JPL D-31229

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

NASA Electronic Parts Program

Programmable Oscillators

Shri Agarwal

JPL Electronic Parts Engineering Office

December 30, 2004

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This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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1. Overview

The flight hybrid crystal oscillators used today are costly and tend to be long-lead items. Moreover, they offer no flexibility in way of changes to the desired frequency, operational voltage, etc. Furthermore, each variant must be procured as a separate line item, which makes it very costly and schedule dependent. But now, there appears to be a solution in the offing: the programmable oscillator, which offers several advantages over the conventional fixed-frequency oscillators.

The advantages of using programmable oscillators in NASA applications would be to

- Provide very low cost solution
- Ensure very short lead times
- Offer total flexibility
- Allow user re-programmability to correct human error.

Programmable oscillators also fit nicely on the NASA technology road map (see Appendix 10).

The focus of this work is on the next generation of oscillators, the low-voltage/low-power versions, which would operate at 3.3 V or less. Two different versions of programmable devices are available: the field instantly programmable oscillator (FIPO) and the multifrequency in-circuit reconfiguration programmable oscillator (MIPO), which can be programmed "on the-fly." FIPOs were evaluated for infusion into NASA programs and projects. Evaluation tests consisted of

- Radiation testing (both single-event latchup (SEL)
- Total ionizing dose (TID))
- Construction analysis
- Low temperature testing
- Screening and qualification methodology.

The testing showed that these programmable oscillators could be utilized by NASA projects provided the projects are able to

- Use a resistor in series and reboot the system for SEL
- Limit the total dose requirement to no higher than 10 krads
- Use reduced metal step coverage
- Use the surface mount device package.

This has been a highly leveraged task with support from NASA projects, other NASA centers, the NASA Electronic Parts Assurance Group (NEPAG), and the manufacturer. The test results obtained during this evaluation have been provided to the manufacturer to enable them to continuously improve product reliability. The near-term goal is for the manufacturer to offer FIPOs as standard flight products. Evaluation of the MIPO has started and will continue into fiscal year 2005.

2. Introduction

The main purpose of the work performed in this study was to facilitate the infusion of commercial off-the-shelf (COTS) programmable oscillators into NASA projects. Successful characterization of these devices would allow the users to procure a large quantity of blank devices and then program them to work at a desired frequency, voltage, output level, etc. The ability to program an oscillator would give an important additional degree of freedom to spacecraft designers. Information about the first-generation FIPOs is discussed in detail as well as how the infusion of FIPOs into NASA projects can occur. The evaluation of MIPOs is also discussed. The focus of this work was on ultralow power parts, i.e., 3 V and less operational voltage.

Over the last 10 years, JPL has been instrumental in developing radiation-hardened hybrid crystal oscillators for space applications; the early devices such as those used on the Cassini spacecraft, worked at 5-V supply whereas the more recent ones developed for technology development projects are lower-power versions that operate at 3.3 V. However, such oscillators are very expensive, the cost of procuring each separate frequency (including the assembly, screening, and qualification) adds up. On the Cassini Project alone, JPL design engineers had several frequencies listed on the JPL drawings. Additionally, it can take somewhere from 36 to 52 weeks to get the flight parts; in fact, even the engineering models can take several months.

All of this pointed to a need to look for alternate flight-worthy hybrid oscillators that could be procured on a shorter cycle and at reduced overall costs. One type that shows promise is the newly announced FIPO, with which the users can create their desired frequency parts by programming crystal oscillator blanks (which could be stored in larger more economical numbers). A limited evaluation of one such device, in the Cardinal Components (CC) family, offered by Cardinal Components of Wayne, New Jersey, was undertaken by NASA. The evaluation was jointly funding by project, institutional, and NASA Electronic Parts Program (NEPP) accounts.

Note: This analysis was intended to see if the commercial FIPO could be upgraded for space application. Although some elements of the FIFO do not have the ruggedness necessary for space application and some metal-step coverage does not meet Mil Standards, the conclusions in this report do not concern the use of the FIFO in the nonspace applications for which it was it ended.

2.1. Functions of the FIPO

The FIPO is erasable erasable programmable read-only memory (EPROM)-based phase-lock-loop technology. The FIPO blank oscillator can be programmed to either 3.3 V from 1 to 100 MHz complementary metal-oxide semiconductor/transistor–transistor logic (CMOS/TTL) or from 5 V MHz in either CMOS or TTL. Tight duty cycle (45% min, 55% max) is available. It can be programmed for both tri-state output and power-down mode. The part can be programmed twice, which allows for reprogramming to correct errors or reuse of the same part for two separate applications with different frequencies, power supplies (5 V or 3.3 V) and/or different output characteristics.

Some salient features of the part include

- <100 ppm stability
- 5 ppm/yr aging
- 50 ps root-mean-square (RMS) jitter.

2.2. Data Sheet

2.2.1. Field Programmable Blank Oscillator

- Programmable with the PG-2000 field oscillator programming instrument within seconds
- Twice programmable
- Sealed, finished custom oscillator
- Standard package options.

2.2.2. Reconfigurable 6-Output Positive-Reference Emitter-Coupled Logic Oscillator

- Fixed and reconfigurable multifrequency oscillator
- Intuitive software and I^2 C interface
- Easily updatable system
- Flexible software: quick upgrades and changes
- Industry-standard packaging,which saves onboard space
- Multiple outputs one package vs. multiple oscillators and associated components.
- Differential positive-reference emitter-coupled logic output.

The full data sheet from Cardinal can be found in Appendix 1.

2.3. Programming Specification

The FIPO programmer enables the user to create a device with a specified frequency, voltage (5, 3.3, or 2.7 V), output characteristics (CMOS or TTL), and some other enabled functions. A user can customize the 'blanks' in a matter of minutes that can be used for breadboards, evaluations, and supplying clocks to devices being burned in.

