Whitaker, Jerry C. “Chapter 9 – Reliability Considerations”
Power Vacuum Tubes Handbook 2nd Edition.
Ed. Jerry C. Whitaker
Boca Raton: CRC Press LLC, 2000

Chapter

9

Reliability Considerations

9.1 Introduction

The ultimate goal of any design engineer or maintenance department is zero downtime. This is an elusive goal, but one that can be approximated by examining the vulnerable areas of plant operation and taking steps to prevent a sequence of events that could result in system failure. In cases where failure prevention is not practical, a reliability assessment should encompass the stocking of spare parts, circuit boards, or even entire systems. A large facility may be able to cost-justify the purchase of backup gear that can be used as spares for the entire complex. Backup hardware is expensive, but so is downtime. Because of the finite lifetime of power vacuum tubes, these considerations are of special significance.

Failures can, and do, occur in electronic systems. The goal of product quality assurance at every step in the manufacturing and operating chain is to ensure that failures do not produce a systematic or repeatable pattern. The ideal is to eliminate failures altogether. Short of that, the secondary goal is to end up with a random distribution of failure modes. This indicates that the design of the system is fundamentally optimized and that failures are caused by random events that cannot be predicted. In an imperfect world, this is often the best that end users can hope for. Reliability and maintainability must be built into products or systems at every step in the design, construction, and maintenance process. They cannot be treated as an afterthought.

9.1.1 Terminology

To understand the principles of reliability engineering, the following basic terms must be defined:

- **Availability**. The probability that a system subject to repair will operate satisfactorily on demand.
- **Average life**. The mean value for a normal distribution of product or component lives. This term is generally applied to mechanical failures resulting from "wear-out."

- **Burn-in**. The initially high failure rate encountered when a component is placed on test. Burn-in failures usually are associated with manufacturing defects and the debugging phase of early service.
- **Defect**. Any deviation of a unit or product from specified requirements. A unit or product may contain more than one defect.
- **Degradation failure**. A failure that results from a gradual change, over time, in the performance characteristics of a system or part.
- **Downtime**. Time during which equipment is not capable of doing useful work because of malfunction. This does not include preventive maintenance time. Downtime is measured from the occurrence of a malfunction to its correction.
- **Failure**. A detected cessation of ability to perform a specified function or functions within previously established limits. A failure is beyond adjustment by the operator by means of controls normally accessible during routine operation of the system.
- **Failure mode and effects analysis (FMEA)**. An iterative documented process performed to identify basic faults at the component level and determine their effects at higher levels of assembly.
- **Failure rate**. The rate at which failure occurs during an interval of time as a function of the total interval length.
- **Fault tree analysis (FTA)**. An iterative documented process of a systematic nature performed to identify basic faults, determine their causes and effects, and establish their probabilities of occurrence.
- **Lot size**. A specific quantity of similar material or a collection of similar units from a common source; in inspection work, the quantity offered for inspection and acceptance at any one time. This may be a collection of raw material, parts, subassemblies inspected during production, or a consignment of finished products to be sent out for service.
- **Maintainability**. The probability that a failure will be repaired within a specified time after it occurs.
- **Mean time between failure (MTBF)**. The measured operating time of a single piece of equipment divided by the total number of failures during the measured period of time. This measurement normally is made during that period between early life and wear-out failures.
- **Mean time to repair (MTTR)**. The measured repair time divided by the total number of failures of the equipment.
- **Mode of failure**. The physical description of the manner in which a failure occurs and the operating condition of the equipment or part at the time of the failure.
- **Part failure rate**. The rate at which a part fails to perform its intended function.

- **Quality assurance (QA)**. All those activities, including surveillance, inspection, control, and documentation, aimed at ensuring that a product will meet its performance specifications.
- **Reliability**. The probability that an item will perform satisfactorily for a specified period of time under a stated set of use conditions.
- **Reliability growth**. Actions taken to move a hardware item toward its reliability potential, during development, subsequent manufacturing, or operation.
- **Reliability predictions**. Compiled failure rates for parts, components, subassemblies, assemblies, and systems. These generic failure rates are used as basic data to predict a value for reliability.
- **Sample**. One or more units selected at random from a quantity of product to represent that product for inspection purposes.
- **Sequential sampling**. Sampling inspection in which, after each unit is inspected, the decision is made to accept, reject, or inspect another unit. (Note: Sequential sampling as defined here is sometimes called *unit sequential sampling* or *multiple sampling*.)
- **System**. A combination of parts, assemblies, and sets joined together to perform a specific operational function or functions.
- **Test to failure**. Testing conducted on one or more items until a predetermined number of failures have been observed. Failures are induced by increasing electrical, mechanical, and/or environmental stress levels, usually in contrast to *life tests*, in which failures occur after extended exposure to predetermined stress levels. A life test can be considered a test to failure using age as the stress.

9.2 Quality Assurance

Electronic component and system manufacturers design and implement quality assurance procedures for one fundamental reason: Nothing is perfect. The goal of a QA program is to ensure, for both the manufacturer and the customer, that all but some small, mutually acceptable percentage of devices or systems shipped will be as close to perfection as economics and the state of the art allow. There are tradeoffs in this process. It would be unrealistic, for example, to perform extensive testing to identify potential failures if the cost of that testing exceeded the cost savings that would be realized by not having to replace the devices later in the field.

The focal points of any QA effort are *quality* and *reliability*. These terms are not synonymous. They are related, but they do not provide the same measure of a product:

- Quality is the measure of a product's performance relative to some established criteria.
- Reliability is the measure of a product's life expectancy.

Stated from a different perspective, quality answers the question of whether the product meets applicable specifications *now*; reliability answers the question of *how long* the product will continue to meet its specifications.

9.2.1 Inspection Process

Quality assurance for components normally is performed through sampling rather than through 100 percent inspection. The primary means used by QA departments for controlling product quality at the various processing steps include:

- *Gates*. A mandatory sampling of every lot passing through a critical production stage. Material cannot move on to the next operation until QA has inspected and accepted the lot.
- *Monitor points*. A periodic sampling of some attribute of the component. QA personnel sample devices at a predetermined frequency to verify that machines and operators are producing material that meets preestablished criteria.
- *Quality audit*. An audit carried out by a separate group within the QA department. This group is charged with ensuring that all production steps throughout the manufacturer's facility are in accordance with current specifications.
- *Statistical quality control*. A technique, based on computer modeling, that incorporates data accumulated at each gate and monitor point to construct statistical profiles for each product, operation, and piece of equipment within the plant. Analysis of this data over time allows QA engineers to assess trends in product performance and failure rates.

Quality assurance for a finished subassembly or system may range from a simple go/no-go test to a thorough operational checkout that may take days to complete.

9.2.2 Reliability Evaluation

Reliability prediction is the process of quantitatively assessing the reliability of a component or system during development, before large-scale fabrication and field operation. During product development, predictions serve as a guide by which design alternatives can be judged for reliability. To be effective, the prediction technique must relate engineering variables to reliability variables.

A prediction of reliability is obtained by determining the reliability of each critical item at the lowest system level and proceeding through intermediate levels until an estimate of overall reliability is obtained. This prediction method depends on the availability of accurate evaluation models that reflect the reliability of lower-level components. Various formal prediction procedures are used, based on theoretical and statistical concepts.

Parts-Count Method

Although the parts-count method does not relate directly to vacuum tube design, it is worthwhile to discuss the technique briefly in the context of overall system reliability. It is fair to point out that this technique has considerable validity when comparisons of vacuum tube vs. solid-state amplifier designs are being considered. To achieve high power levels, far more individual components are necessary for a solid-state design than for a vacuum tube-based system

The parts-count approach to reliability prediction provides an estimate of reliability based on a count by part type (ICs, transistors, vacuum tube devices, resistors, capacitors, and other components). This method is useful during the early design stage of a product, when the amount of available detail is limited. The technique involves counting the number of components of each type, multiplying that number by a generic failure rate for each part type, and summing the products to obtain the failure rate of each functional circuit, subassembly, assembly, and/or block depicted in the system block diagram. The parts-count method is useful in the design phase because it provides rapid estimates of reliability, permitting assessment of the feasibility of a given concept.

Stress-Analysis Method

The stress-analysis technique is similar to the parts-count method, but utilizes a detailed parts model plus calculation of circuit stress values for each part before determining the failure rate. Each part is evaluated in its electric circuit and mechanical assembly application based on an electrical and thermal stress analysis. After part failure rates have been established, a combined failure rate for each functional block is determined.

9.2.3 Failure Analysis

Failure mode and effects analysis can be performed with data taken from actual failure modes observed in the field, or from hypothetical failure modes derived from one of the following:

- Design analysis
- Reliability prediction activities
- Experience with how specific parts fail

In the most complete form of FMEA, failure modes are identified at the component level. Failures are induced analytically into each component, and failure effects are evaluated and noted, including the severity and frequency (or probability) of occurrence. Using this approach, the probability of various system failures can be calculated, based on the probability of lower-level failure modes.

Fault tree analysis is a tool commonly used to analyze failure modes found during design, factory test, or field operations. The approach involves several steps, including the development of a detailed logic diagram that depicts basic faults and events that can lead to system failure and/or safety hazards. These data are used to formulate corrective suggestions that, when implemented, will eliminate or minimize faults considered critical. An example FTA chart is shown in Figure 9.1.

9.2.4 Standardization

Standardization and reliability go hand in hand. Standardization of electronic components began with military applications in mind; the first recorded work was performed by the U.S. Navy with vacuum tubes. The navy recognized that some control at the component level was essential to the successful incorporation of electronics into naval systems.

Standardization and reliability are closely related, although there are many aspects of standardization whose reliability implications are subtle. The primary advantages of standardization include:

- *Total product interchangeability*. Standardization ensures that products of the same part number provide the same physical and electrical characteristics. There have been innumerable instances of a replacement device bearing the same part number as a failed device, but not functioning identically to it. In many cases, the differences in performance were so great that the system would not function at all with the new device.
- *Consistency and configuration control*. Component manufacturers constantly redefine their products to improve yields and performance. Consistency and configuration control assure the user that product changes will not affect the interchangeability of the part.
- *Efficiencies of volume production*. Standardization programs usually result in production efficiencies that reduce the costs of parts, relative to components with the same level of reliability screening and control.
- *Effective spares management*. The use of standardized components makes the stocking of spare parts a much easier task. This aspect of standardization is not a minor consideration. For example, the costs of placing, expediting, and receiving material against one Department of Defense purchase order may range from $300 to $1100. Accepting the lowest estimate, the conversion of 10 separate part numbers to one standardized component could effect immediate savings of $3000 just in purchasing and receiving costs.
- *Multiple product sources*. Standardization encourages second-sourcing. Multiple sources help hold down product costs and encourage manufacturers to strive for better product performance.

9.3 Reliability Analysis

The science of reliability and maintainability matured during the 1960s with the development of sophisticated computer systems and complex military and spacecraft electronics. Components and systems never fail without a reason. That reason may be

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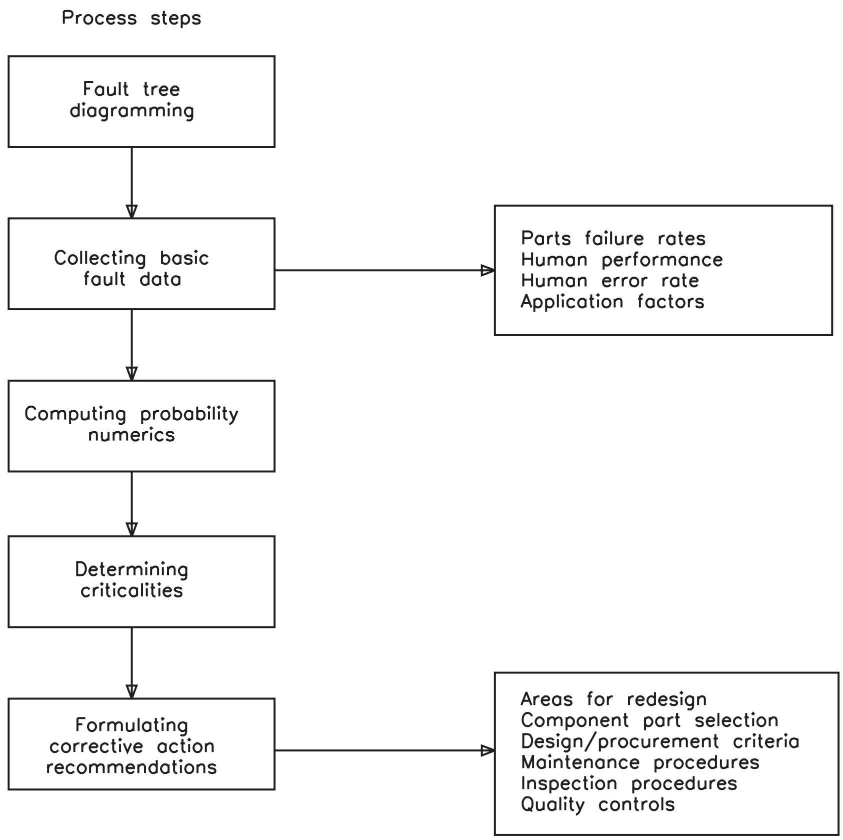

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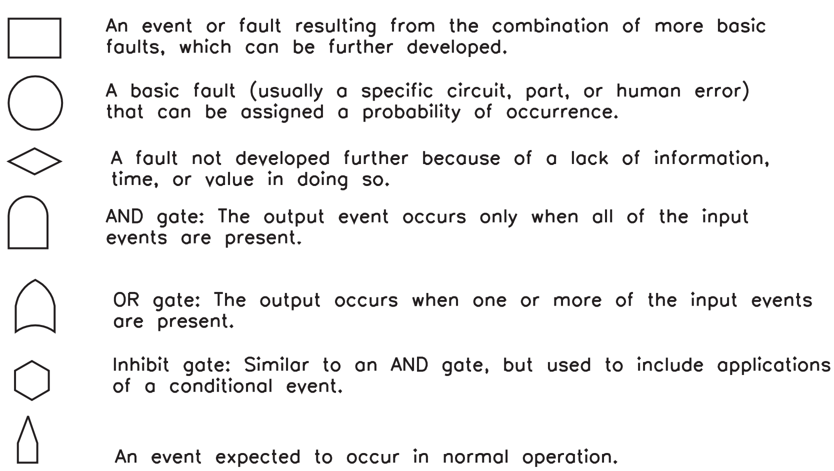


Figure 9.1 Example fault tree analysis diagram: (*a*) process steps, (*b*) fault tree symbols, (*c*, next page) example diagram.

