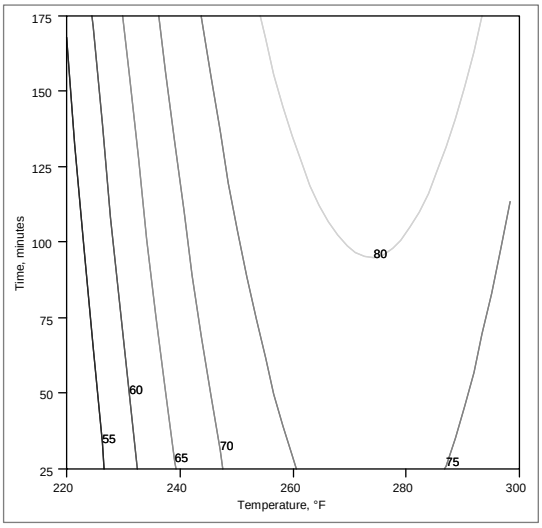


FIGURE 3.4.6.2(j) *Example of quadratic response surface (adhesive peel strength in psi as a function of cure final dwell time and temperature).*

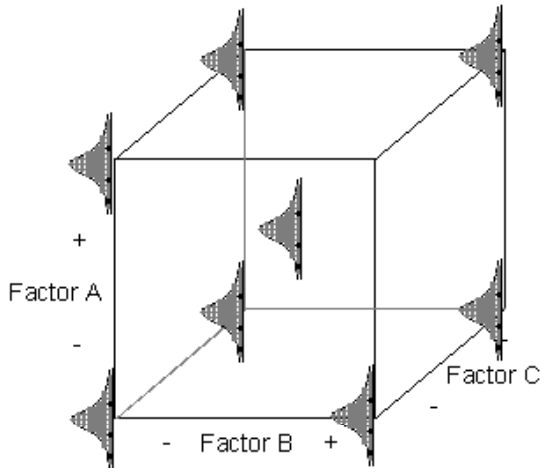


FIGURE 3.4.6.2(k) *Three-factor experimental design.*

One of the superlative features of DOE is the ability to determine effective models without data at all of the points. For the three-factor model, this would mean testing only half of the corners of the box, although in a very specific manner as shown in Figure 3.4.6.2(m). This would allow the generation of a linear model but no interactions. Since there would be four data points, this leaves three degrees of freedom, one for each factor's linear component or main effect. No interactions could be represented, although the alternate data could be generated at a later time. This is termed a fractional factorial. Fractional factorial DOE can also be used with RSM in the same manner as shown above for placing the star points as seen in Figure 3.4.6.2(l).