The PG3000 consists of a USB-connected programmer and software that allow Cardinal's FIPO components to be programmed to user specifications for frequency, supply voltage, drive type and output control function.

Details of the programming specification can be found in Appendix 2.

2.4. Visits to Vendors

In order to fully characterize the device for use in space, it was necessary to conduct vendor visits. The purpose of the visits was to fully understand the manufacturing materials and processes as well as the general manufacturing philosophy of the company about overall quality assurance and process controls.

The vendor/supplier for the FIPOs evaluated in this study is Cardinal Components, Inc., of Wayne, New Jersey. The company was founded in 1986. It has manufacturing plants in the Far East; however, all of the electrical testing is performed at the Wayne facility. Based on the visit, it is clear that there are some improvements needed to the company's electrostatic discharge (ESD) controls; that information was provided as feed back to Cardinal. During the first interface meeting, it was discovered that Cardinal had a new programmer, the PG-3000, for programming devices down to

2.7 V. This programmer is an improvement over the PG-2000, which programs devices at 5 V and 3.3 V. NASA has since acquired and used the PG-3000 programmer.

During the screening of FIPO parts for one of NASA's projects, there were a lot of problems with electrical testing—mainly due to excessive noise in the setup. During the course of reducing the noise to try and take a good reading, a number of parts were damaged mainly due to repetitive handling. The projects were concerned and it was decided to have a face-to-face meeting between the manufacturer, the screening house, and NASA to understand the issues. A technical exchange meeting was held at Cardinal to discuss test and burn-in problems. Cardinal engineering made several suggestions to improve the test setups, which were implemented by the test house. For burn-in, they recommended using special sockets; that recommendation was also implemented.

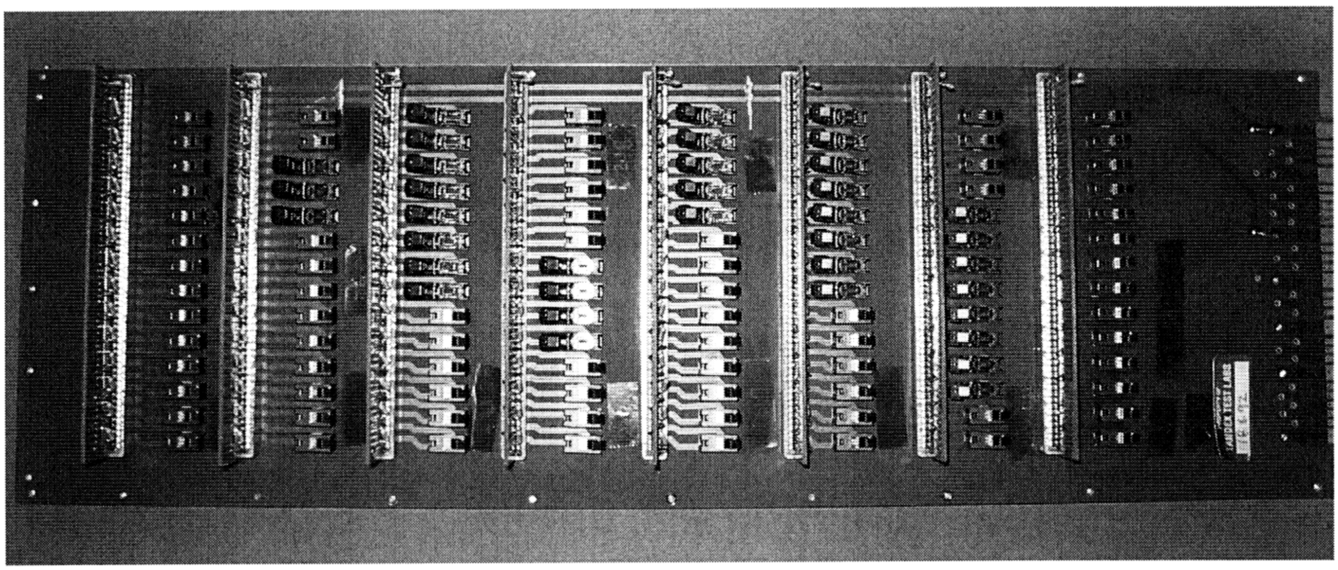


Figure 2-1. Burn-in board utilized for FIPO devices

3. FIPO Evaluation Test Results

The evaluation performed on the FIPOs included radiation, low temperature characterization, construction analysis/destructive physical analysis as well as screening. The details of each test are described in the subsections below. Also, each subsection contains a link to a more detailed report in an appendix.

3.1. Single-Event Latchup

A group of FIPOs was tested under heavy ion dose. All 'unprotected' devices experienced destructive latchup. The latchup rates may be acceptable (once per half century in GEO-extrapolated to 40°C). When tested at 3.3 V with a small series resistor (100 Ω) to the supply pin, plus a small bypass capacitor (0.1 μF), destructive latchup was not observed. The part can be power-cycled to remove the latchup condition. These results are based on a test temperature of 25°C. Also, the resistor-protected devices have not been examined for any latent damage.

The part may be acceptable for space flight applications at 3.3 V with a 100-Ω series resistor and bypass capacitor <0.1 μF, and also when the part can be power-cycled to remove the latchup condition. For more detailed information, see Appendix 3.

3.2. Total Ionizing Dose

Five oscillators were tested for total ionizing dose (TID), using gamma rays in a 60-Co cell. All parts failed functionality, i.e., they stopped operating, at 15 krad (Si) even though the supply current and output voltage (in standby mode) remained within specification. They passed at 10 krad. For additional information, see Appendix 4.

3.3. Low-Temperature Investigation

Oscillators were evaluated for operation between +100°C and –190°C. Performance characterization was obtained in terms of their output frequency, supply current, and output voltage signal level at specific test temperatures. The effects of thermal cycling under a wide temperature range on the operation of the oscillators, and cold-restart capability were also investigated. All oscillators operated well between +100°C and –190°C. In addition, the limited thermal cycling had no effect on their performance, and all oscillators were able to cold start at –190°C. Further testing under long-term cycling is required to fully establish the reliability of these devices and to determine their suitability for use in extreme temperatures. For additional information, see Appendix 5.