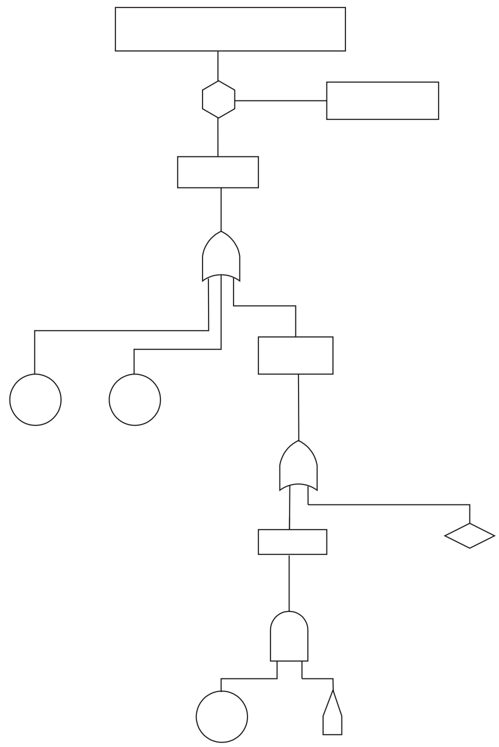


Figure 9.1*c*

difficult to find, but determination of failure modes and weak areas in system design or installation is fundamental to increasing the reliability of any component or system, whether it is a power vacuum tube, integrated circuit, aircraft autopilot, or broadcast transmitter.

All equipment failures are logical; some are predictable. A system failure usually is related to poor-quality components or to abuse of the system or a part within, either because of underrating or environmental stress. Even the best-designed components can be badly manufactured. A process can go awry, or a step involving operator intervention may result in an occasional device that is substandard or likely to fail under normal stress. Hence, the process of screening and/or *burn-in* to weed out problem parts is a universally accepted quality control tool for achieving high reliability.

9.3.1 Statistical Reliability

Figure 9.2 illustrates what is commonly known as the *bathtub curve*. It divides the expected lifetime of a class of parts into three segments: *infant mortality*, *useful life*, and *wear-out*. A typical burn-in procedure consists of the following steps:

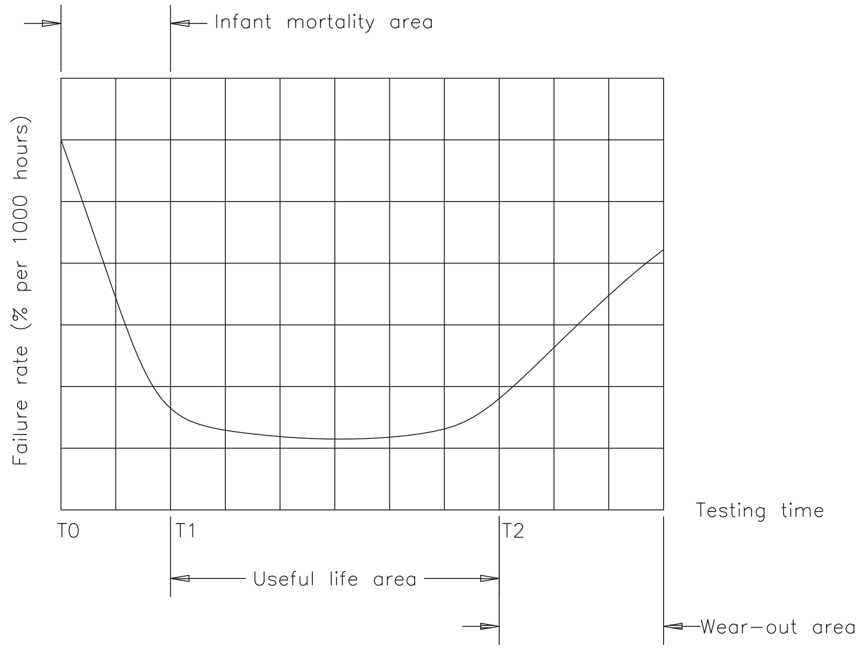


Figure 9.2 The statistical distribution of equipment or component failures vs. time for electronic systems and devices.

- The parts are electrically biased and loaded; that is, they are connected in a circuit representing a typical application.
- The parts are cycled on and off (power applied, then removed) for a predetermined number of times. The number of cycles may range from 10 to several thousand during the burn-in period, depending on the component under test.
- The components under load are exposed to high operating temperatures for a selected time (typically 72 to 168 hours). This constitutes an accelerated life test for the part.

An alternative approach involves temperature shock testing, in which the component product is subjected to temperature extremes, with rapid changes between the *hot-soak* and *cold-soak* conditions. After the stress period, the components are tested for adherence to specifications. Parts meeting the established specifications are accepted for shipment to customers. Parts that fail to meet them are discarded.

Figure 9.3 illustrates the benefits of temperature cycling to product reliability. The charts compare the distribution of component failures identified through steady-state high-temperature burn-in vs. temperature cycling. Note that cycling screened out a significant number of failures. The distribution of failures under temperature cycling usually resembles the distribution of field failures. Temperature cycling simulates

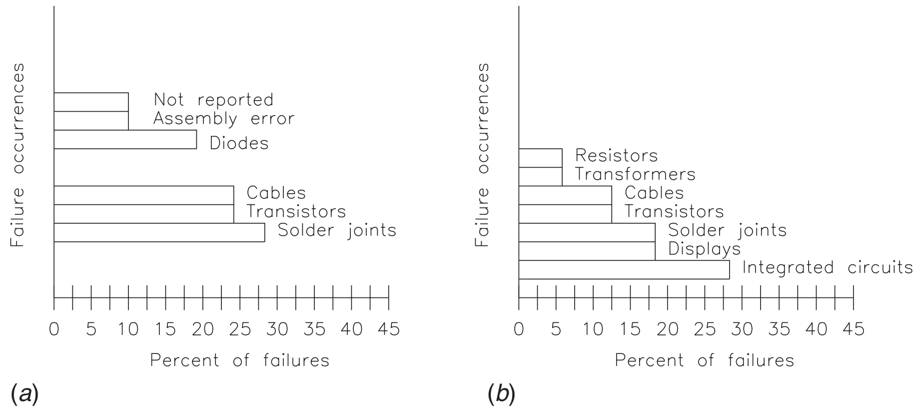


Figure 9.3 Distribution of component failures identified through burn-in testing: (*a*) steady-state high-temperature burn-in, (*b*) temperature cycling.

real-world conditions more closely than steady-state burn-in. The goal of burn-in testing is to ensure that the component lot is advanced beyond the infant mortality stage (*T1* on the bathtub curve). This process is used not only for individual components, but for entire systems as well.

Such a systems approach to reliability is effective, but not foolproof. The burn-in period is a function of statistical analysis; there are no absolute guarantees. The natural enemies of electronic parts are heat, vibration, and excessive voltage. Figure 9.4 documents failures vs. hours in the field for a piece of avionics equipment. The conclusion is made that a burn-in period of 200 hours or more will eliminate 60 percent of the expected failures. However, the burn-in period for another system using different components may well be a different number of hours.

The goal of burn-in testing is to catch system problems and potential faults before the device or unit leaves the manufacturer. The longer the burn-in period, the greater the likelihood of catching additional failures. The problems with extended burn-in, however, are time and money. Longer burn-in translates to longer delivery delays and additional costs for the equipment manufacturer, which are likely to be passed on to the end user. The point at which a product is shipped is based largely on experience with similar components or systems and the financial requirement to move products to customers.

Roller-Coaster Hazard Rate

The bathtub curve has been used for decades to represent the failure rate of an electronic system. More recent data, however, has raised questions regarding the accuracy of the curve shape. A growing number of reliability scientists now believe that the probability of failure, known in the trade as the *hazard rate*, is more accurately represented as a roller-coaster track, as illustrated in Figure 9.5. Hazard rate calculations

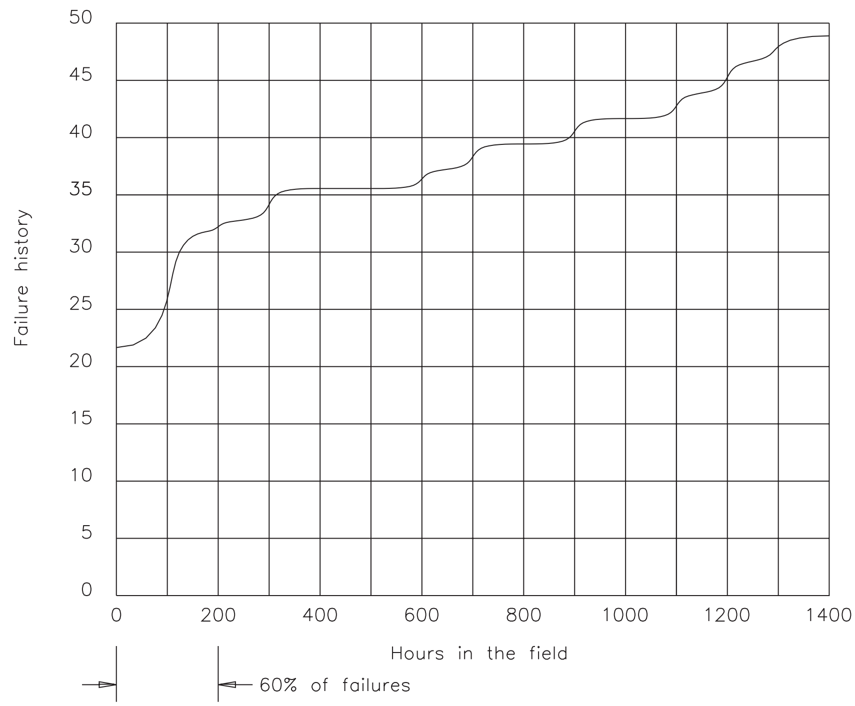


Figure 9.4 The failure history of a piece of avionics equipment vs. time. Note that 60 percent of the failures occurred within the first 200 hours of service. (*After* [1].)

require analysis of the number of failures of the system under test, as well as the number of survivors. Advocates of this approach point out that previous estimating processes and averaging tended to smooth the roller-coaster curve so that the humps were less pronounced, leading to an incorrect conclusion insofar as the hazard rate was concerned. The testing environment also has a significant effect on the shape of the hazard curve, as illustrated in Figure 9.6. Note that at the higher operating temperature (greater environmental stress), the roller-coaster hump has moved to an earlier age.

9.3.2 Environmental Stress Screening

The science of reliability analysis is rooted in the understanding that there is no such thing as a random failure; every failure has a cause. For reasonably designed and constructed electronic equipment, failures not caused by outside forces result from built-in flaws or *latent defects*. Because different flaws are sensitive to different stresses, a variety of environmental forces must be applied to a unit under test to identify any latent defects. This is the underlying concept behind *environmental stress screening* (ESS).

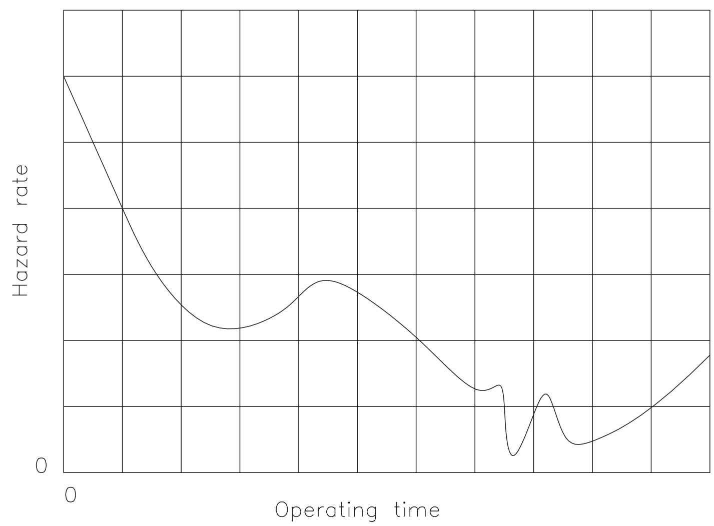


Figure 9.5 The roller-coaster hazard rate curve for electronic systems. (*After* [2].)

