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THE TESTING OF RUBIDIUM FREQUENCY STANDARDS

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ABSTRACT

At the present time, no standards exist for the testing of atomic frequency standards. The methods used for the qualification and acceptance testing of such devices are devised on a case-by-case basis, with the test procedures defined by the manufacturer or customer. Similarly, there are no standard test methods to aid the user in his evaluation of such devices.

An effort is currently beginning under NIST and IEEE sponsorship to define standard test methods for the environmental sensitivities of atomic frequency standards. That project is expected to eventually result in a document (similar to Section 4.9 of MIL-O-55310B) that will define standard test methods to evaluate, quantify, and report the sensitivity of the frequency of standard frequency generators under environmental influences such as magnetic fields, atmospheric pressure, humidity, shock, vibration, acceleration, temperature, ionizing radiation, and intermittent operation.

This paper describes the test methods used at EG&G for measuring the environmental sensitivities of rubidium frequency standards. It discusses the objectives of such tests, the parameters to be considered and measured, the rationale for the test methods, the setups required to implement the tests, and the way that the test results are reported. The paper also considers Environmental Stress Screening (ESS) of rubidium frequency standards. Examples of these tests are given.

It is hoped that the exchange of this information between the organizations involved will facilitate the adoption of standard methods for such test activities.

INTRODUCTION

The success of a rubidium frequency standard (RFS) in a particular application often depends more on its ability to withstand the operating environment than its performance under benign conditions. This is especially true for a tactical RFS in a military application. It is therefore very important that the proper choices be made in specifying the environmental tests and conditions that convey the operational requirements to the vendor and allow the product to be correctly designed and qualified. Similarly, it is vital to choose the appropriate acceptance tests that will most economically ensure compliant production hardware.

An example of a Qualification Test Plan for a tactical RFS is given in Reference 1. That test regimen includes just about every kind of environmental test. Some of these tests verify critical performance parameters (such as stability and phase noise under vibration). Others constrain the design and construction; still others guard against unexpected weaknesses. The list of these tests is familiar; it is during the process of incorporating these tests into a detailed test plan that the specific RFS considerations need to be addressed.

ENVIRONMENTAL TESTS

The environmental requirements for an item of military electronic equipment (such as a rubidium frequency standard) can involve a bewildering maze of data sheets, contractor equipment specifications, and a hierarchy of military specifications (some of which are shown in Table 1)(2-11). It is impossible to generalize about such requirements except to say that the RFS equipment specification (which usually takes precedence) must be carefully written to define the proper requirements. It is unusual for an RFS procurement to involve complete environmental testing because existing test data can often be applied “by similarity.” New designs or particularly demanding applications may, however, require a full series of environmental tests. In those cases, a test plan or procedure should be written and approved before testing begins. In addition to the tests themselves, the plan should define the order of the tests and whether more than one unit can be used, and should address such matters as instrument calibration(12) and discrepancy reporting. It is common to include a table of standard operating conditions and a basic functional test that is used before and after each environmental test to verify normal RFS operation. This usually includes measurement of output level and frequency, dc power input, and monitor readings. The test procedure should contain blank data sheet forms.

The most demanding combination of RFS environmental requirements is usually associated with an airborne application which includes high temperature and severe vibration. While it is possible to design an RFS to operate at the +95°C intermittent conditions of MIL-E-5400 Class 2, it should be realized that the stability of an RFS subjected to extreme temperature and vibration can be far worse than under benign conditions. And an RFS design constrained to meet extreme environments can result in compromised performance under benign conditions. This makes correct environmental specification and test particularly critical.

A list of the most common environmental tests used to evaluate and qualify a rubidium frequency standard is shown in Table 2. Also shown is the most critical RFS parameter associated with each test, whether the test is normally performed as part of the RFS Qualification Test Procedure (QTP) or Acceptance Test Procedure (ATP), and references to common military specifications for these environmental tests(3,4,13,14). While the specific test conditions (temperature range, vibration levels, etc.) will vary with the particular application, certain general considerations apply to these RFS tests and they will be discussed in the following sections of this paper.