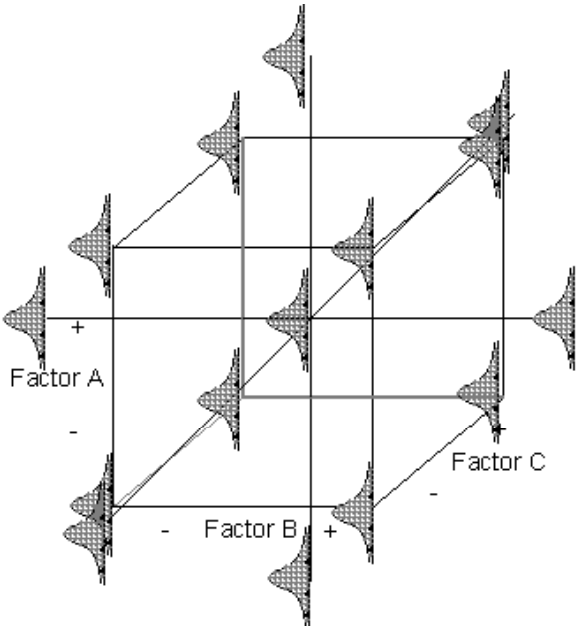


FIGURE 3.4.6.2(l) *Star points outside cube for three-factor design.*

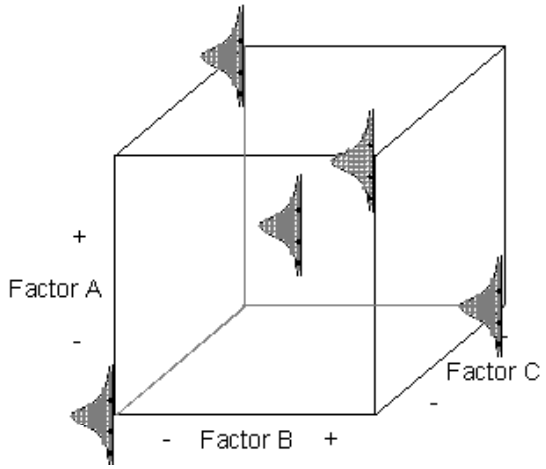


FIGURE 3.4.6.2(m) *Half-fraction (2^{3-1}) for three-factor design.*

Sequential Experimentation

Sequential experimentation is another important aspect of experimental design. At the beginning of the experimental program, little may be known about the relationships involved. DOE can be used to screen through a great number of potential factors to find significant ones. Once these have been found, the data representing non-significant factors can be treated as replicates for those factors that were determined to be significant. Additional data can then be generated, still using prior data, to confirm linear models and identify interactions.

If the center points indicate nonlinearity, then additional data can be generated at the star points identified to support creation of a quadratic model, again still using the previous generated screening and linear model data. This is the most efficient method possible for creation of experimental models for complex phenomena.

Model Checking

Once any model has been fit to a set of data, each assumption used in creation of the model should be checked to see if it was valid. One of the first model checking parameters that can be examined is the R^2. This number gives an assessment of how much variability seen in the data is represented by the model that has been fit. Adding more factors to the equation can always increase this number, whether or not they are statistically significant, so to counter this an adjusted R^2 is also calculated. This number will actually decrease if a statistically insignificant factor is added to the model.

Another confirmation of the model is examination of the residuals for the presence of patterns. The residuals are the differences between the actual value and the model-predicted value for each data point. If the model has picked up all the nonrandom patterns in the data, then the residuals should appear random. Thus patterns in the residuals can provide additional useful information on relationships not currently included in the model.

One of the assumptions for using the regression methodology for fitting a model is that the distribution of the data is normal. Whether or not the residuals are normally distributed can check this assumption. The value of the normalized residual for each data point should usually be within two standard errors, or else it is identified as an outlier. This may indicate some error in generating or collecting the data, or may be indicating an effect that is not well represented by the model.

The Cook's distance is a measure of the relative influence of each of the data points on the model that is being evaluated. If the Cook's distance number is calculated as above one, then it indicates that this data point is very influential in determining the form of model. While this is not inherently undesirable,

any error in this data point will result in proportionally greater error in the model compared to other error introduced by data points with distances of less than one.

3.4.6.3 Taguchi

Several ideas have been promoted in an attempt to quantify the cost incurred as a result of poor quality. Taguchi has suggested the use of a quadratic function for departures from the optimum level. In addition, he has promoted the use of experimental designs that can be much easier to implement in a production environment.

3.4.7 Lot acceptance

This section is reserved for future use.

3.5 MANAGING CHANGE IN MATERIALS AND PROCESSES

3.5.1 Introduction

The need to employ alternate material or process may occur during the course of any program. It is essential to the success of the program that these changes be managed in a systematic and cost effective manner. Although materials and processing changes must be dealt with on a case by case basis, generalized methods or protocols have been developed which may be used to guide the process. The section below details an approach to managing materials and processing change. Critical issues that must be addressed and resolved are identified and described.

3.5.2 Qualification of new materials or processes

Qualification evaluations typically exhibit progressive cost escalations from coupon tests, to elements, to components, to parts, and eventually to aircraft. This progression is commonly known as the "building block" approach to qualification. Chapter 4 of Volume 3 deals with this subject in detail. It is important to conduct initial planning to align and coordinate multiple sources, product forms, and processes early in the qualification effort. This planning allows better utilization of the existing expensive large scale tests by incorporating various considerations in left hand/right hand or upper/lower portions of the test items.