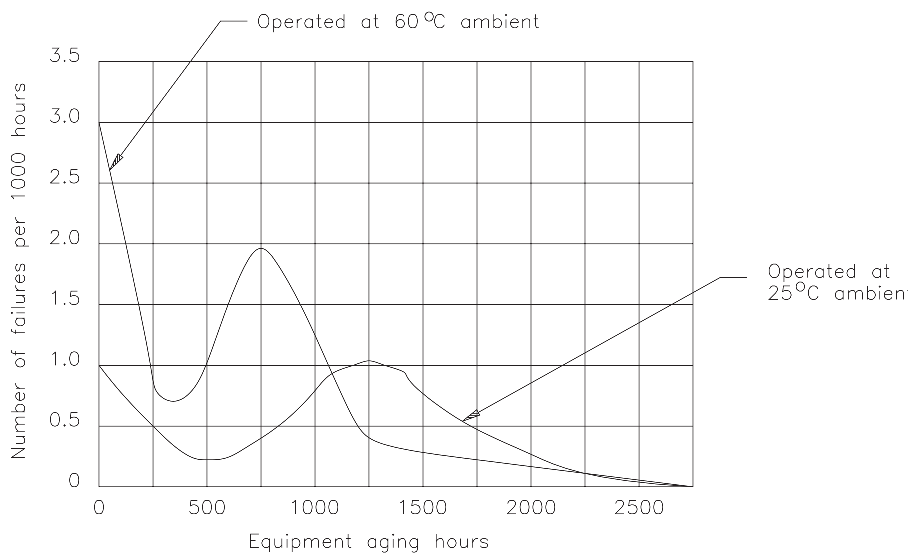


Figure 9.6 The effects of environmental conditions on the roller-coaster hazard rate curve. (*After* [2].)

ESS, which has come into widespread use for aeronautics and military products, takes the burn-in process a step further by combining two of the major environmental factors that cause parts or units to fail: heat and vibration. Qualification testing for

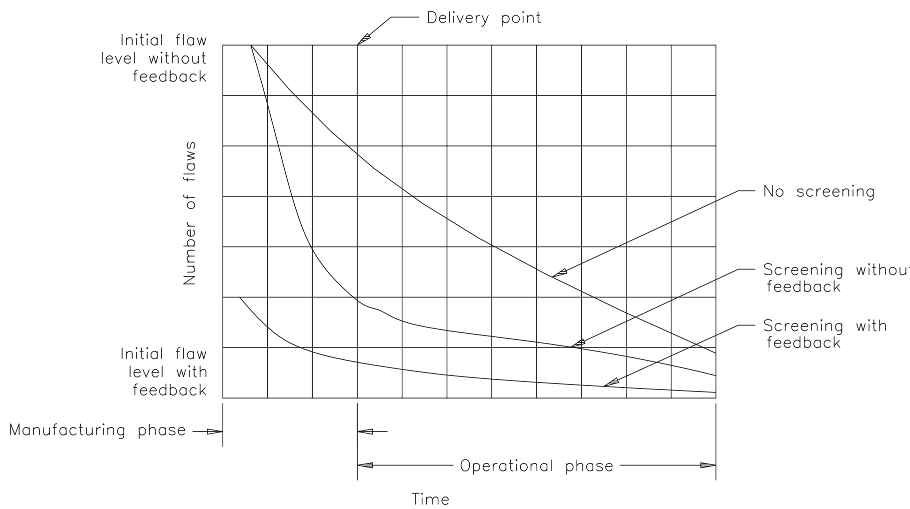


Figure 9.7 The effects of environmental stress screening on the reliability *bathtub* curve. (*After* [3].)

products at a factory practicing ESS involves a carefully planned series of checks for each unit off the assembly line. Units are subjected to random vibration and temperature cycling during production (for subassemblies and discrete components) and upon completion (for systems). The goal is to catch product defects at the earliest possible stage of production. ESS also can lead to product improvements in design and manufacture if feedback from the qualification stage to the design and manufacturing stages is implemented. Figure 9.7 illustrates the improvement in reliability that typically can be achieved through ESS over simple burn-in screening, and through ESS with feedback to earlier production stages. Significant reductions in equipment failures in the field can be gained. Table 9.1 compares the merits of conventional reliability testing and ESS.

Designing an ESS procedure for a given product is no easy task. The environmental stresses imposed on the product must be great enough to cause fallout of marginal components during qualification testing. The stresses must not be so great, however, as to cause failures in good products. Any unit that is stressed beyond its design limits eventually will fail. The proper selection of stress parameters—generally, random vibration on a vibration generator and temperature cycling in an environmental chamber—can, in minutes, uncover product flaws that might take weeks or months to manifest themselves in the field. The result is greater product reliability for the user.

The ESS concept requires that every product undergo qualification testing before integration into a larger system for shipment to an end user. The flaws uncovered by ESS vary from one unit to the next, but types of failures tend to respond to particular en-

Table 9.1 Comparison of Conventional Reliability Testing and Environmental Stress Screening (*After* [2].)

Parameter	Conventional Testing	Environmental Stress Screening
Test condition	Simulates operational equipment profile	Accelerated stress condition
Test sample size	Small	100 percent of production
Total test time	Limited	High
Number of failures	Small	Large
Reliability growth	Potential for gathering useful data small	Potential for gathering useful data good

vironmental stresses. Available data clearly demonstrate that the burn-in screens must match the flaws sought; otherwise, the flaws will probably not be found.

The concept of flaw-stimulus relationships can be presented in Venn diagram form. Figure 9.8 shows a Venn diagram for a hypothetical, but specific, product. The required screen would be different for a different product. For clarity, not all stimuli are shown. Note that there are many latent defects that will not be uncovered by any one stimulus. For example, a solder splash that is just barely clinging to a circuit element probably would not be broken loose by high-temperature burn-in or voltage cycling, but vibration or thermal cycling probably would break the particle loose. Remember also that the defect may be observable only during stimulation and not during a static bench test.

The levels of stress imposed on a product during ESS should be greater than the stress to which the product will be subjected during its operational lifetime, but still be below the maximum design parameters. This rule of thumb is pushed to the limits under an *enhanced screening* process. Enhanced screening places the component or system at well above the expected field environmental levels. This process has been found to be useful and cost-effective for many programs and products. Enhanced screening, however, requires the development of screens that are carefully identified during product design and development so that the product can survive the qualification tests. Enhanced screening techniques often are required for cost-effective products on a cradle-to-grave basis; that is, early design changes for screenability save tremendous costs over the lifetime of the product.

The types of products that can be checked economically through ESS break down into two categories: high-dollar items and mass-produced items. Units that are physically large in size, such as RF generators, are difficult to test in the finished state. Still, qualification tests using more primitive methods, such as cam-driven truck-bed shakers, are practical. Because most large systems generate a large amount of heat, subjecting the equipment to temperature extremes also may be accomplished. Sophisticated ESS for large systems, however, must rely on qualification testing at the subassembly stage.

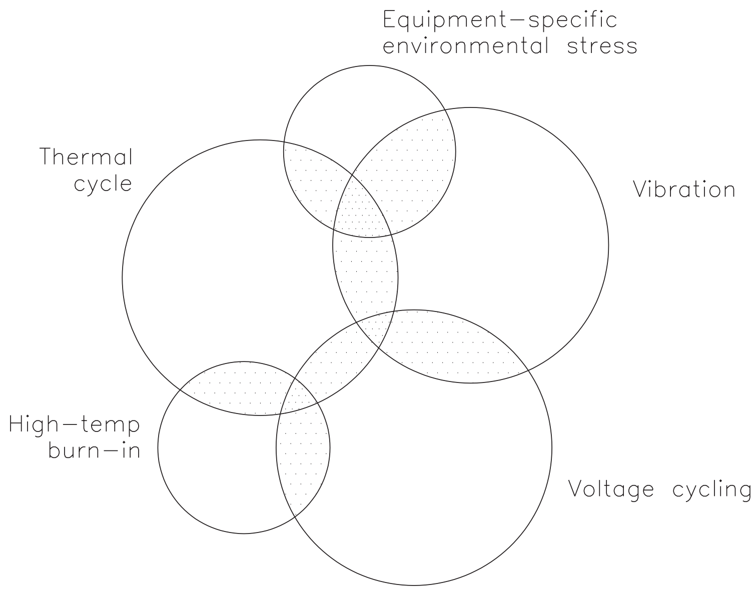


Figure 9.8 Venn diagram representation of the relationship between flaw precipitation and applied environmental stress. (*After* [4].)

The basic hardware complement for an ESS test station includes a thermal chamber shaker and controller/monitor. A typical test sequence includes 10 minutes of exposure to random vibration, followed by 10 cycles between temperature minimum and maximum. To save time, the two tests may be performed simultaneously.

9.3.3 Latent Defects

The cumulative failure rate observed during the early life of an electronic system is dominated by the latent defect content of the product, not its inherent failure rate. Product design is the major determinant of inherent failure rate. A product design will show a higher-than-expected inherent rate if the system contains components that are marginally overstressed, have inadequate functional margin, or contain a subpopulation of components that exhibit a wear-out life shorter than the useful life of the product. Industry has grown to expect the high instantaneous failure rate observed when a new product is placed into service. The burn-in process, whether ESS or conventional, is aimed at shielding customers from the detrimental effects of infant mortality. The key to reducing early-product-life failures lies in reducing the number of latent defects.

A latent defect is some abnormal characteristic of the product or its parts that is likely to result in failure at some point, depending on:

- The degree of abnormality

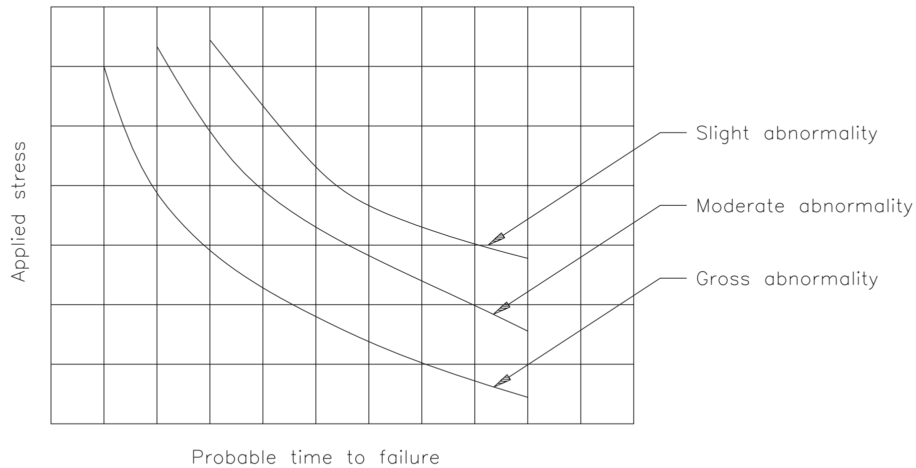


Figure 9.9 Estimation of the probable time to failure from an abnormal solder joint. (*After* [5].)

- The magnitude of applied stress
- The duration of applied stress

For example, consider a solder joint on the connecting pin of a vacuum tube device. One characteristic of the joint is the degree to which the pin hole is filled with solder, characterized as "percent fill." All other characteristics being acceptable, a joint that is 100 percent filled offers the maximum mechanical strength, minimum resistance, and greatest current carrying capacity. Conversely, a joint that is zero percent filled has no mechanical strength, and only if the lead is touching the barrel does it have any significant electrical properties. Between these two extreme cases are degrees of abnormality. For a fixed magnitude of applied stress:

- A grossly abnormal solder joint probably will fail in a short time.
- A moderately abnormal solder joint probably will fail, but after a longer period of time than a grossly abnormal joint.
- A mildly abnormal solder joint probably will fail, but after a much longer period of time than in either of the preceding conditions.

Figure 9.9 illustrates this concept. A similar time-stress relationship holds for a fixed degree of abnormality and variable applied stress.

A latent defect eventually will advance to a *patent defect* when exposed to environmental, or other, stimuli. A patent defect is a flaw that has advanced to the point at which an abnormality actually exists. To carry on the solder example, a cold solder joint represents a flaw (latent defect). After vibration and/or thermal cycling, the joint (it is assumed) will crack. The joint will now have become a detectable (patent) defect. Some latent defects can be stimulated into patent defects by thermal cycling, some by vibration, and some by voltage cycling. Not all flaws respond to all stimuli.

There is strong correlation between the total number of physical and functional defects found per unit of product during the manufacturing process, and the average latent defect content of shipping product. Product- and process-design changes aimed at reducing latent defects not only improve the reliability of shipping product, but also result in substantial manufacturing cost savings.

9.3.4 Operating Environment

The operating environment of an electronic system, either because of external environmental conditions or unintentional component underrating, may be significantly more stressful than the system manufacturer or the component supplier anticipated. Unintentional component underrating represents a design fault, but unexpected environmental conditions are possible for many applications, particularly in remote locations.

Conditions of extreme low or high temperatures, high humidity, and vibration during transportation may have a significant impact on long-term reliability of the system. For example, it is possible—and more likely, probable—that the vibration stress of the truck ride to a remote transmitting site will represent the worst-case vibration exposure of the transmitter and all components within it during the lifetime of the product.

Manufacturers report that most of the significant vibration and shock problems for land-based products arise from the shipping and handling environment. Shipping tends to be an order of magnitude more severe than the operating environment with respect to vibration and shock. Early testing for these problems involved simulation of actual shipping and handling events, such as end-drops, truck trips, side impacts, and rolls over curbs and cobblestones. Although unsophisticated by today's standards, these tests are capable of improving product resistance to shipping-induced damage.