Table 1. Military Specifications for the Testing of Electronic Equipment

RFS USAGE	GENERAL SPECIFICATION	TEST REQUIREMENTS	ENVIRONMENTAL TEST METHODS	EMI TEST METHODS
A11	MIL-STD-454		MIL-STD-810	MIL-STD-461
Airborne	MIL-E-5400	MIL-T-5422		
Ship	MIL-E-16400			
Ground	MIL-E-4158			
Space	DOD-E-8983	MIL-STD-1540		MIL-STD-1541

Table 2. RFS Environmental Tests

Environmental Test	Critical Parameter	QTP	ATP	MIL-O-55310B PARAGRAPH	MIL-STD-202 METHOD	MIL-STD-810 METHOD
Acceleration/Orientation	Frequency	0	N/R	4.9.18,.41	212	513
Acoustic Noise	Phase Noise	N/R	N/R	4.9.39		515
Altitude/Pressure	Frequency	0	N/R	4.9.45-.46	105	500
Bench Handling	Function	R	N/R			516
EMI Susceptibility	Frequency	A/R	N/R	4.9.36	MIL-STD-461	
Explosive Atmosphere	Function	N/R	N/R	4.9.42	109	511
Fungus	Function	N/R	N/R	4.9.54		508
Humidity/Moisture	Function	0	N/R	4.9.49	103	507
Immersion	Function	A/R	N/R		104	512
Magnetic Field	Frequency	R	0	4.9.43	ASTM 346-64	
Radiation	Frequency	A/R	N/R	4.9.47		
Rain	Function	0	N/R	4.9.49	106	506
Salt Fog	Function	0	N/R	4.9.50	101	509
Sand and Dust	Function	N/R	N/R		110	510
Shock, Operating	Function	0	N/R	4.9.40	213	516
Temperature, Operating	Frequency	R	R	4.9.10-.12		
Temperature, Non Op.	Function	0	N/R	4.9.46		
Temperature/Altitude	Frequency	0	N/R			504
Temperature Cycling	Function	R	N/R		102	
Temperature Shock	Function	0	0	4.9.44	107	503
Vibration, Sine	Frequency	R	0	4.9.18-.38	201	514
Vibration, Random	Phase Noise	R	0	4.9.18-.38	214	514

Test Setup. A typical test setup for the environmental testing of an RFS is shown in Figure 1. The RFS under test is installed in an environmental chamber (which may be a temperature, humidity, altitude, or other such chamber, or a shaker, shock machine, or other such apparatus). It is powered from a dc supply and its current and monitor are measured by digital or analog meters, and its recovered signal is observed on an oscilloscope. (Alternatively, a custom “monitor box” may be used, especially if special control or monitor functions are involved.) A stripchart record of the RFS dc supply current is often useful for evaluating performance and diagnosing problems. Besides warm-up and steady-state power, the current record shows lamp ignition and oven stability, and can be integrated to determine RbXO[20] syntonization energy. The primary measurements, however, are the RFS rf output level, frequency, and purity. The frequency measuring system may be simply a vector voltmeter or analog frequency difference meter (to measure RFS phase or frequency change), a frequency counter (perhaps the high resolution interpolating reciprocal type), or a very high resolution heterodyne arrangement (perhaps with computer control and data analysis). The frequency reference may be a crystal oscillator (for low noise), another rubidium standard (for stability, portability, and fast warm-up), or a cesium standard (for absolute frequency determination). The RFS spectral purity may be observed on an rf spectrum analyzer or on a wave or FFT analyzer (after downconversion). A phase noise measuring system may also be necessary (probably using a double-balanced mixer and phase-locked crystal oscillator). The primary concern for this instrumentation is often its portability to an outside testing lab. In such a case, careful planning is critical and all the test instrumentation should be set up "at home" to confirm the test methodology and to avoid missing or malfunctioning items in the field.