3.4. Construction Analysis/Destructive Physical Analysis

Originally the FIPO was obtained in the hermetic metal dual in-line package (DIP). A construction analysis was performed on a number of DIP FIPOs (see 3.4.1). However, while up-screening a lot of DIP FIPOs, it was discovered that they had very poor yield in the particle impact noise detection (PIND) test (1 out of 50 devices passed) due to manufacturing induced particles. Therefore, an alternate package style—the SMD 5 × 7— was substituted for subsequent up-screening.

3.4.1. Dual In-Line Package. Four parts (arbitrarily serialized A, B, Cc and D) were programmed using the PG-2000P (Oscillator Programming System from Cardinal Components, Inc.). Part A was programmed at 5 V and 133 MHz. Part B was first programmed at 5 V and 133 MHz, then was reprogrammed as 3.3 V and 100 MHz. Part C was programmed as 3.3 V and 100 MHz. Part D was first programmed as 3.3 V and 100 MHz, then was reprogrammed as 5 V and 100 MHz. All four parts were successfully written and read. The parts then were forwarded to the JP: Failure Analysis Laboratory for destructive physical analysis (DPA).

The DIP marked as CPP-family part is a hybrid device consisting of two components: a quartz crystal and an integrated circuit (IC) (the Cypress CY2037).
The parts passed the following tests:

- External visual examination
- Hermeticity (both fine and gross leak tests)
- X-ray examination
- Internal examination at low and high magnifications
- Residual gas analysis
- Wirebond pull test
- Die shear test.

IC CY2037 failed scanning electron microscope (SEM) metallization examination per MIL-STD-883E, Method 2018. Ref. JPL DPA report Log 8535 (see Appendix 6a).

This field programmable oscillator is a commercial part not originally intended for space application. This analysis was intended to see if the part could be upgraded for space application. Although some elements of the part do not have the ruggedness necessary for space application and some step coverage do not meet Mil Standards, the conclusions in this report do not concern the use of the part in applications (nonspace) for which it was intended.

- **3.4.1.1. Characterization of Electrostatic Discharge***Test Procedure.* The part was subjected to all of the ESD characterization models (human body, machine, and charged device models) and in both positive and negative voltages.
    - The IMCS-5000 electrostatic discharge (ESD) system was used to test the part in the human and machine models. The Oryx CDM-9000 system was used to test the part in the charge device model.
    - In the charged device model, all four pins of the device were tested at a charged voltage of 200 V.
    - The same test procedure using negative ESD voltage was also applied to all three models.

  See Table 3-1 for details of testing conditions.

Table 3-1. Electrostatic discharge test conditions

Model	Start Voltage	End Voltage	Step Voltage	# of Pulses	Delay between Pulses (s)
Human Body	50	1000	50	3	1
Machine	50	400	50	3	1
Charge Device	50	200	50	3	1

- *Results.* The part passed all tests in all three models. Details are contained the group failure analysis files for further review.

3.4.2. Surface Mount Device Package. A DPA is in progress. A report detailing the results will follow later in fiscal 2005.

4. FIPO Screening Test Results

Screening is being performed for NASA projects . Details of the screening follow.

4.1. Marking Scheme

A marking protocol was developed to maintain traceability of the FIPO parts (some used for flight and some used for evaluation). Each part was marked with a laser as follows:

First Line: CPPX-YYYY-ZZZZ-U

- CPP denotes FIPO product made by Cardinal Components
- X is the package style, 7 means 5 × 7 ceramic SMD package
- YYYY represents the year and the week the part was programmed
- ZZZZ denotes a unique serial number
- U means up-screened (per approved traveler).

Second Line: Frequency in MHz-CMOS/TTL Selection-Enable Pin Selection-Operating Voltage. This line captures the programmed information at the start of screening.

- Frequency (MHz): Up to four places after the decimal
- CMOS or TTL selection: C for CMOS, T for TTL
- Enable selection: E for enabled, X for no preference
- Operating voltage (V): 5.0, 3.3, or 2.7

Third Line (if needed). This line would represent any postscreen changes to the programmed data; it would accommodate situations when a user has no choice but to reprogram the screened part due to unforeseen changes in design. The format would be the same as the one for the second line. *It shall be left blank at initial (prescreen) marking.*

- Frequency (MHz): Up to four places after the decimal
- CMOS or TTL selection: C for CMOS, T for TTL
- Enable selection: E for enabled, X for no preference
- Operating voltage (V): 5.0, 3.3, or 2.7

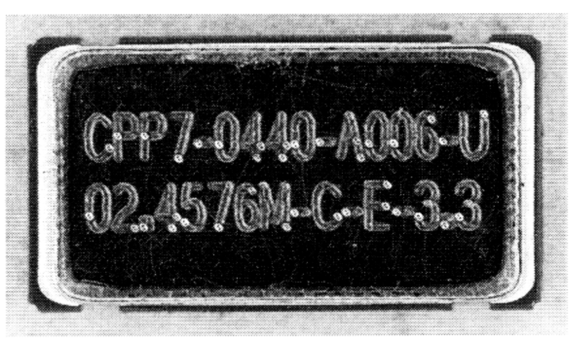


Figure 4-1. Example of marking on an actual FIPO, 5 × 7 ceramic package programmed in the 40th week the year 2004; serial number A006, up-screened; programmed values were 2.4576 MHz frequency, CMOS output, enabled at 3.3 V

4.2. Screening Flow. It is desired that the manufacturer supply flight parts to the end user that have been screened to insure high reliability devices. However, these are commercial devices and there is no data as to their performance per a space level flow. Therefore in order to collect that information and have flight-worthy parts to satisfy immediate needs for the projects, it was decided that NASA should develop a screen. At the same time, the data obtained from this report is being provided to the manufacturer for continuous ongoing improvement of the part.