Alternate materials or processes can be evaluated for specific applications as required, allowing for a partial replacement of the baseline material. It should be noted that if a partial replacement is considered, the cost of multiple drawing changes required to maintain a distinction between two materials must be considered. In addition, some cost must be allocated for analysis review to determine which application can withstand material properties that are not equivalent or are better than the baseline properties.

When a material or process-related change is identified, or a material or process-related problem requires remediation, the stakeholders may use the protocol described here to develop a solution. The elements and sequential stages of this material and process qualification protocol are illustrated in Figure 3.5.2. Two elements, Divergence and Risk, and Production Readiness are particularly critical to a successful materials or process change, and are covered at greater length below.

3.5.2.1 Problem statement

The problem statement bounds the qualification program by providing a clear statement of the desired outcome and success criteria. It delineates responsibilities for the aspects of the program to the material supplier, processor, prime contractor, test house, or customer. It becomes the cornerstone for other decisions and serves as the basis of the business case as well as divergence and risk analyses on which the technical acceptability test matrix is built. When the problem statement is found (1) to be lacking specificity, (2) to be so specific as to limit approaches, or (3) to have a clear technical error, modifications may be made with the agreement of the qualification participants and stakeholders.

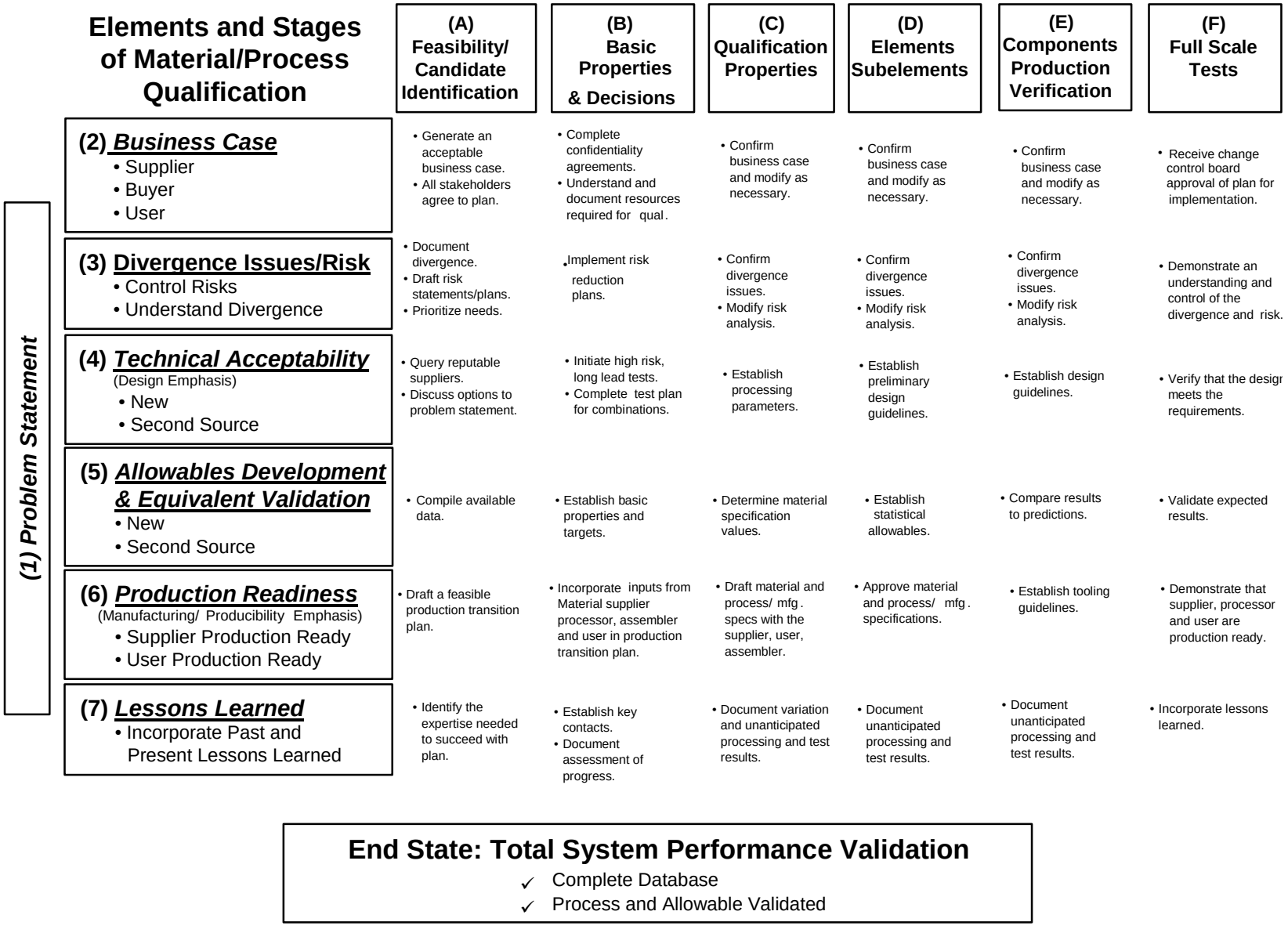


FIGURE 3.5.2 *Elements and stages of material or process qualification.*

3.5.2.2 Business case

Following development of the problem statement, a business case is developed (1) to clarify responsibilities, (2) to show the clear benefit of the qualification to all participants and stakeholders, and (3) to obtain and allocate resources for the qualification effort.

3.5.2.3 Divergence and risk

Divergence and risk analyses are conducted to provide the most affordable, streamlined qualification program while addressing risks associated with using related data, point design qualifications, and so forth. The divergence analysis assists the qualification participants in determining how similar or how different the new material or process is from the known and understood materials or processes. Risk analysis is performed to determine the consequence of reduced testing, sequencing testing and so forth.

