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UNIQUE SIGNAL OVERRIDE PLUG ELECTROMAGNETIC TEST REPORT

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Abstract

The MC4039 Unique Signal Override Plug (USOP) provides the "unique" signal for the B90 when fielded on aircraft that are not equipped with unique signal capability. Since the USOP is field installed, the concern is that it might be susceptible to electromagnetic radiation prior to installation on the weapon. This report documents a characterization of the USOP, evaluates various techniques for attaching electromagnetic shields, and evaluates the susceptibility of a fully assembled passive-USOP.

MASTER

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UNIQUE SIGNAL OVERRIDE PLUG ELECTROMAGNETIC TEST REPORT

1. INTRODUCTION

The MC4039 Unique Signal Override Plug (USOP) provides the "unique" signal for the B90 when it is fielded on an aircraft that is not equipped with unique signal capability. The following tests evaluate the electromagnetic susceptibility of the passive, unconnected USOP. During normal operation the USOP is powered directly from the weapon. During the course of this test program two prototypes were developed; these will be referred to as prototype 1 and prototype 2. Prototype 1 was tested in the Phase One tests and prototype 2 was tested in the Phase Two tests.

Prototype 1 discussion: The prototype 1 USOP internal circuitry contains one SA3727 chip, five diodes, three resistors, and two capacitors; these are mounted on a circular circuit board and contained inside a metal backshell cover, which serves as an electromagnetic shield. The entire assembly is fastened to a Bendix connector (Part No. 8912 IJT06T-17-26P). Two methods for fastening the backshell to the connector are being evaluated in the following tests. The first method uses conductive epoxy, while the second uses set screws. If the backshell is an effective electromagnetic shield, the connector aperture will be the only coupling path to the electronic circuitry. Due to the small radius of the connector aperture, the USOP was expected to be least susceptible at the lower frequency ranges. The response at lower frequencies could have been so low that it would be difficult to measure; thus, microwave frequencies were included in the test series so that a measurable signal could be obtained for at least a part of the frequency span. The selected frequency span is 100 MHz to 8 GHz.

Prototype 2 discussion: The prototype 2 design incorporated four changes. The manufacturer of the SA3727 chip was changed from Lasarray to LSI Logic, the circuit board ground was tied to the case ground through a straight wire, C1 was changed from 1 microfarad to 0.1 microfarads, and the circuit board was changed, as required, to support the above. The circuit board is normally tied to ground through two SA3020-19 zener diodes; however, in the prototype a straight wire was used. Finally, the case was attached to the shell with epoxy; this was identical to one of the fastening methods evaluated in the Phase One test. The changes between the two prototypes should not significantly alter the susceptibility of the USOP and thus would not dictate different approaches in the susceptibility analysis. However, since 1-kilowatt power amplifiers became available in time for the Phase Two tests, free-field illumination of the USOP was possible and for this reason a less complex test was used.

2. TEST METHOD FOR PHASE ONE TESTS (Test of Prototype 1)

Two types of tests were conducted on the unpowered USOP. These were low-level transfer function tests and high-level pass/fail tests. The low level tests were designed to measure the transfer function associated with the electromagnetic leakage. This data was then extrapolated to component damage levels so that an estimate of destructive incident field levels could be made. The high-level tests were conducted at power levels that are equivalent to a pulsed environment of 10 kV/m for 1 μ s, and a cw environment of 500 V/m. The intent was to provide an overtest environment and thus verify survival.

2.1 Continuous Wave Tests

The continuous wave (cw) tests provided a transfer function that quantified the amount of energy that penetrates to a point inside the USOP. Three test objects were used for the test. The first two consist of the connector and backshell/shield; one of these was fastened with epoxy only (referred to as USOP 1) and the second was fastened with three setscrews (referred to as USOP 3). The fasteners attach the backshell to the connector. The coupling was measured inside the backshell, between pin M and the connector shield, on these test objects. The third test object was a complete USOP with an epoxy fastener (referred to as USOP 2). The internal signal was measured between pin 20 of the active chip and ground. The measurement method placed a 50-ohm cujac (solid copper coaxial cable) in parallel with the measurement point. The USOP was then illuminated with a low-power free-field electromagnetic wave. The incident electric field was oriented in three directions. These were axial with respect to the backshell cylinder, radially from pin M to the connector cylinder wall, and at a 45° angle which was half way between the first two orientations (Figure 1).