Table 4-1. The screening flow as used at the test house (Tandex)

Step	Process	Description	Notes
01	FLO	Develop traveler	Flow prepared by Tandex/Approved by JPL
02	QCI	Tandex performs quality control inspection	Flow approved by Tandex
03	RCV	Verify part number; Enter into incoming log	N/A
04	SER	Laser marking/Serialization	N/A
05	ELEC	Electrical test @ 25°C	N/A
06	PULL	Pull control samples #A001 and #A022	N/A
07	PIND	Particle Impact Noise Detection per MIL-STD-883 Method 2020	N/A
08	TEMP	Temperature Cycling per MIL-STD-883 Method 1010, Condition C –65°C to +150°C	10 cycles
09	ACC	Constant Acceleration per MIL-STD-883 Method 2001, Condition E (Y1 only)	N/A
10	XRAY	Radiography per MIL-STD-883 Method 2012 (2 views)	N/A
11	ELEC	Electrical Test per MFG. Data Sheet; Read and Record 100% of Samples (Temperature soak time = 30 min.)	+25°C, +125°C, –55°C
12	BI	Dynamic Burn-in T= 240 hours, TA = +125°C	Prior to burn-in CSI to verify Burn-in boards
13	ELEC	Electrical Test per MFG. Data Sheet; Read and Record 100% of Samples (Temperature soak time = 30 min.)	+25°C, +125°C, –55°C
14	HERM	Hermeticity Seal Test 100% per MIL-STD-883, Method 1014	Fine and Gross Leak
15	PULL	Pull 10 plus 1 Control Sample to perform Qualification for each job	N/A
16	MARK	Mark Acceptable samples with a green dot	N/A
17	QCI	Tandex Quality Control Inspection	N/A
18	PKG	Use Original Container or Tandex Packaging	Mark with Part # and FLIGHT HARDWARE
19	QAR	Tandex Quality Assurance Review	Ship to JPL

4.3. Attributes Data

The results from typical screening tests are summarized in Table 4-2.

Table 4-2. Screening results (pass/fail)

Step	Process	Quantity	Rejected	Accepted
04	SER	42	0	42
05	ELEC	42	0	42
06	PULL	2		
07	PIND	40	0	40
08	TEMP	40	0	40
09	ACC	40	0	40
10	XRAY	42	0	42
11	ELEC	42	1	41
12	BI	39	0	39
13	ELEC	41	0	41
14	HERM	39	0	39
15	PULL	10 + 1	*	
16	MARK			
17	QCI			
18	PKG			
19	QAR			

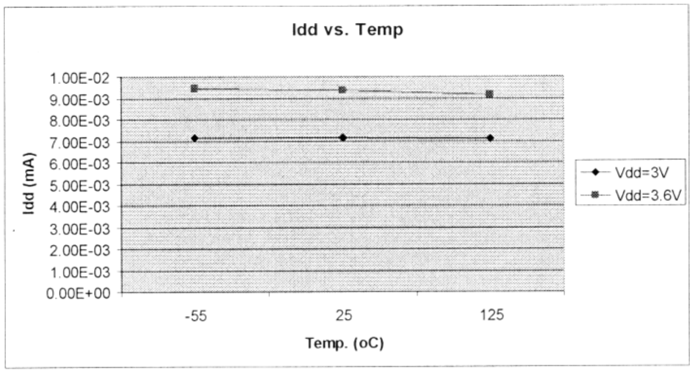
* Some boxes deliberately left blank.

4.4. Variables Data

Shown below in Figure 4-2 are typical parametric variations over temperature. Graphs (a) through (e) present the relationship between supply current (Idd) and temperature. Figure 4-3,graphs (a) and (e)) represent the relationship between frequency and temperature. This data as well as other screening data, including the parametric shifts across burn-in, will be provided to the manufacturer and also discussed with the projects that are considering using these parts.

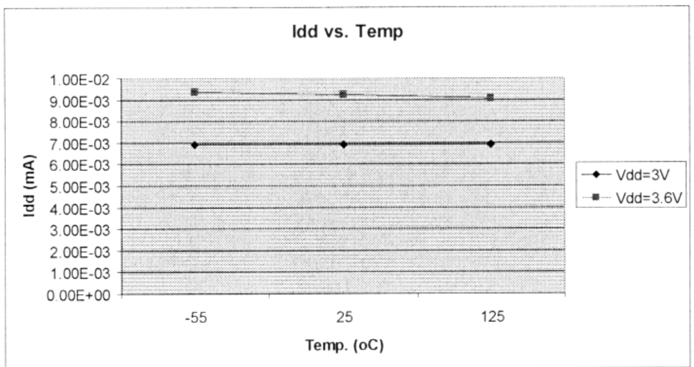
As can be seen in Figure 4-2 (a) through (e), Idd does not vary much with respect to change in temperature, regardless of programmed oscillator operating frequency. However, in Figure 4-3 (a) through (e), frequency varied with respect to temperature change.