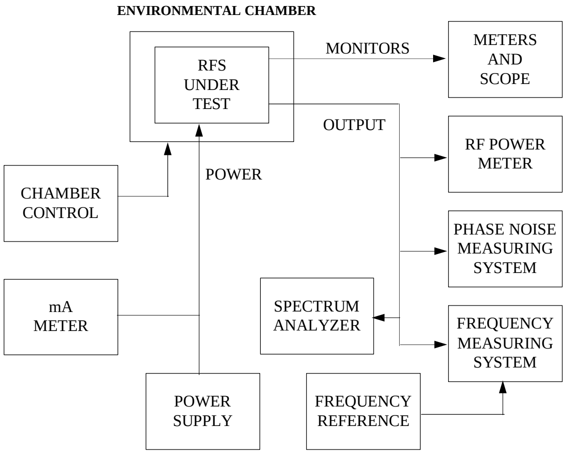

Figure 1. Typical RFS Environmental Test Setup

Acceleration/Orientation. Unlike a quartz crystal, an RFS does not have any inherent static acceleration sensitivity (either "tip-over effect" or centrifuge). It is possible, however, for an RFS to show some frequency change due to acceleration and reorientation because of thermal effects. A test for RFS orientation sensitivity should therefore allow sufficient time (about five minutes) to reestablish thermal equilibrium. It is also possible to have some change in the physical distribution of the rubidium in the lamp under high static g forces that can cause a small frequency change. This effect will occur if the acceleration forces molten rubidium into the body of the lamp, and will be reversed by acceleration in the opposite direction or by quiescent operation. It is possible (but not always easy) to make the precision frequency measurements necessary to see these effects via the slip rings of a centrifuge. Redundant slip rings should be used for both power and RFS output to reduce contract noise.

A separate "2g tip-over" test may be required for the crystal oscillator portion of an RbXO. The test results should be reported as the resultant of the g-sensitivity vector.

Dynamic acceleration can have a profound effect on the stability and purity of an RFS, and those tests are discussed in the Vibration section below.

Acoustic Noise. Acoustic noise is usually not a significant factor affecting RFS operation. The RFS is typically suspended on elastic cords during exposure; frequency and phase noise should be measured.

Altitude/Barometric Pressure. The main considerations for the sensitivity of an RFS to ambient pressure are; (a) frequency shift due to absorption cell buffer gas pressure change caused by deflection of the glass cell envelope (about $1x10^{-10}$/atm), (b) frequency shift due to thermal effects involving the physics package ovens and Rb lamp, and (c) thermal effects due to heat transfer of the electronic circuits. Effect (a) is proportional to the pressure change; effects (b) and (c) are small until the pressure is reduced to about 10 Torr (100,000 feet altitude). Oven power will be less and stabilization factor better in vacuum. The electronic circuits must be designed for adequate heat transfer without air, and temperature profiling may be necessary to ensure reliable operation in vacuum. The barometric sensitivity of an RFS can also be measured as part of a temperature-altitude test. Unlike a cesium frequency standard, an RFS does not use high voltages and can be safely operated throughout the full pressure range from sea level to hard vacuum without any corona discharge hazard.

Bench Handling. A bench handling shock test is perhaps the most severe yet realistic and practical way to check an RFS for ruggedness. The unit should be removed from its enclosure as it if were being serviced. After completing the test, the unit should be inspected for damage and operated to show any resulting frequency offset.

EMI Susceptibility. The most significant form of EMI susceptibility in an RFS is usually due to ripple (CS01) and transients (CS06) on the dc input power. This aspect of RFS design is covered by military and other standards(4,11,15), but specific requirements may also be imposed. Ripple susceptibility is generally worst at the RFS servo modulation rate; large frequency offsets are possible due to interference with the servo that locks the VCXO to the Rb reference. A phase comparator, vector voltmeter, or analog frequency difference meter is very useful for showing RFS EMI susceptibility, as is observation of the RFS recovered signal on an oscilloscope. Ripple susceptibility testing does not actually require a screen room or specialized EMI test instrumentation, and can be investigated with ordinary laboratory equipment. The EMI susceptibility test procedure must include a pass/fail criterion; a frequency change of $1\mathrm{x}10^{-10}$ is a reasonable value for a tactical RFS. The radiated susceptibility test setup should pay particular attention to the shielding and grounding of the RFS power/monitor leads; this is often the primary path for interfering rf into the unit. It is also advisable to use a linear (rather than switching) dc supply to power the RFS during all EMI testing.

The requirements for transient protection(16-18) vary depending on the degree of external power conditioning. Reverse and overvoltage protection is often necessary and must be tested. Applying a precharged capacitor across the dc input is one simple way to simulate voltage transients. RFS turn-on (inrush current) and turn-off (voltage spike) transients can be a problem for the host system. A manually tipped mercury relay and a digital storage oscilloscope is an effective means to simulate and observe these transients.

Explosive Atmosphere. An RFS does not use high voltages or mechanical relays and switches, and can be operated in an explosive atmosphere with minimal likelihood of causing an explosion. Since an RFS is not normally sealed, the outer cover should be removed or loosened during the test to facilitate the penetration of the explosive vapor.

Fungus. A fungus test is usually conducted "by analysis" to verify that the design uses only components and materials that are inherently fungus inert.