3.5.2.4 Technical acceptability

Technical acceptability is achieved by fulfilling the objectives included in the problem statement, answering technical questions based on historic knowledge and practices, and by showing through test, analysis, and the results of the divergence/risk analyses that the material or process system is understood. Its strengths and weaknesses are then identified and communicated through design and analysis guidelines.

3.5.2.5 Allowables development and equivalency validation

The allowables development and equivalency validation focuses on the quantitative aspects of the qualification.

3.5.2.6 Production readiness

In the past, qualification programs have often fallen short because they ended with the quantitative aspects of design databases. However, a successful qualification program must include the transition needed to assure production readiness. Production readiness includes raw material suppliers, formulators, fiber suppliers, preformers, processors, quality conformance testing, adequate documentation, and other areas. Again, this protocol methodology does not provide all the answers for specific qualifications. Instead, it provides discussion to stimulate thought by the qualification participants and prompts appropriate planning based on the problem statement, business case, divergence or risk analyses, and technical acceptability testing established for the particular case by knowledgeable stakeholders.

3.5.2.7 Lessons learned

Finally, the methodology admits that no qualification is perfect. Lessons learned from the past should be incorporated into the plan as soon as the tie is identified in the divergence or risk analyses. In addition, lessons learned from the current qualification should be documented and acted upon throughout the qualification.

This methodology requires the qualification participants to revisit each qualification element and make modifications as necessary throughout the sequential stages of qualification. Figure 3.5.2.7 provides a flowchart of the composite material and process qualification procedure.

3.5.3 Divergence and risk

Divergence and risk analyses are conducted to provide the most affordable, streamlined qualification program while addressing risks associated with using related data, point design qualifications, and so forth. The divergence analysis assists the qualification participants in determining how similar or how dif-

ferent the new material or process is from the known and understood materials or processes. Risk analysis is also performed to determine the consequence of reduced testing, sequencing testing and so forth.