(a)



CPP7-0440-A017-U
2.4576 M-C-E-3.3

(b)



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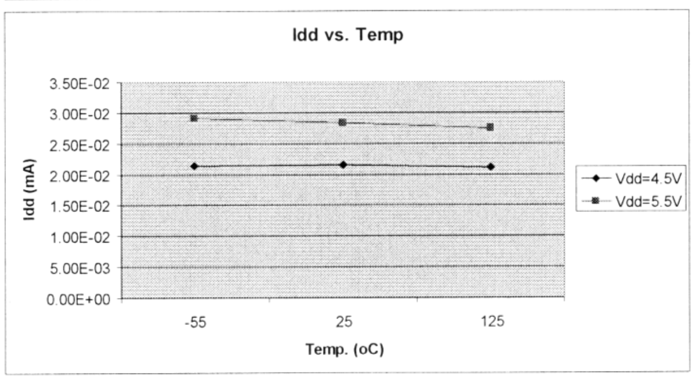
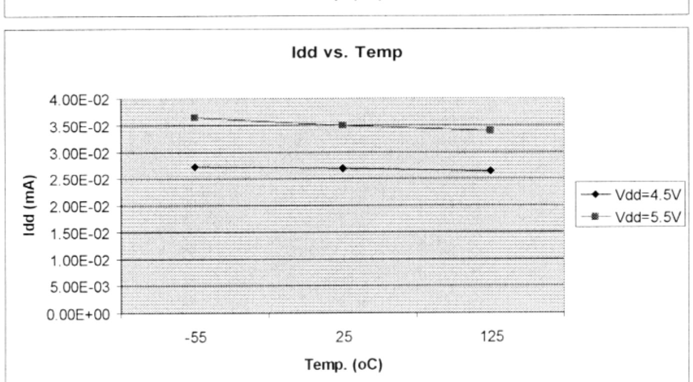
0.73600M-C-E-3.3

(c)



CPP7-0440-A057-U
32.0000M-C-X-5.0

(d)

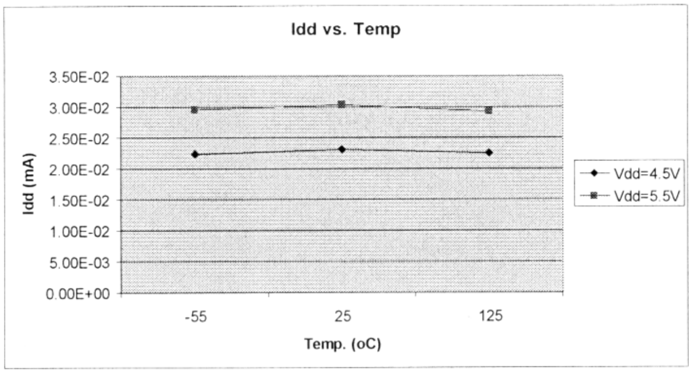


CPP7-0440-A092-U
66.0000M-C-X-5.0

Figure 4-2. Examples of supply current (Idd) variations over temperature for FIPOs (continued on next page)

(e)

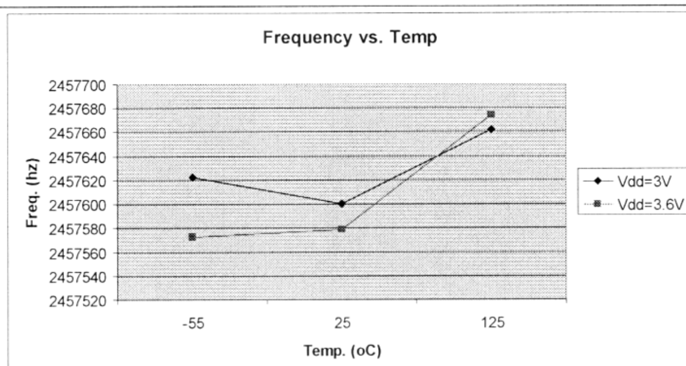
9100



CPP7-0440-A100-U
72.0000M-C-X-5.0

Figure 4-2. Examples of supply current (Idd) variations over temperature for FIPOs (contd)

(a)



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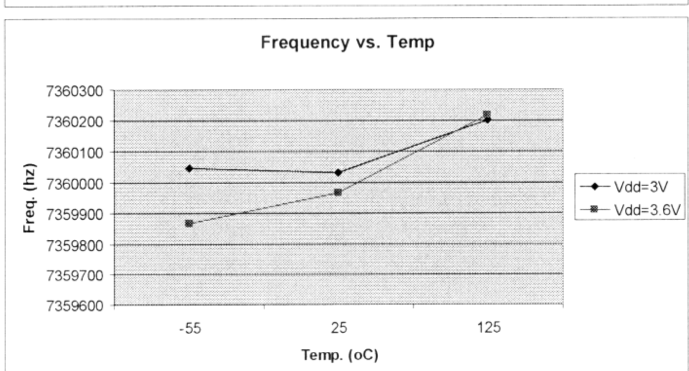
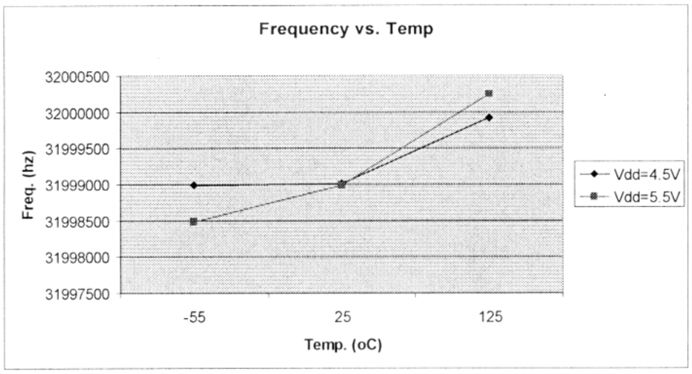
b)



CPP7-0440-A041-U
0.73600M-C-E-3.3

Figure 4-3. Examples of frequency variations over temperature for FIPOs
(continued on the next page)

(c)



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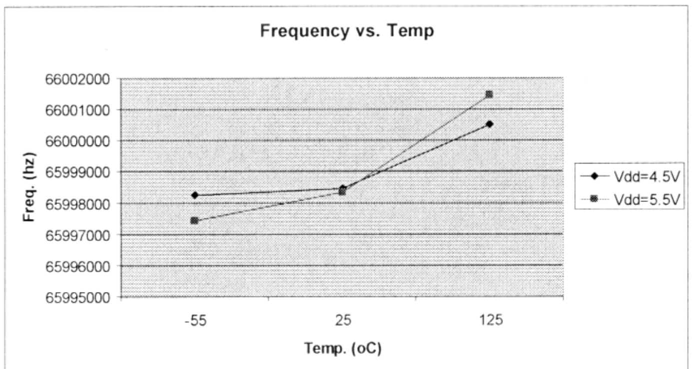
(d)