Humidity/Moisture. A typical humidity test consists of five, 48-hour temperature-humidity cycles with RFS operation near the end of each cycle. With an unsealed unit, the test results depend strongly on the adequacy of conformal coating and encapsulating processes, and these should closely represent the actual production processes for the test results to be valid. RFS moisture sensitivity is most often associated with the high impedance servo amplifier synchronous detector/integrator circuits.

Immersion. The capability to withstand immersion in water is seldom a requirement for an RFS. Immersibility requires a sealed case and connectors, but it otherwise does not affect RFS design or performance.

Intermittent Operation/Retrace. (See Power/Temperature Cycling below.) A test for the frequency retrace of an RFS under intermittent operation should, by definition, return the unit to exactly the same operating conditions so as not to confuse retrace with environmental sensitivity. The main concern is that the retrace error be non-accumulative. The test must define; (a) operating conditions (temperature, etc.), (b) off time, (c) restabilization time, and (d) number of retrace cycles. A well-designed RFS should have an excellent retrace characteristic ($\mathrm{pp}10^{11}$) that has little dependency on temperature, off time, or restabilization time. The test emphasis should therefore be on performing enough cycles to verify that the retrace error does not accumulate.

Magnetic Field. An RFS (unlike an XO) has an inherent sensitivity to dc magnetic field and contains magnetic shielding to reduce this sensitivity. The largest magnetic sensitivity is along the physics package optical axis (the direction of the internal bias field), and has a quadratic dependence of frequency on dc magnetic field ($\Delta f/f = 8.38\mathrm{x}10^{-8}$ H, Gauss^2). Since the magnetic sensitivity varies with C-field frequency adjustment, the test procedure must specify the RFS frequency setting (minimum, nominal, upper range, or maximum); nominal is usually used.

The test procedure must also define the magnetic field environment. The electrical reversal of a 3 Gauss field from a pair of 4' Helmholtz coils [19] is recommended. This field is easy to produce yet considerably larger than the Earth's field (about 0.5 Gauss), and field reversal tends to eliminate offsets due to the Earth's field (a shielded room is impractical). Other considerations for the test field are; (a) uniformity (coils much larger than RFS, away from metallic objects), (b) calibration (measure field at center w/o RFS), and (c) magnitude (affects shielding factor and measurement resolution). Care should be exercised when deenergizing the Helmholtz coils; unplugging them can produce a hazardous high voltage.

Magnetic sensitivity is generally a qualification test, but variations in C-field and/or shield permeability and fit can require 100% testing for critical applications. AC magnetic field sensitivity is generally part of EMI susceptibility testing.

Radiation. The radiation sensitivity of an RFS is essentially that of its electronic circuits; the Rb physics package is inherently quite hard. RFS survivability can be a critical requirement for both transient and total dose radiation environments. Transient radiation testing usually requires a Flash X-Ray (FXR) facility to generate an intense gamma pulse. The RFS is operated during the exposure and may be required to "operate through" or to quickly recover frequency accuracy; in all cases, it must not suffer latchup, burnout, or other permanent degradation. The test setup generally includes extensive recording of RFS output level, phase, frequency, light monitor, VCXO control voltage, and dc input current (as well as radiation dosimetry). Transient radiation testing is very desirable to verify analysis of the RFS circuits, and is meaningful even for a single sample having generic parts. The most critical parts for latchup are usually CMOS devices; all circuits may require resistors or other means for current limiting.

Total dose radiation testing requires a different methodology. Analysis (based on piece part test data) is often preferable to a test of the entire RFS because a worst-case error budget can be done. The most critical devices are usually servo amplifier and temperature controller op amps and the C-field voltage reference. RFS testing, if done to confirm the analysis, must be done with hardened parts. Total dose testing is likely to damage the unit as it is exposed to a series of successively higher radiation levels. The test setup is usually quite simple if the unit does not have to be operated during the exposure; before and after frequency (and perhaps monitor) measurements are generally all that is required. Total gamma dose is usually done by placing the unit in a Co^{60} cell. Dose rate and annealing effects should be considered. If the unit is operating during exposure, the RFS photodetector will respond to the gamma irradiation. Neutron exposure is usually done by placing the unit in a reactor. The unit may become radioactive because of neutron activation of the magnetic shields and other high-Z materials. The most critical part for neutron fluence is usually the silicon photodetector, which loses output due to lattice damage.