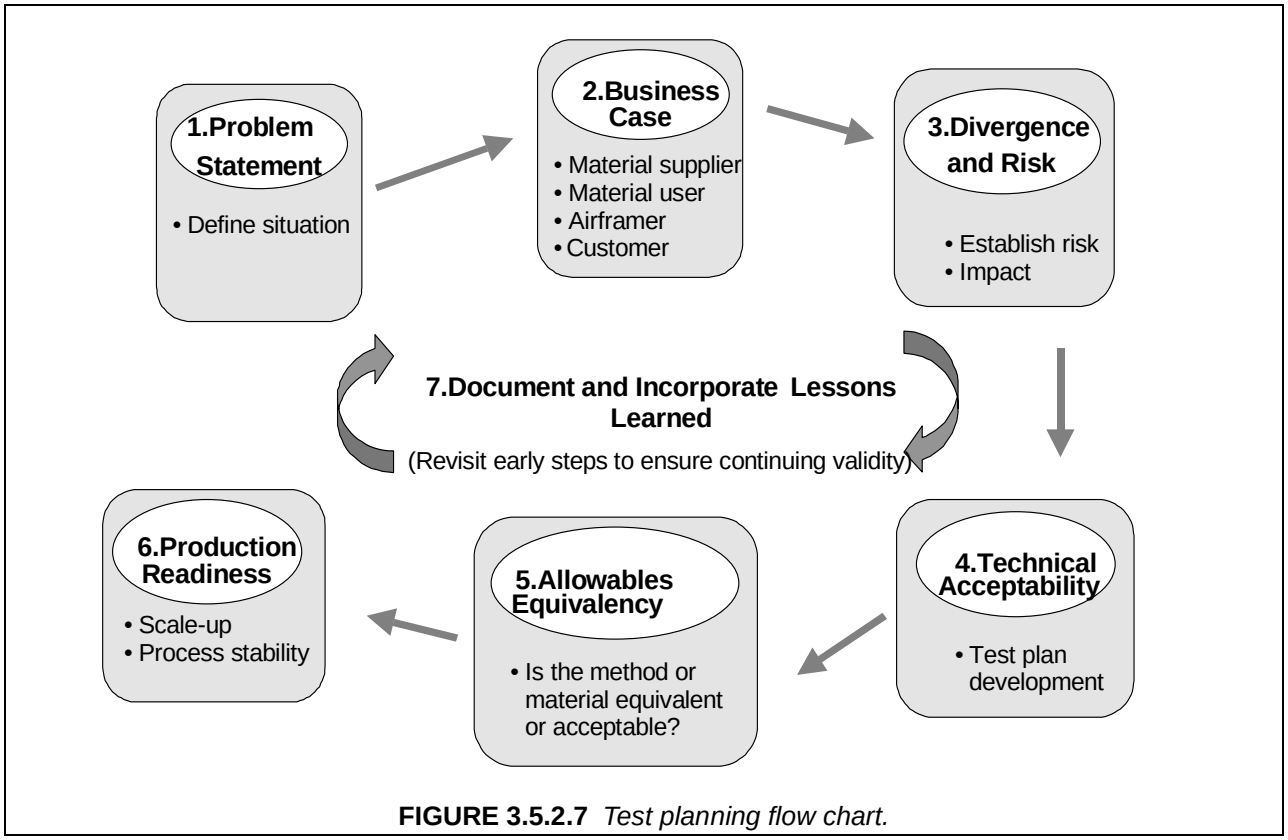


FIGURE 3.5.2.7 *Test planning flow chart.*

The level of divergence of a qualification program is determined by assessing how similar or how different the "new" or "modified" material/process is from that used in the baseline, in past experience, or in the general history of composite material and process usage. It is an acknowledgment of those areas of similarity to common knowledge versus those areas that are a departure from common knowledge and experience.