9.3.5 Failure Modes

Latent failures aside, the circuit elements most vulnerable to failure in any piece of electronic hardware are those exposed to the outside world. In most systems, the greatest threat typically involves one or more of the following components or subsystems:

- The ac-to-dc power supply
- Sensitive signal-input circuitry
- High-power output stages and devices
- Circuitry operating into an unpredictable load, or into a load that may be exposed to lightning and other transient effects (such as an antenna)

Derating of individual components is a key factor in improving the overall reliability of a given system. The goal of derating is the reduction of electrical, mechanical, thermal, and other environmental stresses on a component to decrease the degradation rate and prolong expected life. Through derating, the margin of safety between the operating stress level and the permissible stress level for a given part is increased. This adjustment provides added protection from system overstress, unforeseen during design.

9.3.6 Maintenance Considerations

The reliability and operating costs over the lifetime of an RF system can be affected significantly by the effectiveness of the preventive maintenance program designed and implemented by the engineering staff. In the case of a *critical-system* unit that must be operational continuously or during certain periods, maintenance can have a major impact—either positive or negative—on downtime.

The reliability of any electronic system may be compromised by an *enabling event phenomenon*. This is an event that does not cause a failure by itself, but sets up (or enables) a second event that can lead to failure of the system. Such a phenomenon is insidious because the enabling event may not be self-revealing. Examples include the following:

- A warning system that has failed or has been disabled for maintenance
- One or more controls that are set incorrectly, providing false readouts for operations personnel
- Redundant hardware that is out of service for maintenance
- Remote metering that is out of calibration

Common-Mode Failure

A *common-mode failure* is one that can lead to the failure of all paths in a redundant configuration. In the design of redundant systems, therefore, it is important to identify and eliminate sources of common-mode failures, or to increase their reliability to at least an order of magnitude above the reliability of the redundant system. Common-mode failure points in a high-power RF system include the following:

- Switching circuits that activate standby or redundant hardware
- Sensors that detect a hardware failure
- Indicators that alert personnel to a hardware failure
- Software that is common to all paths in a redundant system

The concept of software reliability in control and monitoring has limited meaning in that a good program will always run, and copies of a good program will always run. On the other hand, a program with one or more errors will always fail, and so will the copies, given the same input data. The reliability of software, unlike hardware, cannot be improved through redundancy if the software in the parallel path is identical to that in the primary path.

Spare Parts

The spare parts inventory is a key aspect of any successful equipment maintenance program. Having adequate replacement components on hand is important not only to correct equipment failures, but to identify those failures as well. Many parts—particularly in the high-voltage power supply and RF chain—are difficult to test under static conditions. The only reliable way to test the component may be to substitute one of known quality. If the system returns to normal operation, then the original component is defective. Substitution is also a valuable tool in troubleshooting intermittent failures caused by component breakdown under peak power conditions.

9.4 Vacuum Tube Reliability

The end user should keep an accurate record of performance for each tube at the facility. Shorter-than-normal tube life could point to a problem in the RF amplifier or related hardware. The average life that may be expected from a power tube is a function of many operational parameters, including:

- Filament voltage
- Ambient operating temperature
- RF power output
- Operating frequency
- Operating efficiency

The best estimate of life expectancy for a given system at a particular location comes from on-site experience. As a general rule of thumb, however, at least 4000 hours of service can be expected from most power grid tubes. Klystrons and other microwave devices typically provide in excess of 15,000 hours. Possible causes of short tube life include the following:

- Improper power stage tuning
- Inaccurate panel meters or external wattmeter, resulting in more demand from the tube than is actually required
- Poor filament voltage regulation
- Insufficient cooling system airflow
- Improper stage neutralization

An examination of the data sheet for a given vacuum tube will show that a number of operating conditions are possible, depending upon the class of service required by the application. As long as the maximum ratings of the device are not exceeded, a wide choice of operating parameters is possible. When studying the characteristic curves of each tube, remember that they represent the performance of a *typical* device. All electronic products have some tolerance among devices of a single type. Operation of a given device in a particular system may be different than that specified on the data sheet. This effect is more pronounced at VHF and above.

9.4.1 Thermal Cycling

Most power tube manufacturers recommend a warm-up period between the application of *filament-on* and *plate-on* commands; about 5 minutes is typical. The minimum warm-up time is 2 minutes. Some RF generators include a time-delay relay to prevent the application of a plate-on command until a predetermined warm-up cycle is completed.

Most manufacturers also specify a recommended cool-down period between the application of *plate-off* and *filament-off* commands. This cool-down, generally about 10 minutes, is designed to prevent excessive temperatures on the PA tube surfaces when the cooling air is shut off. Large vacuum tubes contain a significant mass of metal, which stores heat effectively. Unless cooling air is maintained at the base of the tube and through the anode cooling fins, excessive temperature rise can occur. Again, the result can be shortened tube life, or even catastrophic failure because of seal cracks caused by thermal stress.

Most tube manufacturers suggest that cooling air continue to be directed toward the tube base and anode cooling fins after filament voltage has been removed to further cool the device. Unfortunately, however, not all control circuits are configured to permit this mode of operation.

9.4.2 Tube-Changing Procedure

Plug-in power tubes must be seated firmly in their sockets, and the connections to the anodes of the tubes must be tight. Once in place, the device typically requires no maintenance during its normal operating lifetime.

Insertion of a replacement tube must be performed properly. Gently rock and slightly rotate the tube as it is being inserted into the socket. This will help prevent bending and breaking the fingerstock. Be certain to apply sufficient force to seat the tube completely into the socket. Never use a lever or other tool on the tube to set it in place. Manual pressure should be adequate.

An intermediate point is reached when the grid contact fingerstock slides up the tube sides and encounters the contact area. It is important that the tube is fully inserted in the socket beyond this initial point of resistance.

Some sockets have adjustable stops that are set so that the tube grid contacts rest in the middle of the contact area when the tube is fully inserted. This positioning can be checked by inserting, then removing, a new tube. The scratch marks on the grid contacts will indicate the position of the tube relative to the socket elements. Figure 9.10 shows the minute scoring in the base contact rings of a power grid tube. A well-maintained socket will score the tube contacts when the device is inserted. If all fingers do not make contact, more current will flow through fewer contact fingers, causing overheating and burning, as shown in Figure 9.11.

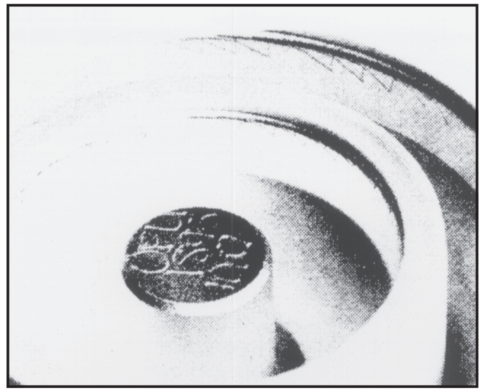


Figure 9.10 Proper fingerstock scoring of filament and control grid contacts on a power tube. (*Courtesy of Varian.*)

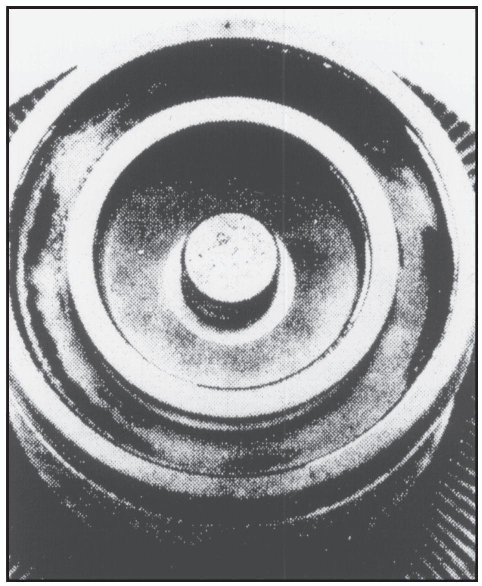


Figure 9.11 Damage to the grid contact of a power tube caused by insufficient fingerstock pressure. (*Courtesy of Varian.*)

Poor contact between a tube and its socket will always lead to problems. If the socket connectors fail to provide the proper electrical contact with the cylindrical tube elements, concentration of RF charging currents will result, leading to local overheating that may be destructive. After the connector loses its spring action, the heating is aggravated, and damage to the tube is likely. Some socket designs include a wire-wound spring encircling the outer circumference of the fingerstock to increase the contact pressure of the individual fingers. These springs should be replaced if they break or lose tension.

When a tube is removed from its socket, the socket should be blown or wiped clean and carefully inspected. Any discoloration caused by overheating of the socket fingerstock could signal impending tube/socket failure.

Many industrial and low-frequency tubes are not socketed, but installed by bolted or clamped connections. Stainless steel has a much lower coefficient of thermal expansion than copper. Therefore, clamped stainless steel anode connections should have some method of strain relief to prevent excess pressure from collapsing the tube anode as it heats.

All bolted or screwed connections should be tight. Verify that the clamps are snug and provide a good electrical contact around the entire circumference of the device. Because of the RF fields present, all clamps and bolts should be made from nonmagnetic materials. Copper, brass, and nonmagnetic series 300 stainless steel fasteners are preferred. Stainless steel is not a good conductor of electricity, so, although it may be used for clamping, it should not be part of the current path.

Before a new tube is installed in a system, it should be inspected for cracks or loose connections (in the case of tubes that do not socket-mount). Manufacturers typically recommend that after a new tube—or one that has been on the shelf for some time—is installed in the transmitter, it should be run with *filaments only* for at least 30 minutes, after which plate voltage may be applied. Next, the drive (modulation) is slowly brought up, in the case of an amplitude-modulated system. Residual gas inside the tube may cause an interelectrode arc (usually indicated as a plate overload) unless it is burned off in such a warm-up procedure.

9.4.3 Power Tube Conditioning

Large power tubes are subjected to rigorous processing during exhaust pumping at the time of manufacture [6]. Active elements are processed at temperatures several hundred degrees Celsius higher than those expected during normal operation. This procedure is designed to drive off surface and subsurface gas from the metals in the device to lower the possibility of these gases being released during the service life of the tube. Free gas molecules, however, always will be present to some degree in a fully processed tube. Gas, particularly oxygen-containing compounds, can combine chemically with cathode material to either permanently or temporarily destroy the electron emission capability of the cathode. Free gas molecules, when struck by electrons moving from the cathode to the anode, also may be ionized by having one or more electrons knocked from their systems. If enough of these ions, plus freed electrons, are present, a conduction path will be established that is not subject to control by the grid. This can result in runaway arcing that may involve all elements of the device. Current then will be limited primarily by the source voltage and impedance. (The space charge, to some degree, is neutralized by the presence of both electrons and positive ions.)

Electrons from sources other than the heated cathode provide low-current paths between elements when the voltage gradient is sufficiently high at the negative element for pure field emission. The voltage gradient at the negative element is governed by the following parameters:

- The applied voltage between elements
- The spacing between elements

- The surface contour of the negative element

A large voltage gradient can exist in the following areas:

- In front of a point on the negative element
- In front of a particle adhering to the negative element
- In front of a clump of gas molecules on the surface of the negative element

Field emission occurs readily from a cold surface if the operating conditions provide the necessary voltage gradient.

Ionization of free gas can result from bombardment by field-emitted electrons. Arcing is likely to occur as a result of field emission in operating equipment because the plate voltage is maximum during that part of the signal cycle when ordinary plate current from the cathode is shut off by the control grid. For this reason, an important part of tube processing is high-voltage conditioning to remove sharp points or small particles from tube elements. This part of tube processing may, and sometimes should, be repeated in the field after shipment or storage if the tube is intended for use at a plate voltage in excess of 10 kV.

High-voltage conditioning (sometimes called *spot-knocking* or *debarnacling*) consists of applying successively higher voltages between tube elements, permitting the tube to spark internally at each voltage level until stable (no arcing). The voltage then is raised to the next higher potential until the tube is stable at a voltage approximately 15 percent higher than the peak signal voltage it will encounter in service.

The equipment used for tube conditioning is simple but specialized. It may provide dc or ac voltage, or both. The current required is small. The voltage should be continuously variable from practically zero to the highest value required for proper conditioning of the tube. The energy per spark is controlled by the internal resistance of the supply plus any external series resistor used. In dc conditioning, a milliammeter typically is included to measure the level of field emission current prior to sparking, or simply to determine whether the field emission current is within the specified range for a tube being tested. Also in dc conditioning, a capacitor may be placed across the tube under test to closely control the energy released for each spark. If the conditioning is to proceed effectively, the amount of energy delivered by the capacitor must be great enough to condition the surfaces, but not so large as to cause permanent damage.

Power Supply

The power supply is the heart of any high-voltage tube conditioning station [6]. Current-limiting resistance is desirable; the power supply may have an internal resistance on the order of 100 kΩ. In addition to the power supply, a current-limiting resistor of 100 to 300 kΩ should be provided in the circuit to the tube being conditioned. In dc processing, a storage capacitor of 1000 to 3000 pF can be placed directly across the device under test (DUT), with a high-voltage noninductive resistor of approximately 50 Ω connected between the tube and the capacitor. Naturally, this shunt capacitor must be capable of withstanding the full applied potential of the power supply.