No standard procedures apply to RFS radiation testing; each case requires careful planning and expert advice.

Rain. The test procedure should specify which sides of the RFS are to be exposed to rain. Typically, waterproof cables are attached throughout the test, and the unit is operated near the end of each exposure.

Salt Fog. Since the RFS is typically not operated during exposure, its connectors should be covered. The unit should not be washed after exposure (as allowed by MIL-STD-810). EMI testing should follow salt fog exposure since salt deposits and corrosion could affect grounding and shielding.

Sand and Dust. The test procedure should specify the RFS face to be exposed. Since the RFS is non-operating during exposure, connectors should be covered. Penetration of dust should not necessarily be considered a failure.

Shock. The RFS under test should be powered to best show intermittent failures under shock. Test cables should have strain relief and should be supported close to the unit to prevent whipping and damage which could affect RFS measurements. The RFS should be observed for timing error and permanent frequency offset. Rubidium motion in the lamp (as described under Acceleration) may occur.

Temperature, Operating. Temperature sensitivity is often the most significant environmental factor affecting the performance of an RFS. A stability of $3x10^{-10}$ is typical for a small tactical RFS over a military temperature range, whereas the unit will not have that much frequency aging over several years. Furthermore, there is considerable unit-to-unit variation of this important parameter which is not necessarily monotonic and which may have regions of high incremental sensitivity. The RFS temperature stability is usually specified as the maximum (peak-to-peak) variation in frequency anywhere within the operating temperature range. RFS operating temperature range is usually specified from a minimum ambient value to a maximum baseplate value. The distinction between ambient and baseplate temperatures is necessary (because of the RFS internal dissipation) unless the unit is attached to a large heatsink or is otherwise well coupled to the ambient. It is sometimes necessary to specify the thermal resistance of the heat sink (from ambient air to RFS baseplate).

RFS temperature stability should be measured as part of the ATP for every unit. It is best to make continuous frequency measurements on a stripchart recorder as the RFS is stepped or ramped over its full operating temperature range (rather than just measure the RFS frequency at a few discrete temperatures) so that a region of large sensitivity or anomalous behaviors is detected. An averaging time should be chosen long enough to average the measurement noise while not masking rapid changes; 100 seconds is usually a good choice. Sufficient dwell time must be allowed, especially at the temperature extremes, and the record should be examined for noise, “glitches,” and retrace.

If the RFS uses C-field temperature compensation, it may exhibit disparate frequency-temperature characteristics at different frequency adjustments; similar to the XO “trim effect”. (EG&G does not use this method.)

Temperature, Non-Operating. Sufficient soak time must be used to ensure that RFS internal temperatures reach the specified limits.

Temperature Cycling. (See Power/Temperature Cycling below).

Temperature Shock. Temperature shock testing is not as effective with an RFS as with small components because of the slow internal temperature response of the ovens. The severity of the test is indicated more by the internal temperature extremes than the rate of change of ambient temperature, which may be expensive to produce.

Temperature/Altitude. The Temperature/Altitude test has been deleted from the latest revision of MIL-STD-810. It is better to measure the effects of pressure (altitude) and temperature separately.

Vibration. The stability and purity of an RFS are affected by mechanical vibration primarily because of the acceleration sensitivity of the quartz crystal used in the VCXO that produces the output signal. Direct vibrational modulation of the crystal oscillator generally affects the RFS phase noise and spectral purity at vibration frequencies higher than the servo bandwidth without producing a frequency offset. Vibrational modulation of the VCXO at the 2nd harmonic of the servo modulation rate, however, can cause a frequency offset. Low frequency vibrational modulation of the crystal oscillator can cause a frequency offset due to loss of microwave power. These XO effects are reduced by a high modulation rate, a wide servo bandwidth, and a low crystal g-sensitivity.

RFS stability can also be affected by vibrational modulation of the physics package light beam at or near the servo modulation rate. This problem is reduced by rigid physics package construction. Circuit board and wiring microphonics can also affect RFS stability.