Risk can be defined as an undesirable situation which has a probability of occurring with attendant negative impacts on the success of the effort. An obvious undesirable situation in the context of a material qualification effort is a failure in the alternate material when it is implemented. Areas of failure could include processing difficulties, a structural failure of the component itself, or any other event or development that adversely impacts cost or schedule.

There is always some level of risk associated with the qualification of composite materials. The risk level for a second or alternate source is related to the divergence between the baseline material or process and the alternative material or process. The highest risk is the case where a new material system or process is being qualified as part of a new production program. For this situation there is no baseline material or process, and thus divergence is at its greatest. Although most of the same considerations apply, this case is not addressed in this protocol.

This section discusses the impact of material divergence on the qualification test program. Guidelines are provided on how to establish the level of divergence, assess risk, establish the qualification plan, establish the test sample size, and select test methodologies. It is recommended that all the stakeholders participate in the process defining the level of divergence.

3.5.3.1 Divergence

The first effort in establishing the level of risk is to define the magnitude of divergence between the baseline and the alternate material or process. This is done by listing all the properties, characteristics, descriptors, and attributes associated with the baseline composite materials and processes, then assessing the differences for each of the items on the list.

The list may be top level or detail in nature. Divergence criteria may include: (1) a change in the raw material source; (2) a change in the processing site or equipment; (3) a change in fiber sizing; (4) a change in fabric style; or (5) a change in resin. The difference could also include a change in the part fabrication process, such as going from hand collation to fiber placement, or from hand collation to resin transfer molding. There could be a material change associated with the fabrication process change or there could be no changes in the material. There may also be equipment changes within the fabrication process. The magnitude of divergence between the material and process combinations defines the starting level of risk.

For example, one of the items on the list may be "resin". In one case, the baseline material is a 350°F curing epoxy. To be rated as "no divergence", the alternate material need only be a 350°F curing epoxy resin. In another situation, however, the definition of "no divergence" is an alternate resin mixed at an alternate site, but chemically equivalent to the baseline.

An assessment is made for each item on the list to determine the level of divergence between the baseline material and alternative material. By definition there will be acceptable levels of divergence for some items (such as the qualification of a new prepreg line) and there will be some items where no divergence is allowed (for example, the resin formulation for qualification of a licensed resin).

Relevant testing requirements are defined and identified with respect to these areas of divergence. At times the testing is used to validate that the divergence does not negatively impact the material or the end use of the material, while at other times testing is used to validate that there is no divergence.

A key element of the divergence assessment is to define the accept/reject criteria to be used in analyzing the test data, audit findings, and processing trials. Establishment of criteria requires a clear understanding of the divergence requirements: equivalent versus equal, similar versus identical, statistically based versus typical values, and so forth.

Representative areas of divergence are listed below:

- **Resin**
  - Raw material sources
  - Mixing equipment
  - Mixing parameters
  - Filming equipment
  - Filming parameters
- **Fiber**
  - Precursor source
  - Fiber line
  - Fiber processing parameters
  - Sizing type
  - Sizing source
  - Fiber tow size (filament count)
  - Fabric style for fiber preforms
  - Weaving source for fiber preforms (location)
- **Prepreg Manufacture**
  - Impregnation line
  - Impregnation parameters
  - Auxiliary processing
- **Component Fabrication**
  - Collation method
  - Tooling concept
  - Cure cycle
  - Bagging procedures

This list is intended as a guideline and is not all-inclusive. It references divergence areas that have been commonly seen in past qualifications, but future qualifications will present new and unique areas of divergence that are as yet unknown.

Sample Generation of Divergence Assessment List

In this example, the qualification objective is to qualify a second impregnation line which has been altered to increase fiber wet-out. There is no change in the fiber or resin, including resin mixing.