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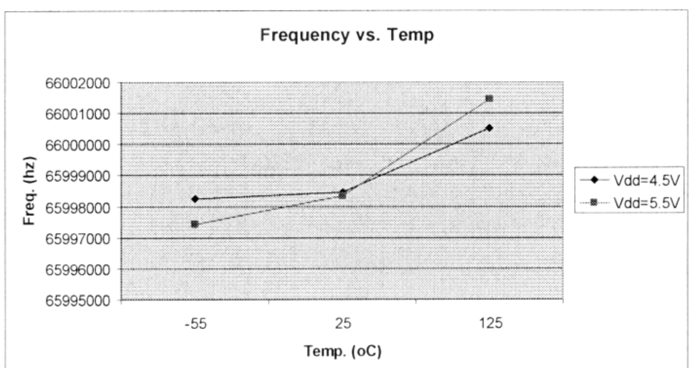
(e)



CPP7-0440-A100-U
72.0000M-C-X-5.0

Figure 4-3. Examples of frequency variations over temperature for FIPOs (contd)

4.5. Life Test

There are two NASA projects that have devices currently on life test for various durations. One life test is for 1000 hours and the other is for 2000 hours, with interim data taken at 500-hour intervals. A report detailing the results will follow later in fiscal 2005.

4.6. Aging

The manufacturer's generic data on oscillator aging is shown in Appendix 9. They recommend that the aging tests be done on the lot currently being screened for the NASA projects.

5. Failure Analysis Results

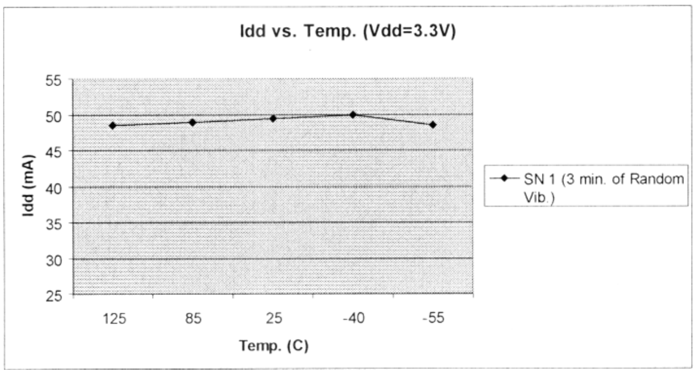
Failure analysis is in progress. A report detailing the results will follow later in fiscal 2005.

6. Future Work: Evaluation of Multifrequency In-Circuit Reconfigurable Programmable Oscillator

6.1. Initial Characterization

Shown below, in Figures 6-1 and 6-2, are typical parametric variations over temperature. In Figure 6-1,(a) through (d) present the relationship between Idd and temperature. Figure 6-2 represents the relationship between frequency and temperature. This data as well as other screening data including the parametric shifts across burn-in will be provided to the manufacturer.

(a)



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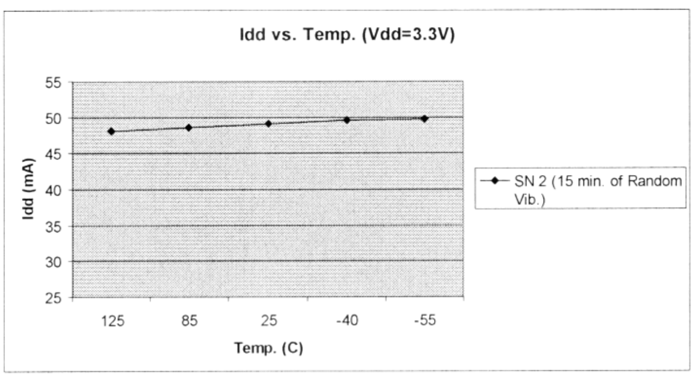
(b)



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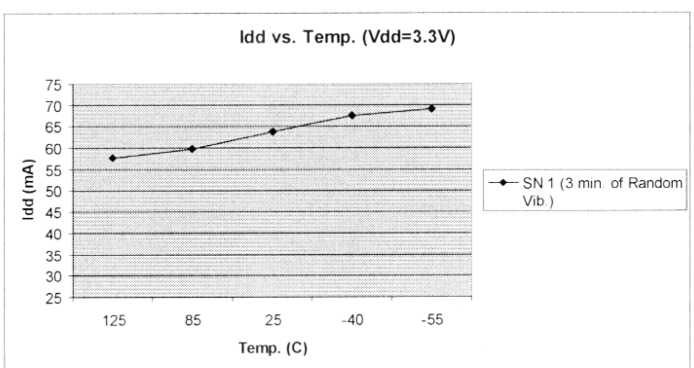
07.3600M-R-C-3.3

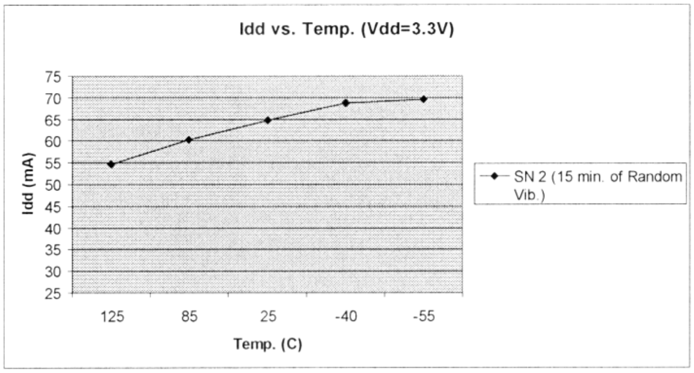
(c)