Using both polarities on the tube elements is advantageous in high-voltage conditioning, suggesting that an ac supply might be the best choice for field tube conditioning. The advantage of the dc system, on the other hand, is that exact levels of field emission current and breakdown voltage may be determined for comparison with known "clean" tubes, and with the manufacturer's specification. The polarity of the applied voltage may be reversed by mounting the DUT on an insulating frame so that the positive and negative high-voltage leads may be interchanged during processing. Also, the power supply rectifier and dc meters may be bypassed with suitable switching so that ac is obtained from the supply for initial tube cleanup. The storage capacitor across the tube should be disconnected if ac is used.

Conditioning Procedure

Manufacturers of large power tubes typically specify an upper limit for field emission between the filament, control grid, and screen grid connected together, and the anode [6]. Such devices should be allowed to spark until stable at the voltage where sparking first occurs. The voltage then is increased in steps determined by the voltage that initiates sparking again. This process is continued until the tube is stable at the maximum test voltage. It is advisable to reverse the polarity of the supply if dc testing is employed.

Usually, no field emission specifications exist for applied voltage between grids and between grid and filament, but these elements normally should hold off 10 kV internally. The need for conditioning between these elements is indicated if internal sparking occurs at a significantly lower voltage. Consult the tube manufacturer for specific recommendations on conditioning voltages.

During high-voltage processing, particularly between grids and between grid and filament, some of the redistributed gas molecules may be deposited on the cold filament, causing a temporary loss of emission. If this happens, operate the tube for approximately 1 hour, with normal filament power only, to drive off the volatile material. Normal electron emission from the filament will be reestablished by this procedure. It is recommended that routine practice include operation of the filament for approximately 1 hour as an immediate follow-up to high-voltage conditioning.

After conditioning, the tube should be stored in the same position (orientation) as that used for high-voltage conditioning and installation in the equipment. Movement of the tube after conditioning should be minimized to prevent any redistribution of particles within the device.

Considerations for Very Large Tubes

High-voltage ac conditioning is not recommended for very large tubes, such as the 8971/X2177, 8972/X2176, 8973/X2170, 8974/2159, 4CM400000A, and similar devices [6]. High-potential 50 or 60 Hz voltage can excite natural mechanical resonances in the large filament and grid structures of these tube types. Excitation of these resonances can break the filament and/or grids, thus destroying the device. If ac conditioning must be used, the following precautions should be taken:

- Connect all filament terminals together (external to the tube).
- Connect all terminals of the tube to a terminal of the high-voltage power supply. For example, if high voltage is to be applied between the screen and anode, the filament, grid, and screen should be connected together, then to one terminal of the supply. If high voltage is to be applied between the filament and grid, connect the grid, screen, and anode together and to one terminal of the supply. No terminal of the tube should be allowed to float electrically during high-voltage conditioning.
- As the test voltage is increased, listen carefully for vibration inside the tube. If any is detected, immediately remove the ac high voltage.

These precautions will reduce the risk of damage from ac conditioning of very large tubes. However, because of the special procedures required and the risk of damage resulting from mechanical resonances, it is recommended that only dc conditioning be used for such devices.

Safety

Personnel protection dictates that the tube being processed, as well as the power supply, be enclosed in a metal cabinet with access doors interlocked so that no high voltage can be applied until the doors are closed [6]. The enclosure material, wall thickness, and dimensions must be chosen to limit X-ray radiation from the DUT to safe levels. A steel-wall thickness of in has been found adequate for dc testing up to approximately 70 kV. For conditioning up to 100 kV dc, it is necessary to add 0.05 in of lead sheet as a lining to the steel enclosure.

The field of health standards regarding x-radiation dosage for a given period of time is complex and should be discussed with experts on the subject. Calibrated film badges or other reliable measuring devices normally are used to determine human exposure to X rays over time.

9.4.4 Filament Voltage

A *true reading* rms voltmeter is required for accurate measurement of filament voltage. The measurement is taken directly from the tube socket connections. A true-reading rms meter, instead of the more common *average responding* rms meter, is suggested because it can accurately measure a voltage despite an input waveform that is not a pure sine wave. Some filament voltage regulators use silicon controlled rectifiers (SCRs) to regulate the output voltage. Saturated core transformers, which often deliver nonsine waveforms, also are commonly used to regulate filament input power.

Long tube life requires filament voltage regulation. A tube whose filament voltage is allowed to vary along with the primary line voltage will not achieve the life expectancy possible with a tightly regulated supply. This problem is particularly acute at mountain-top installations, where utility regulation is generally poor.

To extend tube life, some end-users leave the filaments on at all times, not shutting down at sign-off. If the sign-off period is 3 hours or less, this practice can be beneficial.

Filament voltage regulation is a must in such situations because the primary line voltages may vary substantially from the carrier-on to carrier-off value.

When a cold filament is turned-on, damage can be caused by two effects [7]:

- Current inrush into the cold filament, which can be up to 10 times the normal operating current if the filament supply is of low impedance.
- Grain reorientation, which occurs at about 600 to 700 ºC, known as the *Miller-Larson effect*. This grain reorientation will result in a momentary plastic state that can cause the filament wire to grow in length and, therefore, become thinner.

The Miller-Larson effect is aggravated by variations in the cross-sectional area of the filament wires along their length. This will cause hot spots in the thinner sections because of the greater current densities there. The higher temperatures at the hot spots cause increased growth during warmup through the 600 ºC temperature range, when they have a higher current density than the rest of the wire, and a much higher power dissipation per unit length as a result of the higher resistance. Each time the filament is turned-on, the wire becomes thinner until the hot spot temperature enters a runaway condition.

Filament voltage for a klystron should not be left on for a period of more than 2 hours if no beam voltage is applied. The net rate of evaporation of emissive material from the cathode surface of a klystron is greater without beam voltage. Subsequent condensation of the material on gun components may lead to voltage holdoff problems and an increase in body current.

Black Heat

One practice used occasionally to extend the life of the thoriated tungsten power tube filament is to operate the device at a low percentage of rated voltage during sign-off periods [7]. This technique, known as *black heat*, involves operating the filament at 25 to 40 percent of the rated filament voltage. This range produces a temperature high enough to maintain the filament above the 600 ºC region where the Miller-Larson effect occurs, and sometimes low enough so that forced cooling is not required during stand-by.

Operating histories of several black heat installations indicate that the trauma of raising the filament voltage from 25 percent up to the operating voltage is still potentially damaging. For this reason, a higher stand-by voltage of about 80 to 90 percent of the full rated value (*orange heat*) has been used with some success.

The voltage range of 40 to 80 percent should be avoided because the filament can act as a getter within this range, and absorb gases that will raise the work function of the thoriated tungsten filament. For orange heat operation, cooling system operation is required. Before attempting to implement a black heat or orange heat filament management program, consult with the tube and transmitter manufacturers.

9.4.5 Filament Voltage Management

As outlined in Chapter 3, the thoriated-tungsten power grid tube lends itself to life extension through management of the applied filament voltage. Accurate adjustment of the filament voltage can extend the useful life of the device considerably, sometimes to twice the normal life expectancy. The following procedure typically is recommended:

- Install the tube, and tune for proper operation.
- Operate the filament at its full rated voltage for the first 200 hours following installation.
- Following the burn-in period, reduce the filament voltage by 0.1 V per step until system power output begins to fall (for frequency-modulated systems) or until modulating waveform distortion begins to increase (for amplitude-modulated systems).
- When the *emissions floor* has been reached, increase the filament voltage approximately 0.2 V peak-to-peak (P-P).

Long-term operation at this voltage can result in a substantial extension of the useful life of the tube, as illustrated in Figure 9.12.

The filament voltage should not, in any event, be operated at or below 90 percent of its rated value. At regular intervals, about every 3 months, the filament voltage is checked and increased if power output begins to fall or waveform distortion begins to rise. Filament voltage never should be increased to more than 105 percent of the rated voltage.

Note that some tube manufacturers place the minimum operating point at 94 percent. Others recommend that the tube be set for 100 percent filament voltage and left there. The choice is left to the user, after consultation with the manufacturer.

The filament current should be checked when the tube is installed, and at annual intervals thereafter, to ensure that the filament draws the expected current. Tubes can fail early in life because of an open filament bar—a problem that could be discovered during the warranty period if a current check is made upon installation.

For 1 week of each year of tube operation, the filament should be run at full rated voltage. This will operate the *getter* and clean the tube of gas.

Klystron Devices

Filament voltage is an equally important factor in achieving long life in a klystron. The voltage recommended by the manufacturer must be accurately set and checked on a regular basis. Attempts have been made to implement a filament voltage management program—as outlined previously for a thoriated-tungsten tube—on a klystron, with varying degrees of success. If filament management is attempted, the following guidelines should be observed:

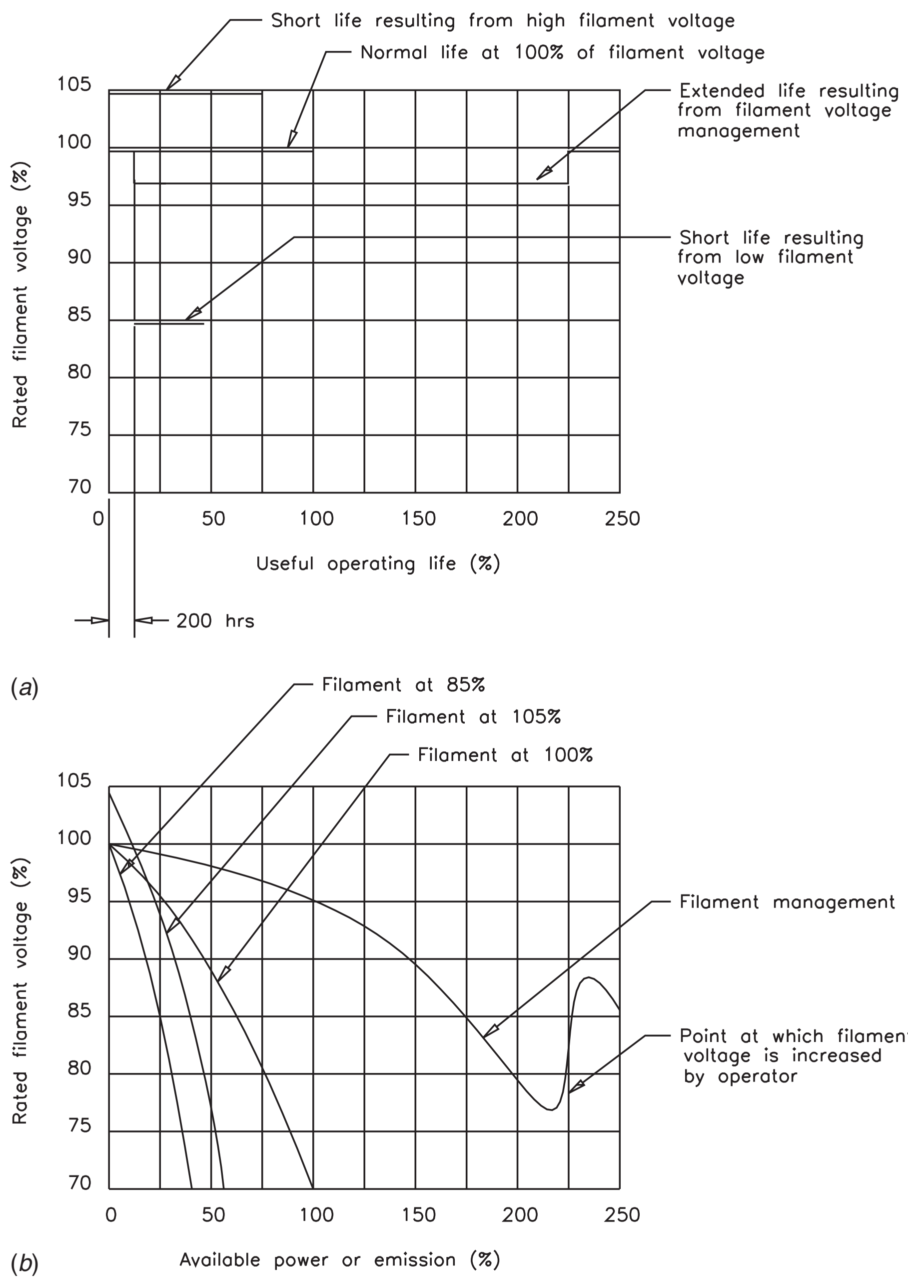


Figure 9.12 The effects of filament voltage management on a thoriated-tungsten filament power tube: (*a*) useful life as a function of filament voltage, (*b*) available power as a function of filament voltage. Note the dramatic increase in emission hours when filament voltage management is practiced.

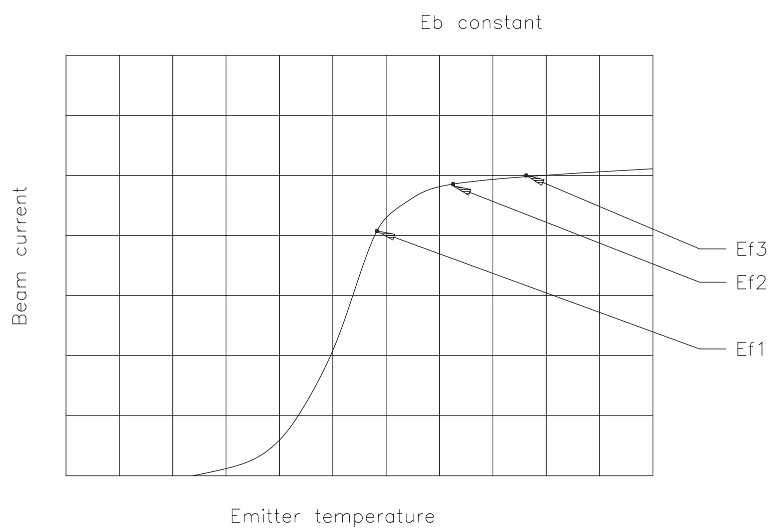


Figure 9.13 The effect of klystron emitter temperature on beam current.