Potential Impregnation Line Changes	***Divergence between Lines***
line width	same
fiber creel arrangement	same
fiber tensioning method	same
fiber path	changed
fiber spreading method	changed
resin application method	same
impregnation method	changed
impregnation parameters	changed
chill plate method	same
prepreg slitting	same
prepreg roll-up	same
carrier papers	same

In this example, the objective of qualifying the new impregnation line is resultant equipment that will yield prepreg that is better suited for slitting into narrow tape for a fiber placement process. The two key areas where the change is being affected are: (1) fiber spreading/collimation and (2) impregnation. The intention of the changes is to improve fiber collimation and increase the level of fiber wet-out.

Once the divergence has been defined, the next step is to assess the risk associated with each area of change.

3.5.3.2 Risk assessment

Risk is directly associated with the uncertainties that stem from the level of divergence. The objective is to manage the risk and reduce it to an acceptable level by effectively structuring and conducting the qualification program. The qualification program focuses on the testing of the alternate material, but risk is also reduced through other activities such as audits, processing trials, and drawing on previous experience.

Risk assessments may be subjective. What is viewed as high risk to one person may be viewed as a medium risk to another. Past experiences and familiarity with the new material or process will influence a person's perception of the risk level. For these reasons, it is important that the level of material or process divergence be quantified and that a systematic risk assessment process be documented.

Risk assessment builds on the defined differences so that the risk can be fully defined. When the, "What can go wrong?" question is asked, it is important to apply the question at the correct level within the program. It is not meant to be a global question. ("What can go wrong if the new material is not qualified?") At this stage an assessment is being made for each individual area of divergence.

Continuing with our sample qualification, a risk assessment for each area of divergence follows:

- Fiber path - The change in fiber path has the potential of damaging the fibers. The qualification plan should include tests that are sensitive to fiber damage.

- Fiber spreading method - As with the change in fiber path, a new fiber spreading method also has the potential of damaging the fibers. This is especially true if the intent of the change is to increase the fiber tension. Again, tests that are sensitive to fiber damage are warranted for the qualification test plan.

- Impregnation method and parameters - The change in the method of impregnation and associated parameters has the potential of changing the level of resin advancement and the physical configuration of the prepreg (with less resin on the surface). These changes could result in loss of tack, shortened out-time, reduced resin flow, and elimination of volatile escape paths. They will also help in the formation of a clean edge during the slitting process (the goal of the changes).

The qualification plan should then include tests or evaluations that address fiber damage, changes in potential resin advancement, and handling properties. The plan should also include an assessment that validates what the changes in the impregnation line do to improve the slitting and fiber placement processes.

3.5.3.3 Risk analysis

In this step, the risk is analyzed to determine its magnitude. What is the likelihood of the risk developing? What are the possible consequences of the risk? What category does the risk fit into: cost, schedule, or technical?

The likelihood or probability that a risk will develop can range from not likely to near certainty, depending on the approach being taken to mitigate the risk. If a risk develops, impacts of various magnitudes will result. These magnitudes need to be defined from no impact to unacceptable, so that the qualification plan can be structured to address the identified risks. The risks are then minimized through performance of the qualification plan.

A typical risk analysis spread sheet is shown in Figure 3.5.3.3. This particular spreadsheet is generic to programmatic risk analysis but applicable across a wide range of other risk analysis. The user must assign new definitions to the levels of likelihood and consequence wherever those shown are not appropriate.

3.5.4 Production readiness

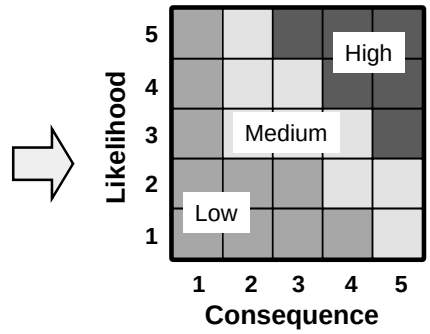
Production readiness assessment must address the ability of each of the following to adhere to appropriately documented processes and to adequately record all pertinent information for traceability:

- The suppliers of the constituent materials
- The formulator/processor/prepregger
- The part fabricator
- The assembly facility
- Any subcontractors, intermediate suppliers, processors, inspectors, etc.