RFS vibration testing requires measurement of frequency offset, frequency stability (Allan variance) and phase noise under dynamic conditions while the unit is on a shaker. It should also include before and after measurements to check for a permanent frequency offset. Phase noise is the primary parameter of concern during random vibration, and frequency stability is the most critical factor under sine vibration. Particular attention should be paid to frequency stability while the RFS is vibrated at the servo modulation rate and its harmonics. An analog frequency difference meter is an effective measurement tool; counter measurements are subject to beats due to coherence between the gate time and vibration frequency. The RFS recovered signal should also be observed, as should the lock detector output. Checks should be made for interference from the magnetic field of an electrodynamic shaker (by holding the unit slightly above the top of the shaker). A slip table can help by allowing separation between the shaker and the RFS under test. Ground insulation (rigid) or an isolation transformer in the RFS output can also help to avoid hum and interference; measurements should not be made at 60 Hz harmonics.

POWER/TEMPERATURE CYCLING

RFS units intended for frequent on-off and temperature cycling (in particular, the Rb reference of a RbXO[20]) should be subjected to a Design Verification Test (DVT) to prove their endurance under such cycling. The physics package of a fast-warm-up RFS turned on after a cold soak experiences severe thermal stresses; nevertheless, with proper design, a unit can survive such cycling and provide a stability comparable to a unit that operates continuously. A typical DVT would subject four RFS units to 20 on-off cycles per day while subjecting them to a -62 to +68°C temperature cycle each day for 180 days. The daily temperature cycles include a cold soak at the low temperature extreme. The internal temperature of the Rb physics package should decay essentially all the way to the air temperature between turn on. The 3600 on-off cycles and 180 temperature cycles of the DVT simulate 20 years of normal RFS operation.

The DVT should also include frequency measurement data after each turn-on cycle. A plot of RFS frequency vs. temperature should show a consistent pattern for each daily temperature cycle, similar to the static temperature stability characteristic. A plot of average daily frequency vs. time should show a retrace characteristic trend similar to the normal RFS aging behavior.

A DVT such as this should be performed on any basic Rb physics package design that is intended for an application that involves frequent on-off and temperature cycling. EG&G has also, as part of our RFS development process, subjected an Rb physics package to over 7500 fast warm-up turn-on cycles over a period of 25 months without any sign of wearout due to thermal fatigue stress. A cold soak and turn-on is also an effective means of environmental stress screening for production RFS units as discussed below.

ENVIRONMENTAL STRESS SCREENING

The purpose of Environmental Stress Screening (ESS)(21,22) is different from other environmental tests. The latter are intended to verify the adequacy of the RFS design, construction, and performance under the anticipated environments. The purpose of ESS is to reduce the number of service failures by applying temperature and vibration screens to each production unit to precipitate latent manufacturing defects as detectable failures.

To devise a suitable ESS test, vibration and temperature surveys are performed to arrive at tailored levels which will show flaws without damaging a sound RFS unit(23,24). A typical tailored vibration screen is random vibration of 5 grms (0.028 g^2/Hz from 80 to 350 Hz, decreasing at 3 dB/octave to 20 Hz and 2000 Hz), applied for ten minutes in each of three axes with the RFS unit operating and the input current and lock monitor signal recorded. Wideband random vibration is far more effective than sine vibration because the random excites all vibrational modes simultaneously and for the full duration of the exposure. Single axis excitation is usually selected because of shaker availability.

A typical tailored temperature screen consists of 12 temperature cycles with power applied after a cold soak of one hour. The cold soak is necessary to adequately stress the physics package ovens and temperature control circuitry in terms of temperature rates and excursions. The cold soak duration is determined by the thermal time constants of the physics package ovens. The effectiveness of temperature cycling in precipitating and detecting failures is greatly increased by operating and monitoring the test unit, and by recording the input current and the lock monitor signal. In particular, a cold soak and turn-on is much more effective than exposing a fast-warm-up RFS to an external temperature shock. A temperature rate of 5°C/minute is generally selected (rather than a faster rate which requires a higher performance test chamber) since the internal response of the RFS is not significantly different for the slower rate.

Our experience has shown that a properly chosen ESS test is a cost-effective way to find latent defects and thereby ensure a lower failure rate in the field. An important part of the ESS process is to review the test records to refine both the RFS manufacturing processes and the effectiveness of the ESS test.

CONCLUSION

Environmental performance is critical for many applications of rubidium frequency standards. No standards currently exist for the testing of atomic frequency standards (such as those of Section 4.9 of MIL-O-55310B for crystal oscillators). Standardized environmental test methods would be helpful for both the vendors and users of such devices. Such standardization would ease device specification, eliminate test duplication, simplify test plan preparation, clarify test results, and lead to improved environmental performance for these devices. It is hoped that the exchange of information like this paper will lead to the adoption of such a document.

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