CCE6-0440-A003-U
02.4576M-R-E-6.0

Figure 6-1. Initial test results showing supply current ove r temperature for MIPOs
(continued on the next page)

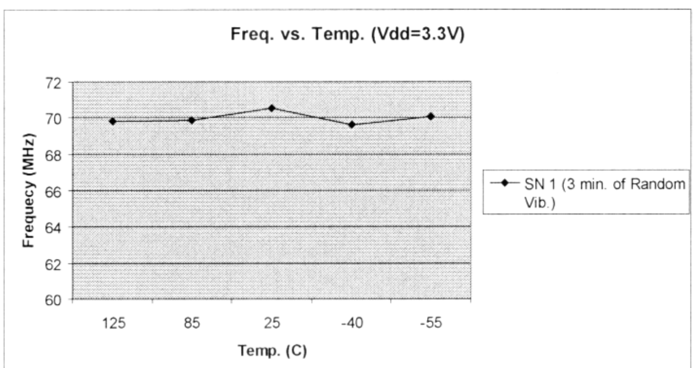
(d)



CCE6-0440-A003-U
02.4576M-R-E-6.0

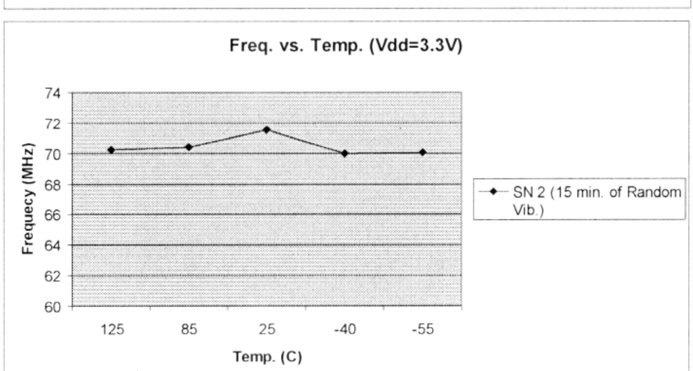
Figure 6-1. Initial test results showing supply current over temperature for MIPOs (contd)

(a)



CCE6-0440-A001-U
02.4576M-R-C-3.3

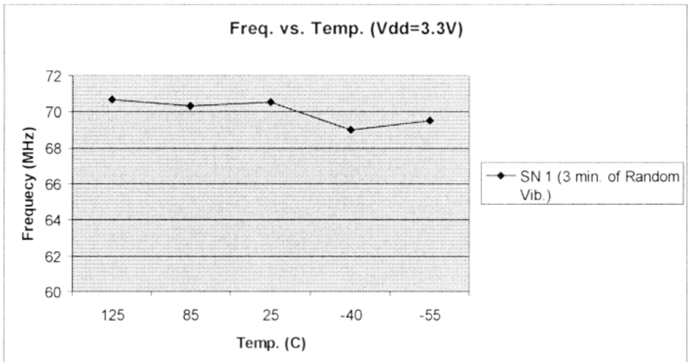
(b)



CCE6-0440-A002-U
07.3600M-R-C-3.3

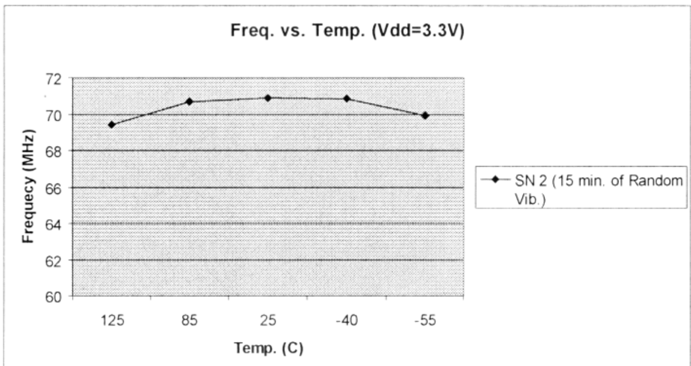
Figure 6-3. Initial test results showing frequency variations over temperature for MIPOs (continued on the next page)

(c)



CCE6-0440-A003-U
02.4576M-R-E-5.0

(d)



CCE6-0440-A004-U
07.3600M-R-C-5.0

Figure 6-2. Initial test results showing frequency variations over temperature for MIPOs (contd)

6.2. Construction Analysis Results

No gross deficiencies were found during the course of this analysis. However, several tests and examinations could not be performed due to the limited sample size (1 part). The following tests and examinations will be performed on additional samples in order to obtain a more complete construction analysis dataset:

- Determination of solder type and melting temperature used on the hybrid substrate
- Cross section of the hybrid printed circuit board to examine the plating quality in the vias
- Residual gas analysis of the hybrid and of the separate quartz crystal case
- Additional SEM metalization examination of the oscillator control IC.

Details of the construction analysis are contained in Appendix 11.

7. Lessons Learned and Recommendations

7.1. Introduction

Industry is several years ahead of government in developing new technology; therefore, it's never too early to evaluate commercial products as they become available because the characterization/evaluation takes a considerable amount of time.

When NASA evaluates commercial EEE parts for space applications, the most accepted approach is to examine each part type on a case-by-case basis. It should be understood that not all commercial parts are the same as far as radiation tolerance and reliability. So a general attitude of "wait-and-see" or to have low expectations with regards to the part type meeting NASA requirements prior to testing is perhaps the best way to approach each part.

Some commercial parts meet NASA mission requirements and some parts do not meet any requirements. Many commercial parts ending up being used, with some "work-arounds" or with some reservations.The method for assessing the overall mission worthiness of a commercial part is to evaluate the radiation tolerance and to assess the reliability for mission conditions.