Production readiness is a key consideration in the risk reduction process to assure control of cost, schedule, and technical acceptability of the end product. It is necessary to start at the earliest point of change, because one initial change can often affect processing and documentation at subsequent points in the path to the final product. The necessary documentation takes two forms: 1) that required to delineate procedures and 2) that used for traceability or for stating what has actually occurred, specific to a particular run or final part.

Often, the qualification testing is performed in a pre-production environment. However, scale-up traditionally has had the greatest impact on cost, schedule, or technical parameters in production. For this reason, it is essential to plan batches, processing runs, and part trials which represent processing boundaries in the overall definition and demonstration of production capability. Results must be systematically documented because these will become part of the history file for this process.

What is the likelihood the risk will happen?		
Level		Planned Approach and Processes
1	Not Likely	• Will effectively avoid or mitigate this risk based on standard practices
2	Low Likelihood	• Have usually mitigated this type of risk with minimal oversight in similar cases
3	Likely	• May mitigate this risk, but workarounds will be required
4	Highly Likely	• Cannot mitigate this risk, but a different approach might
5	Near Certainty	• Cannot mitigate this type of risk; no known processes or workarounds are available



Given the risk is realized, what would be the magnitude of the impact?			
Level	Technical	Schedule	Cost
1	• Minimal or no impact	• Minimal or no impact	• Minimal or no impact
2	• Minor perf shortfall, • same approach retained	• Additional activities required; able to meet key dates	• Budget increase or unit production cost increase <1%
3	• Mod perf shortfall, but workarounds available	• Minor schedule slip;will miss need date	• Budget increase or unit production cost increase <5%
4	• Unacceptable, but workarounds available	• Program critical path affected	• Budget increase or unit production cost increase <10%
5	• Unacceptable, no alternatives exist	• Cannot achieve key program milestone.	• Budget increase or unit production cost increase >10%

FIGURE 3.5.3.3 *Risk analysis spreadsheet.*

When there is a change in production rate/usage, shop characteristics become important and sometimes require change. These aspects need to be understood and stabilized as early as possible. Capital equipment needs and calibration/certification, personnel training, and process flow are some of the typical elements which must be addressed.

The following paperwork must be put in place for production processing: procurement documents, specifications, process instructions (planning including work orders, travelers and the like), quality techniques, etc.

A thorough production readiness review should assess the capability/readiness of the raw material supplier, prepreg supplier, resin supplier, weaver, preformer, and part fabricator (including all subcontractors). Qualify only those materials/processes that are production ready or have a clear path to production.

Readiness should be evaluated at the lowest practical level. Any changes during or after the qualification will have an impact which needs to be checked against the protocol.

If several processors will be utilized, be sure to evaluate each with production-like conditions at this time.

ISO 9000 methodologies should be used throughout the qualification process. It is important to establish a product dependability program. *ISO 9000-4* explains what a product dependability program is and how it should be managed. The effort begins by defining a policy, which explains what is meant by product dependability and specifies dependability characteristics. Product dependability requirements are defined by researching customer needs. Resources and organizational functions are defined, tools put in

place, needed documents are defined, an information tracking system is put in place, and review procedures are established. A program dependability plan is implemented which includes requirements, activities, practices and resources. Included in this effort are procedures to analyze, predict and review the dependability of the products and also the purchased materials. Estimates of life cycle costs and cost savings are important. A product improvement plan should be established, and a feedback system from the customer must be in place. Once this is accomplished, then requirements can be established for purchased materials, equipment and facilities, procedures and processes, and quality, all of which will enable meeting the product dependability requirements.

REFERENCES

3.2.1(a) MIL-STD-414, *Sampling Procedures and Tables for Inspection by Variables for Percent Defective*, Change Notice 1, 8 May 1968.

3.2.1(b) Federal Aviation Regulation Part 21 "Certification Procedures for Products and Parts".