- Install the tube, and tune for proper operation.
- Operate the filament at its full rated voltage for the first 200 hours following installation.
- Following the burn-in period, reduce the filament voltage by 0.1 V per step until collector current begins to decrease. After each filament voltage change, wait at least 5 minutes to allow for cathode cooling.
- When the emissions floor has been reached, increase the filament voltage approximately 0.25 V P-P.

Figure 9.13 charts the relationship between emitter temperature and beam current. The filament should be adjusted to a point between E_{f1} and E_{f2}, which will vary with each klystron. Note that continued operation below the E_{f1} level, or at a point that causes emission instability, can result in beam defocusing, leading to increased modulating anode current and body current.

For operation at a reduced filament voltage, it may be necessary to allow a longer warm-up period when bringing the tube up from a cold start. If loss of emission is noted at turn-on, it will be necessary to either extend the warm-up time or raise the filament voltage to overcome the loss.

9.4.6 PA Stage Tuning

The PA stage of an RF generator may be tuned in several ways. Experience is the best teacher when it comes to adjusting for peak efficiency and performance. Compromises often must be made among various operating parameters.

Tuning can be affected by any number of changes in the PA stage. Replacing the final tube in a low- to medium-frequency RF generator usually does not significantly alter stage tuning. It is advisable, however, to run through a touch-up tuning procedure just to be sure. Replacing a tube in a high-frequency RF generator, on the other hand, can significantly alter stage tuning. At high frequencies, normal tolerances and variations in tube construction result in changes in element capacitance and inductance. Likewise, replacing a component in the PA stage may cause tuning changes because of normal device tolerances.

Stability is one of the primary objectives of tuning. Adjust for broad peaks or dips, as required. Tune so that the system is stable from a cold startup to normal operating temperature. Readings should not vary measurably after the first minute of operation.

Tuning is adjusted not only for peak efficiency, but also for peak performance. These two elements, unfortunately, do not always coincide. Tradeoffs must sometimes be made to ensure proper operation of the system.

9.4.7 Fault Protection

An arc is a self-sustained discharge of electricity between electrodes with a voltage drop at the cathode on the order of the minimum ionizing potential of the environment [8]. The arc supports large currents by providing its own mechanism of electron emission from the negative terminal, plus space-charge neutralization.

All power vacuum tubes operate at voltages that can cause severe damage in the event of an internal arc unless the tube is properly protected. This damage can be relatively minor in tubes operating from low-energy power supplies, but it will become catastrophic in cases where a large amount of stored energy or follow-on current is involved. Because any high-voltage vacuum device may arc at one time or another, some means of protection is advised in all cases; it is mandatory in those instances where destructive quantities of energy are involved. In addition to protecting the tube in the event of a tube or circuit malfunction, such measures also protect the external circuitry.

Most power grid tubes employing thoriated-tungsten filaments are capable of withstanding relatively high energy arcs. However, while employing substantial materials, such devices usually incorporate fine wire grids that must be protected. In large tube applications, it is often found that the screen grid or bias supply, in addition to the anode supply, is capable of delivering destructive energy to the tube structure in the event of an internal arc. Consequently, protection must be provided in all cases where potentially destructive energy is involved. Large tubes usually are capable of withstanding up to 50 joules (J) total energy without permanent damage.

In the design of a power amplifier, the stage should be tested to ensure that the 50 J limit is not exceeded by any of the power supplies feeding the tube. Each supply, whether anode or grid, should be short-circuit-tested through a 6-in length of 0.255-mm-diameter (no. 30 AWG) soft copper wire. A similar test should be made from plate-to-screen grid to ensure that the tube is protected in the event of a plate-to-screen arc. A protective spark gap between the screen grid and cathode is recommended so that, if an arc occurs, the resulting spark from screen to cathode is external to the tube structure. The test wire will remain intact if the energy dissipated is less

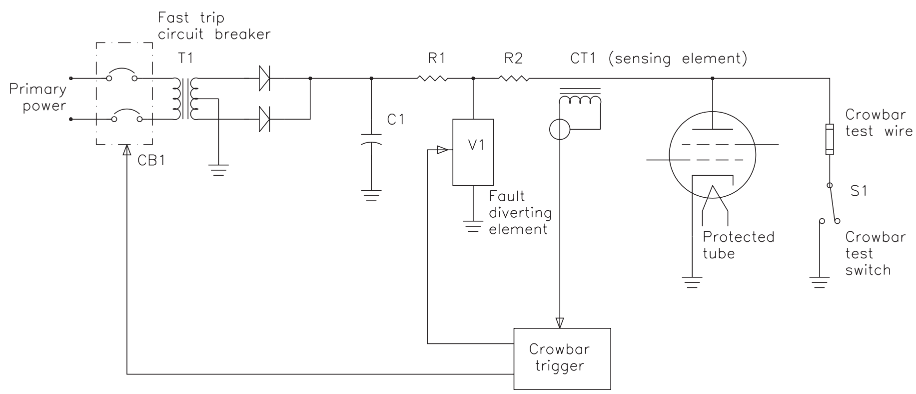


Figure 9.14 Arc protection circuit utilizing an energy-diverting element.

than 50 J. The 50 J test includes total energy delivered from the energy storage device and/or from the follow-on current from the power supply prior to the opening of the primary circuit.

Each power supply in the system must pass this test, or some form of energy-diverting or energy-limiting circuit must be employed. Figure 9.14 shows an energy-diverting circuit for a high-power tube. Energy diverters at high-power levels are complex. They typically employ large high-speed diverting elements such as thyratrons, ignitrons, triggered spark gaps, and, in some cases, a high-speed vacuum switch. These devices may be required to handle thousands of amperes of peak current. Resistor R1 in Figure 9.14 is used to limit the peak current into the energy-diverting switch V1, as well as to limit peak current demand on the transformer and rectifiers in the power supply. Resistor R2 must be large enough to keep the voltage across V1 from dropping so low under load-arc conditions as to inhibit the proper firing of the fault-diverting elements. R1 and R2 must also damp circuit ringing sufficiently to prevent current reversal in V1, which could cause V1 to open before the fault conditions are cleared. R1 and R2 are sized to minimize average power losses and to handle the required voltage and power transients while properly performing their functions. The sensing element CT1 detects any abnormal peak-current levels in the system. Signals from the current transformer are used to trigger V1 in the event of an overcurrent condition. A crowbar test switch, S1, can be used to perform the wire test outlined previously, to ensure that the total energy dissipated in an arc is less than 50 J. Typically, S1 is a remote-controlled high-voltage switch of either air or vacuum construction.

In a typical test, when S1 is closed, current transformer CT1 senses the fast rising current and fires the energy-diverting element V1; it simultaneously sends a fast trip signal to the main circuit breaker. Most energy diverters fire within a few microseconds of the time the fault is detected; all voltages and currents are removed from the protected device in tens of microseconds.

By using this technique, it is possible to limit the energy delivered during an arc to much less than the recommended maximum. In a properly operating system, essentially no damage will occur within the tube even under severe arcing conditions. The test wire must be connected at the tube itself to take into account all stored energy (*L* and *C*) in the system.

9.4.8 Vacuum Tube Life

The vacuum tube suffers wear-out because of a predictable chemical reaction. Life expectancy is one of the most important factors to be considered in the use of vacuum tubes. In general, manufacturers specify maximum operating parameters for power grid tubes so that operation within the ratings will provide for a minimum useful life of 4000 hours. Considerable variation can be found with microwave power tubes, but 15,000 hours is probably a fair average useful life. It should be noted that some microwave devices, such as certain klystrons, have an expected useful life of 30,000 hours or more.

The cathode is the heart of a power tube. The device is said to *wear out* when filament emissions are inadequate for full power output or acceptable waveform distortion. In the case of the common thoriated-tungsten filament tube, three primary factors determine the number of hours a device will operate before reaching wear-out:

- The rate of evaporation of thorium from the cathode
- The quality of the tube vacuum
- The operating temperature of the filament

In the preparation of thoriated tungsten, 1 to 2 percent of thorium oxide (thoria) is added to the tungsten powder before it is sintered and drawn into wire form. After being mounted in the tube, the filament usually is *carburized* by being heated to a temperature of about 2000 K in a low-pressure atmosphere of hydrocarbon gas or vapor until its resistance increases by 10 to 25 percent. This process allows the reduction of the thoria to metallic thorium. The life of the filament as an emitter is increased because the rate of evaporation of thorium from the carburized surface is several times smaller than from a surface of pure tungsten.

Despite the improved performance obtained by carburization of a thoriated-tungsten filament, the element is susceptible to deactivation by the action of positive ions. Although the deactivation process is negligible for anode voltages below a critical value, a trace of residual gas pressure too small to affect the emission from a pure tungsten filament can cause rapid deactivation of a thoriated-tungsten filament. This restriction places stringent requirements on vacuum processing of the tube.

These factors, taken together, determine the wear-out rate of the device. Catastrophic failures due to interelectrode short circuits or failure of the vacuum envelope are considered abnormal and are usually the result of some external influence. Catastrophic failures not the result of the operating environment usually are caused by a defect in the manufacturing process. Such failures generally occur early in the life of the component.

The design of the RF equipment can have a substantial impact on the life expectancy of a vacuum tube. Protection circuitry must remove applied voltages rapidly to prevent damage to the tube in the event of a failure external to the device. The filament turn-on circuit also can affect PA tube life expectancy. The surge current of the filament circuit must be maintained below a certain level to prevent thermal cycling problems. This consideration is particularly important in medium- and high-power PA tubes. When the heater voltage is applied to a cage-type cathode, the tungsten wires expand immediately because of their low thermal inertia. However, the cathode support, which is made of massive parts (relative to the tungsten wires), expands more slowly. The resulting differential expansion can cause permanent damage to the cathode wires. It also can cause a modification of the tube operating characteristics and, occasionally, arcs between the cathode and the control grid.

Catastrophic Failures

Catastrophic failures can be divided into two primary categories:

- The short-circuiting of broken or warped elements within the tube
- A loss of vacuum in the device

Air in the tube causes a loss of dielectric standoff between the internal elements. It is not possible to distinguish between an interelectrode short circuit and a loss of vacuum in the operating equipment.

Catastrophic failures that occur during initial installation are usually the result of broken elements. Failures that occur after an initial burn-in period are more likely to be caused by a loss of vacuum. In either case, continued efforts to operate the tube can result in considerable damage to the device and to other components in the system.

Note that a loss of vacuum can result from any of several anomalies. The two most common are:

- A latent manufacturing defect in one of the ceramic-to-metal seals
- Circulating currents resulting from parasitic oscillations and/or improper tuning

Intermittent overloads are the most difficult to identify. They can be caused by circuit operating conditions or internal tube failures. A broken or warped filament element, for example, can move around inside the device and occasionally short circuit to the grid, causing a loss of grid bias and subsequent plate overload. Intermittent overloads also can be caused by a short circuit or high VSWR across the load.

9.4.9 Examining Tube Performance

Examination of a power tube after it has been removed from a transmitter or other type of RF generator can reveal a great deal about how well the equipment-tube combination is working. Contrast the appearance of a new power tube, shown in Figure 9.15, with a component at the end of its useful life. If a power tube fails prematurely,

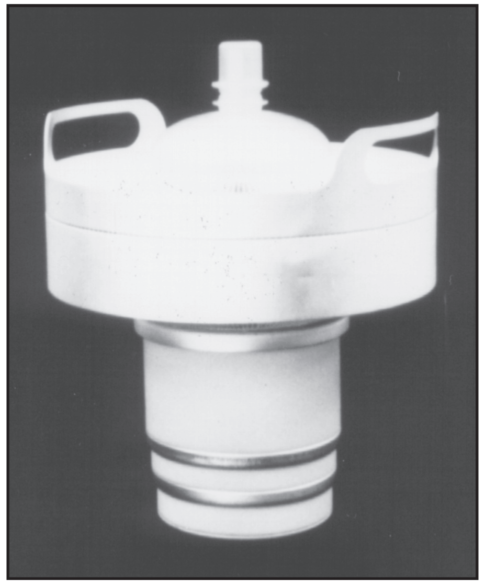
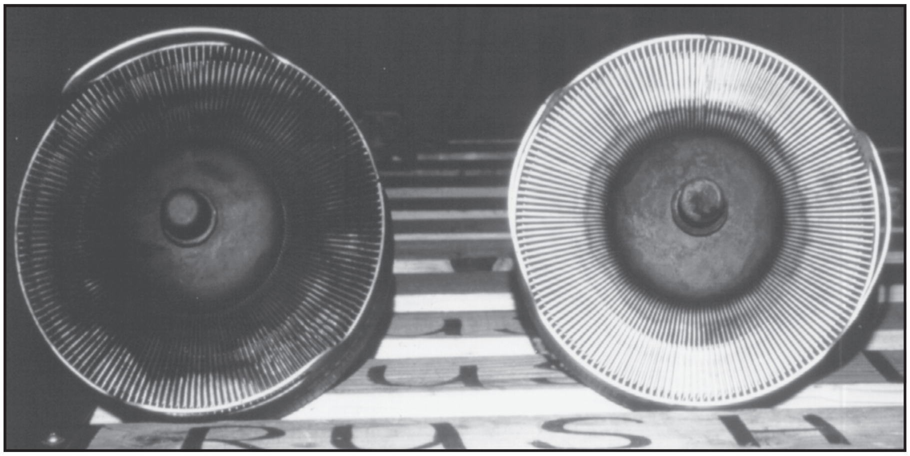


Figure 9.15 A new, unused 4CX15000A tube. Contrast the appearance of this device with the tubes shown in the following figures. (*Courtesy of Varian*.)