7.1 Approach to Upscreening FIPOs

There have been instances in the past where the NASA evaluation of existing COTS PEM products found them to be SEL immune and rad-hard to higher than 50-krad levels. The examples would include Linear Tech LTC1419A 14-bit A/D converter and the National LMX23XX series of phase-locked loops (PLLs). On the other hand, NASA evaluation of 10 different high-speed,low-power 8- and 10-bit COTS PEM A/D converters yielded only one potential candidate. The COTS FIPO evaluated in this report fall somewhere in between the two extremes. Based on our experience, we recommend the following approach for identifying FIPOs for potential space applications.

- NASA parts engineers should take on the added responsibility and leadership to be on the lookout for exciting new products.
- The approach has to be different than that for Class S parts: parts engineers need to raise their expectations.
- Rather than expecting a commercial product to meet the requirements of a fully qualified rad-hard SEL immune Class S product, parts specialists should start the upscreening task) by evaluating the capabilities of the commercial product as it is available off-the-shelf. Once a device has been evaluated, the project can incorporate it into a design.
- Phase 2 of the work should include making improvements to the product to enable a broader usage across NASA.

7.3. Lessons Learned

- The most important thing learned about these particular crystal oscillators was the need to use 100-Ω resistors in series with the output to dampen the ringing. Without a resistor, over- and undershoots would occur, giving false V_{OH} and V_{OL} readings.
- On the setup used to test the part, two scope probes were used: one was connected to the scope HP54001 (2-pf load), and the other (passive ×10 scope probe) to the frequency counter. At the higher frequencies, the passive probe would start to load down the crystal, distorting the waveform. This distortion was minor, but it would

effect the rise and fall times. To solve this loading issue, when the next evaluation occurs, an active field-effect transistor (FET) should be used. Adding an active FET will minimize the loading effect of the second probe.

- The other thing observed was that when the device was programmed at 2.7 V, 3.3 V, etc., it would work at the higher voltages. (There was no investigation to determine if a device programmed to the higher voltages would work at the lower voltages, but it might be worth doing one.
- The next evaluation should break the tasks up according to voltage levels, that is, all 5-V parts should be tested together, all 3.3-V parts together, 2.7-V parts together, etc.)
- Multiple frequencies can be tested/burned in together However, each frequency should also be kept separate from all others, i.e., *no mixing of frequencies in both shipping and handling containers.* Furthermore, each container should be well marked..
- Labels should match serial numbers.

7.3. Recommendations

The following recommendations not only apply to the crystal oscillators evaluated in this report but can apply to other COTS as well. Conduct weekly reviews with the test lab to maintain open communication. Air conflicts and technical obstacles and adjust schedule changes, as necessary.

- Make use of the contract technical manager and onsite customer source inspection because they can be extremely valuable to NASA in that doing so allows the parts-evaluation specialist to focus on their task. (Due to limited funding, for the evaluations discussed in this report, the parts specialist monitored the testing on the oscillators.)
- Don't rely solely on the technical expertise of the test laboratories. Technical issues and problems that arose required judgment and guidance by NASA specialists in consultation with the manufacturer. (In the middle of our task, we had lots of problems related to the electrical and burn-in test setups. The result was a trip to the manufacturer by NASA and test lab representatives to discuss the issues and take corrective action.)
- Communicate with prospective NASA users. For example, NASA organized a parts user group (PUG) meeting where the manufacturer's chief engineer made a presentation at JPL with other NEPAG member organizations tied in via phone links. Holding the meeting resulted in money and time saved later on in the task.
- Develop new approaches as needed. For example, a new marking scheme was devised by NASA to ensure proper traceability and identification of the programmed parts (see Section 4.1).
- Maintain flexibility when planning for any tests/tasks.
- Take advantage of new-product evaluation opportunity to enhance in-house test capabilities. (Even with a limited budget of $120k, NASA spent over $20k to buy new equipment, including new meters, a programmer, and special test and burn-in sockets.)
- Maintain focus, and cultivate optimism and patience.

8. Acknowledgments

This task was funded by the NASA Electronic Parts Program Office. The collaboration and support provided by NASA Electronic Parts Assurance Group, NASA Solar Dynamics Project, NASA Glenn Research Center, the NASA [NASA] Lyman-Alpha Mapping Project, NASA ST-7 Project, NASA Dawn Project, NASA Goddard Space Flight Center Radiation Test Center, Cardinal Components, Inc., and Tandex Test Labs are acknowledged and appreciated. In addition, the support of the following JPL colleagues is appreciated: Mike Sander, David Peters, Duc Vu, Jim Okuno, and David Gerke.

9. Acronym List

COTS	commercial off-the-shelf
CPP	Cardinal Components
CTM	contract technical manager
DIP	dual in-line packaging
DPA	destructive physical analysis
EPROM	erasable programmable read-only memory
ESD	electrostatic discharge
FET	field-effect transistor
FIPO	field instantly programmable oscillator
GEO-extrapolatedgeo-synchronous orbit	
LAMP	[NASA] Lyman-Alpha Mapping Project
MIPO	multifrequency in-circuit
NEPAG	NASA EEE Parts Assurance Group
NEPP	NASA Electronic Parts and Packaging (Program)
PECL	positive-referenced emitter-coupled logic
PEM	plastic encapsulated microcircut
PUG	parts user group
RMS	root-mean-square
SEL	single-event latchup
SEM	scanning electron microscope
SMD	surface-mount device
TID	total ionizing dose
TTL	transistor–transistor logic
VOH	V_{OH}, logic high-voltage output
VOL	V_{OL}, logic low-voltage output

Appendix 1 – Data Sheet

Appendix 2 – Programming Specification

Appendix 3 – SEL Report

Appendix 4 – TID Report

Appendix 5 – Low Temperature Testing Report

Appendix 6 – Construction Analysis/DPA Report

Appendix 6a – DIP Package

Appendix 7 – Screening Test Flow

Appendix 8 – Life Testing of FIPO

Appendix 9 – Manufacturer's Aging Data

Appendix 10 – Roadmap