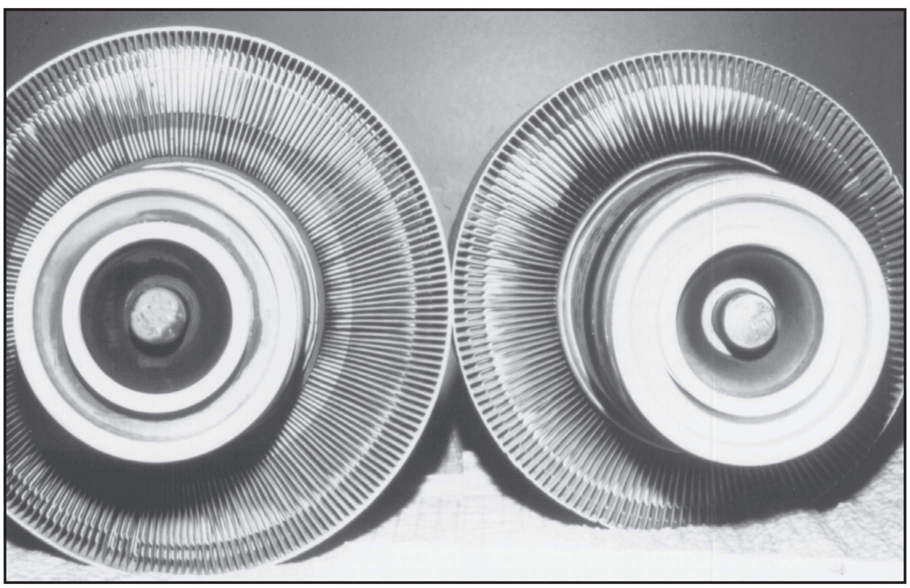
the device should be examined to determine whether an abnormal operating condition exists within the transmitter. Consider the following examples:

- Figure 9.16. Two 4CX15000A power tubes with differing anode heat-dissipation patterns. Tube (*a*) experienced excessive heating because of a lack of PA compartment cooling air or excessive dissipation because of poor tuning. Tube (*b*) shows a normal thermal pattern for a silver-plated 4CX15000A. Nickel-plated tubes do not show signs of heating because of the high heat resistance of nickel.
- Figure 9.17. Base-heating patterns on two 4CX15000A tubes. Tube (*a*) shows evidence of excessive heating because of high filament voltage or lack of cooling air directed toward the base of the device. Tube (*b*) shows a typical heating pattern with normal filament voltage.
- Figure 9.18. A 4CX5000A tube with burning on the screen-to-anode ceramic. Exterior arcing of this type generally indicates a socketing problem, or another condition external to the tube.
- Figure 9.19. The stem portion of a 4CX15000A tube that had gone down to air while the filament was on. Note the deposits of tungsten oxide formed when the filament burned up. The grids are burned and melted because of the ionization arcs that subsequently occurred. A failure of this type will trip overload breakers in the RF generator. It is indistinguishable from a short-circuited tube in operation.
- Figure 9.20. A 4CX15000A tube that experienced arcing typical of a bent fingerstock, or exterior arcing caused by components other than the tube.



(*a*) (*b*)

Figure 9.16 Anode dissipation patterns on two 4CX15000A tubes: (*a*) excessive heating, (*b*) normal wear. (*Courtesy of Econco Broadcast Service*.)



(*a*) (*b*)

Figure 9.17 Base heating patterns on two 4CX15000A tubes: (*a*) excessive heating, (*b*) normal wear. (*Courtesy of Econco*.)

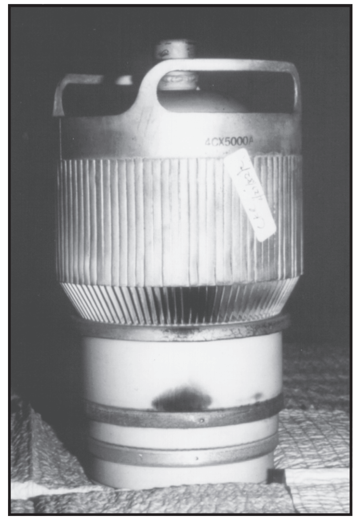


Figure 9.18 A 4CX5000A tube that appears to have suffered socketing problems. (*Courtesy of Econco.*)

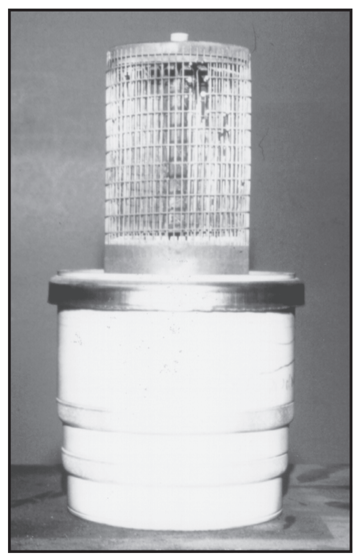


Figure 9.19 The interior elements of a 4CX15000A tube that had gone to air while the filament was lit. (*Courtesy of Econco.*)

Note that the previous examples apply to silver-plated power grid tubes.

The external metal elements of a tube typically are plated with nickel or silver. Tubes that go into sockets are usually silver-plated. The soft silver provides a better contact interface than the much harder nickel, and it deforms slightly under contact pressure, providing greater contact area. Silver plating has a dull, whitish cast, whereas nickel has a hard, metallic appearance.

Nickel is resistant to discoloration due to heat at normal tube operating temperatures, but silver will tarnish easily. As demonstrated in this section, the heat patterns on

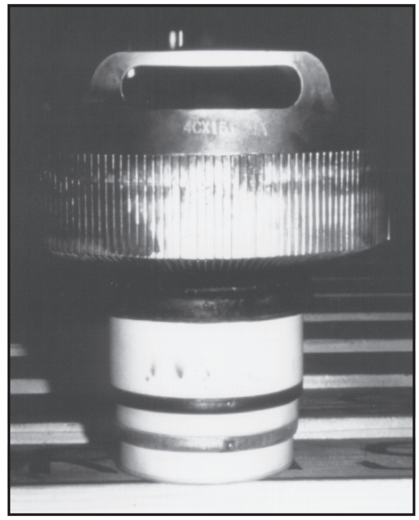


Figure 9.20 A 4CX15000A tube showing signs of external arcing. (*Courtesy of Econco.*)

silver-plated tubes are helpful in problem analysis. If a nickel-plated tube shows signs of heat discoloration, a significant cooling or operating problem exists. Nickel will not discolor until it reaches a temperature much higher than a tube normally achieves under typical operating conditions.

9.4.10 Shipping and Handling Vacuum Tubes

Because of their fragile nature, vacuum tubes are packaged for shipment in foam-filled or spring-supported shipping containers. When it is necessary to transport a tube from one location to another, use the original packing material and box or crate. The tube should be removed whenever the RF equipment is relocated. Never leave a tube installed in its socket during an equipment move.

During installation or service, always keep the tube in its typical operating position (most commonly horizontal). Never allow a tube to roll along a surface. Damage to the filament or to other elements in the device may result.

It is occasionally necessary for an RF generator to be moved from one location to another within a plant. Equipment used in this manner must be equipped with air-filled casters; do not use solid casters.

When it is necessary or desirable to store a tube for an extended period of time, place it in a plastic bag to protect it from moisture, and return the device to its shipping box. Maintenance engineers are discouraged from placing markings on a power tube. Some engineers note service dates using ink or pencil on tubes. This practice is not recommended. Instead, attach a separate service record to the tube using a tie-wrap or similar removable device. Do not use self-adhesive labels for this purpose. When removed, adhesive labels usually leave some residue on the attachment surface.

Although it is not recommended that a power tube be stored indefinitely, most modern devices utilizing metal and ceramic envelopes can be stored for long periods of time without deterioration. It usually is not necessary to rotate a spare tube through an operating socket to degas the device.

Older vacuum tubes utilizing glass as the insulating medium tend to leak gas over time. The glass is not the problem, but, instead, the Kovar alloy used to seal the glass-to-metal parts of the tube. Kovar also is subject to rusting when moisture is present. Glass-insulated vacuum tubes should be sealed in a plastic bag for storage and rotated through the equipment at least once every 12 months. The larger the physical size of the tube, the greater the problem of gassing.

9.5 Klystron Reliability

Klystron amplifiers are well known as reliable, long-life microwave devices that provide the user thousands of hours of trouble-free service. Many of the guidelines discussed in Section 9.4 for power vacuum tubes in general also apply to klystrons and related microwave devices. However, several considerations are specific to the klystron, including:

- Cooling system maintenance
- Ceramic element cleanings
- Gun element reconditioning
- Focusing electromagnet maintenance
- Protection during prime power interruption
- Shutoff precautions

9.5.1 Cleaning and Flushing the Cooling System

One of the major problems encountered in field operation of a klystron cooling system is the formation of corrosion products [9]. Corrosion frequently occurs in the cooling channels of the klystron body on the surface of the water/vapor-cooled collector, and in the cooling channels of the electromagnet. It is the result of a chemical reaction between free oxygen-laden coolant and the hot copper channel wall. Corrosion, as described here, is different from *scale formation*, which can be caused by the use of a coolant other than clean distilled water, or may be the by-product of electrolysis between dissimilar metals in the heat-exchange system. Scale formation can be controlled through the use of on-line purification loops.

New transmitter water lines frequently contain contaminants, including:

- Solder
- Soldering or brazing flux
- Oils
- Metal chips or burrs

- Pieces of Teflon sealing tape

When the water lines are installed, these contaminants must be flushed and cleaned from the system before the klystron and magnet are connected.

The following guidelines are suggested for cleaning the cooling passages of water- and vapor-cooled klystrons and associated RF generation equipment. The procedures should be performed before a klystron is installed, then repeated on a periodic basis while the tube is in service.

Transmitter Flushing

Proper cleaning of the circulating water system in an RF generator is vital to long-term reliability. Although each design is unique, the following general procedures are appropriate for most installations [9]:

- Disconnect the tube and the magnet.
- Add jumper hoses between the input and output of the klystron and the electromagnet water lines.
- Disconnect or bypass the pump motor.
- Fill the system with hot tap water, if available.
- Open the drain in the transmitter cabinet and flush for 15 minutes or until it is clean.
- Flush the water lines between the tank and pump separately with hot tap water, if available, until they are clean.
- Connect all water lines, and fill the system with hot tap water, if available, and one cup of nonsudsing detergent. Trisodium phosphate is recommended.
- Operate the water system with hot tap water for 30 minutes. An immersion heater may be used to maintain hot water in the system.
- Drain the system, and flush with hot tap water for 30 minutes.
- Remove and clean the filter element.
- Refill the water system with tap water (at ambient temperature).
- Operate the water system. Maintain the water level while draining and flushing the system until no detergent, foam, or foreign objects or particles are visible in the drained or filtered element. To test for detergents in the water, drain a sample of water into a small glass test tube, and allow it to stand for 5 minutes. To generate foam, shake the test tube vigorously for 15 s, then allow it to stand 15 s. A completely foam-free surface indicates no foam-producing impurities.
- Repeat the two previous steps if detergent foam is still present.
- Drain the system and refill with distilled water when the tube and transmitter water lines are clean.

- Remove, clean, and replace the filter before using.

Flushing Klystron Water Lines

Although most klystrons are shipped from the manufacturer with water passages clean and dry, it is good engineering practice to flush all cooling passages before installing the tube. Occasionally, tubes that have been in service for some time develop scale on the collector and also must be flushed. Contaminated water further contributes to dirty water lines, requiring flushing to clear. The following general procedure is recommended for tubes with contaminated water lines, corrosion, scale, or blocked passages [9]:

- Remove the input water fitting (Hansen type), and add a straight pipe extension, approximately 1 to 2 in long, to the tube.
- Attach a hose to this fitting, using a hose clamp to secure it. This connection will serve as the drain line; it should be discharged into a convenient outlet.
- On some tube types, the normal body-cooling output line is fed to the base of the vapor-phase boiler. Remove the hose at the base of the boiler. Do not damage this fitting; it must be reused and must seal tightly.
- Attach a 2 to 3 in-long extension pipe that will fit the small hose at one end and a garden hose at the other end. Secure the extension with hose clamps.
- Connect the garden hose to a tap water faucet. Hot tap water is preferable, if available.
- Back-flush the klystron-body cooling passages for 10 to 15 minutes at full pressure until they are clean.
- Reconnect the input and output water lines to the klystron.
- If scale is present on the vapor-phase collector, use a solution of trisodium phosphate for the first cleaning. Perform this step after cleaning the transmitter water system (as described previously).
- Connect the klystron to the transmitter water lines, and fill the system with tap water (hot, if available) and one cup of nonsudsing detergent.
- Operate the water system for 15 minutes. Make certain that the water level completely covers the collector core.
- Drain the system, and flush for 30 minutes or until no detergent foam is present.
- Remove and clean the filter element.
- Fill the system with distilled water.
- Drain the system, and refill with distilled water.

Cleaning Klystron Water Lines

If heavy scaling has formed on the vapor-phase collector and/or blocked water passages, they may be cleaned using a stronger cleaning agent. A solution of *Ty-Sol*[1] may be used to remove scale and corrosion. The following procedure is recommended [9]:

- Clean the transmitter water system (as described previously).
- Connect the tube to the transmitter water system.
- Fill the system with hot tap water (if available) and add 2 gallons of cleaning solution for every 50 gallons of water.
- Operate the water system for 15 minutes, or until scale has been removed and the collector has a clean copper color.
- Make certain that the water level covers the top of the collector during cleaning. Evidence of cleaning action may be observed in the flow meters.
- Drain the system, and flush with tap water.
- Remove and clean the filter element, then replace.
- Refill the system with distilled water and flush for 30 minutes to 1 hour.
- Check for detergent foam at the end of the flushing period; also check the pH factor. Continue flushing with distilled water if foam is present or if the pH factor is not within the specified range.
- Refill the system with clean distilled water.

Chlorine present in common tap water is harmful to the water passages of the klystron. Thorough flushing with distilled water will remove all chlorine traces. Never use tap water for final refill or for make-up water.

Flushing and Cleaning Magnet Water Lines

The magnet water lines may be flushed and cleaned in the same manner as described for the klystron.

General Cleaning

Two remaining items must be clean to achieve efficient operation: the sight glass and float of the water-flow indicators. The water-flow indicators often become contaminated during use. This contamination collects on the sight glass and on the float, making flow-reading difficult. If too much contamination is present on the glass and float, sticking or erroneous readings may result. The detergent and cleaning solutions may

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1 Chemical Research Association, Chicago, IL.

not remove all of this contamination. If this is the case, remove and clean the flow meter using a brush to clean the glass surface.

9.5.2 Cleaning Ceramic Elements

Foreign deposits on the ceramic elements of a klystron should be removed periodically to prevent ceramic heating or arc paths that can lead to klystron failure. The recommended procedure is as follows:

- Remove the klystron from the RF generator, and mount it to a stand or other suitable fixture.
- Remove loose debris with a soft-fiber bristle brush.
- Clean the ceramic with a mild abrasive cleanser, preferably one that includes a bleaching agent. (Household cleansers such as Comet and Ajax are acceptable.) While cleaning, do not apply excessive force to the ceramic. Normal hand pressure is sufficient.
- Flush the ceramic with clean water to remove the cleanser.
- Flush a second time with clean isopropyl alcohol.
- Air dry the device. Be certain that all moisture has evaporated from the tube before returning it to service.

9.5.3 Reconditioning Klystron Gun Elements

During the operational life of a klystron, voltage standoff problems may be experienced when the operating mode of the device is changed from one collector voltage to a higher voltage, or from continuous to pulsed service [10]. In both of these cases, the difference of potential between the internal elements is increased over values used in the previous mode of operation. In some instances, this elevated difference of potential can lead to internal arcing as a result of long-term buildup of electrical leakage between elements. This is a part of the normal aging process in klystrons. In many cases, however, this particular process can be reversed through high-voltage conditioning. Maintenance engineers have found it useful to clear any residual leakage between the various elements before pulsing an older klystron, or when increasing the operating potentials applied to an older klystron.

Klystron electron gun leakage can be checked, and, in many cases, the gun elements reconditioned, by applying a high dc potential between these elements. The process is termed *hi-potting*. It requires a current-limited (5 mA maximum), continuously-variable dc supply with a range of 0 to 30 kV. The procedure is as follows:

- Turn off the heater, and allow the cathode sufficient time to cool completely (approximately 1 to 2 hours).
- Remove all electrical connections from the klystron, except for the body and collector grounds.

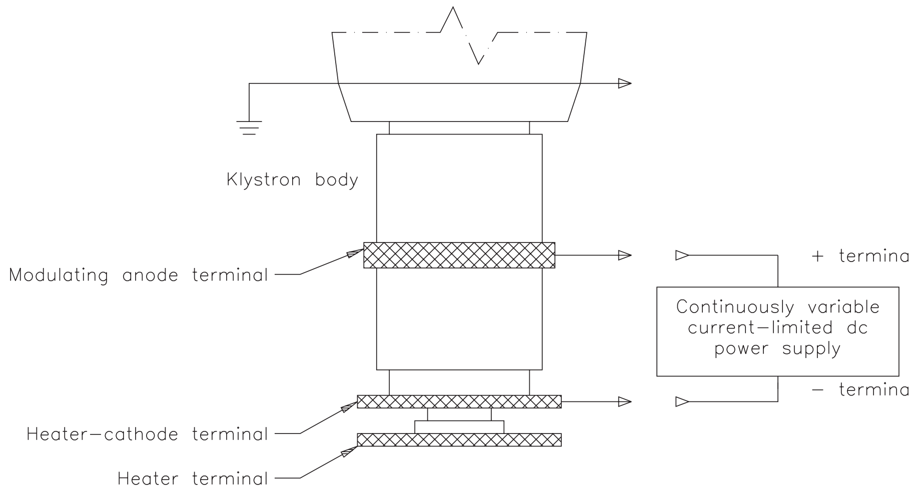

Figure 9.21 Electrical connections for reconditioning the gun elements of a klystron.

- Connect the negative high-voltage output of the hi-potter to the heater-cathode terminal, and connect the positive ground lead to the mod-anode as shown in Figure 9.21. Increase the voltage output gradually, noting the leakage current.
- If high levels of current are observed, reduce the voltage and allow it to stand at the 1 to 2 mA level until the leakage current reduces (burns off).
- Continue to raise the hi-potter output until the voltage applied is equal to the normal operating value for the klystron being checked. The typical leakage level is 200 to 400 μA.
- Check the mod-anode-to-body ground leakage; reduce, if necessary, in the same fashion. For this purpose, the negative high-voltage output is connected to the mod-anode terminal and the positive ground lead to the klystron body.

The leakage level indicated as optimum for this procedure (200 to 400 μA) is a typical value. Tubes still should operate normally above this level, but they may be more susceptible to internal arcing.

9.5.4 Focusing Electromagnet Maintenance

The focusing electromagnet of a klystron, given sufficient preventive maintenance, will provide many years of service [11]. Maintenance personnel can extend the lifetime of the device by reducing the operating temperature of the electromagnet windings and by minimizing thermal cycling. Field experience has shown that the major failure modes for a focusing electromagnet are short-circuited turns in the coil windings and/or short circuits from the windings to the coolant tubes.

Short-circuited turns result in lower magnetic flux density available to focus the klystron beam and are indicated by higher klystron body current. To counteract this effect, the transmitter operator often will increase the electromagnet current to a point above the rating necessary to obtain the magnetic field strength needed for rated klystron body current. This increases the heat dissipation in the device, which may lead to further problems. Such failures are the result of insulation breakdown between turns in the windings, and/or between the windings and the coolant tubes. Insulation breakdown usually is caused by excessive operating temperatures in the individual windings. Excessive temperature is the result of one or more of the following operational conditions:

- Excessive inlet coolant temperature
- Insufficient coolant flow
- Excessive ambient temperature
- Excessive operating current

Insulation breakdown also may result from excessive thermal cycling of the coil windings. Abrasion of internal insulation may occur during expansion and contraction of the winding assembly. Generally speaking, the life of a focusing electromagnet can be doubled for every 10°C drop in operating temperature (up to a point).

To minimize the effects of thermal cycling, the electromagnet temperature should be maintained at or below its operating value during standby periods by running at rated or reduced current, and at rated coolant flow. If neither running nor reduced current is available during standby conditions, heated coolant should be circulated through the electromagnet.

9.5.5 Power Control Considerations

Under certain conditions, high-voltage transients that exceed the specified maximum ratings of a klystron can occur in an RF generator. These transients can cause high-voltage arcing external to the tube across the klystron modulating anode and cathode seals. In some cases, such arcs can puncture sealing rings, letting the tube down to air. High-voltage transient arcing is not common to all installations, but when it does occur, it can result in a costly klystron failure. Overvoltage transients in power circuits can be traced to any of several causes, including lightning.

Collection of moisture on the tube is another potential cause of arc-induced failure. Integral-cavity klystrons, which are installed with the cathode down, may collect moisture in the high-voltage (cathode) area because of water leakage or condensation, leading to external arcing and loss of vacuum.

To provide a measure of protection against these types of failures, arc shields may be used on some tubes to protect the gun components that are the most likely to be damaged by arcs. The shield typically consists of an aluminum cover fitted on a portion of the tube. Although arc shields provide considerable protection, they cannot prevent all failures; the magnitude of a potential arc is an unknown quantity. It must be understood that an arc shield does not eliminate the cause of arcing, which should be addressed separately by the maintenance engineer. It is, instead, intended as a stop-gap measure to prevent destruction of the tube until the root cause of the arcing is eliminated.

Installation of a gas-filled spark-gap transient voltage suppressor also can serve to protect the klystron in the event of an arc or other transient discharge. The rating of the suppressor is determined by the type of tube being protected. The device is connected between ground and the cathode, installed as close as possible to the cathode. The suppressor will prevent the application of transient voltages that exceed the standoff rating of the klystron ceramic.

Power-line suppression components are useful for protecting transmission equipment from incoming line transients and other disturbances, but may not be effective in protecting against a system-induced arc within the transmitter or power supply that could damage or destroy the klystron. Therefore, protection of the klystron itself is recommended.

Primary Power Interruption

Unexpected interruptions of primary power, which occur seasonally during winter storms and summer lightning strikes, can damage or destroy a klystron unless adequate protection measures are taken [12]. There are three main factors involved in such failures:

- Mechanical and/or electrical malfunction of the main circuit breaker of the transmitter. This condition results when the breaker remains closed after the primary power is interrupted. With the loss of primary power, all excitation to the transmitter is removed. If the main circuit breaker remains closed when the power is restored, high voltage can be applied to the klystron before the magnet supply can provide adequate focusing. This allows full beam power dissipation in the body of the klystron, which can melt the drift tube.
- Loss of focusing during shutdown resulting from a power interruption at the transmitter in a system that does not employ magnet power supply filtering. When a loss of primary power occurs, the various power supplies start to discharge. The time constant of the associated filter circuit determines the rate of discharge. If there is no filter capacitance in the magnet supply, it will decay almost instantaneously while the beam filtering allows the high voltage to decay comparatively slowly. This permits defocusing of the electron beam and dissipation of the beam power in the drift tube region. Melting of the drift tube will result.
- Loss of one phase of the primary power supply. In some transmitters, the magnet supply and the protection circuits are fed from a common leg of the 3-phase incoming power line. A loss of this phase will cause a loss of focusing and disable the protection circuits, including body-current protection. If the low-voltage-sensing relay in the main breaker is misadjusted or nonoperational, the

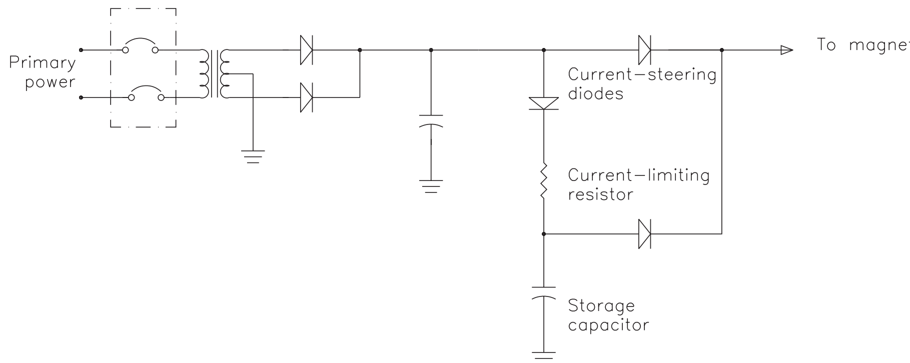

Figure 9.22 Diode-steering filtered power supply for a klystron focusing electromagnet.

high-voltage supply will remain on (although somewhat reduced) and, without focusing or protection, may melt the tube body.

To prevent these types of failures, the following steps are recommended:

- Conduct regular tests of the main circuit breaker in accordance with the manufacturer's instructions. Note that turning the breaker on and off using the transmitter control circuitry checks only half of the system. Tests also should be conducted by interrupting the primary feed to the breaker.
- Compute or measure the discharge time constant of the filtering circuits of both the beam and magnet supplies. Capacitance should be added to the magnet supply if the time constant is less than that of the beam supply. Be careful, however, not to increase the magnet supply filtering too much because it may also increase the ramp-up time of the magnet voltage. This could result in the beam supply being applied before the magnet supply is at its full potential. A simple diode-steering arrangement, such as the one shown in Figure 9.22, will prevent such problems in most cases.
- Consider installing a multipole vacuum relay at the high-voltage input power lines (between the main breaker and the high-power supply) to prevent instantaneous application of high voltage in the event of a malfunction of the main breaker. The primary or low-voltage circuit configuration of the vacuum relays should be such that it will prevent reenergizing of the relays before the magnetic field has built up when primary power is restored after a line loss.
- Install a solid-state phase-loss sensor if this protection is not already provided.
- Install an electromagnet undercurrent protection circuit that will remove the high voltage if the magnet current falls below a preset level.

An end user who is contemplating any of these changes should consult the original equipment manufacturer before proceeding.

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