2.1.1 Continuous Wave Tests without Electronics. This test configuration resulted in a response which was close to the maximum possible drive between a pin and the case, and thus provided a practical upper bound for the driver on a single pin. Additionally, this configuration provided the most data concerning the relative shielding effectiveness of the two connector mating techniques (i.e., set screws versus conductive epoxy). As shown in Figure 1, a pin near the edge of the connector was selected. This pin was instrumented because (1) the method for instrumentation was uncomplicated by jumper wires and (2) most of the connections to the circuit board are made from pins on the connector edge. Pins near the center of the connector had a larger E-field driver; however, a measurement between a pin in the connector center and the shell involves series inductance. Series inductance reduces the signal applied to the measurement cable and thus would not necessarily result in larger measured signals. It is, therefore, better to use the less complex measurement point and allow a safety factor for the possibility that a stronger signal could be coupled. A safety factor of five is adequate.

Figure 1. USOP Configuration

The cw parameter of interest was the coupling cross section, σ . The coupling cross section is very similar to the effective area of an antenna, and is defined [Ref. 1] as:

$$\sigma = P_d/S,$$

where

P_d = power delivered to an internal point

S = incident power density.

It is therefore necessary to measure the incident power density as well as the power delivered to an internal point. This was accomplished using a microwave B-dot sensor.

Test Sequence One - Test of USOP 1 and 3

The following steps were used in test sequence one to acquire the raw data which was used to evaluate σ .

1. The test equipment was configured as shown in Figure 2. Note:
 - The separation, d , between the antenna and the test object was minimized to increase the dynamic range. It is, however, important to keep $d > D^2/4\lambda$, where D is the largest dimension of the transmitting antenna.
 - The 8511 was located close to the test object to reduce the high frequency loss.
 - The B-dot sensor was located in the same position as the test object on alternate exposures, so that the incident field could be measured on sequentially acquired data sweeps.
2. The source and the antenna were configured for a sweep of 0.1 GHz to 8 GHz and a maximum E-field polarization (as shown in Figure 1). The response for both the USOP and the reference antenna (B-dot or horn) were then recorded.
3. The received signal was examined to ensure that it was well above the noise floor. Since this was the case, no external amplifiers were required for the test.
4. The 0.1-GHz to 8-GHz data was recorded for the remaining two polarizations.

2.1.2 Continuous Wave Tests with Electronics. The above test provided an upper bound on the driver for a single pin and provided a comparison between two methods for attaching the connector backshell; this test provided an estimate of the USOP susceptibility. An estimate of susceptibility can be achieved if both the coupling cross section and the component damage threshold are known. The test point is the input to the chip, pin 20 (see Figure 3).

Test Sequence Two - Test of USOP 2

Test sequence two was identical to test sequence one.

2.1.3 Continuous Wave Tests inside a Mode-Stirred Chamber. The mode-stirred chamber (MSC) test provided a second check on the sensitivity of the angle of incidence. USOP 2 was placed inside an 80-inch by 72-inch by 48-inch rectangular parallelepiped, high Q cavity. The cavity was excited with a strip line antenna over the frequency range of 0.1 GHz to 8 GHz. The outputs of the USOP and that of a reference B-dot sensor were monitored. The test configuration is shown in Figure 4.

Figure 2. Test Equipment Configuration

Figure 3. Schematic of USOP Circuit

Figure 4. Mode-Stirred Chamber Test

Test Sequence Three

The following steps were used in test sequence three to evaluate the USOP coupling cross section inside the MSC:

1. The test setup was configured as shown in Figure 4 with a frequency span of 0.1 GHz to 8 GHz.
 - The B-dot was placed in the cavity simultaneously with the test object.
 - The measurements were made on one object at a time, either the B-dot or the USOP.
 - The output cable of the unused item was capped with a 50-ohm terminator so that the cavity Q would remain constant.
2. The transfer function was recorded, first for the B-dot and then for the USOP.

2.2 High-Power Tests

The goal of the high-power test was to expose the USOP to a stress which is equivalent to that provided by a 10-kV/m, 1- μ s wide pulse, or a 500-V/m cw free-field signal. Because of the size of the USOP, the test volumes required for free-field illumination must have a cross section of at least 36 square inches. At the time of the Phase One tests the 1-kilowatt amplifiers were not available; however, 200-watt radio frequency (rf) amplifiers were available over the entire frequency range of interest. If 200 watts of power were radiated over a 6-inch by 6-inch area, the available power density would be approximately 1 watt/cm², or an electric field strength of 18 V/cm (1800 V/m). This is approximately a factor of five lower than was desired for the pulsed case. Therefore, three approaches were considered to increase the field strength:

1. The USOP could have been moved closer to the source and the resultant distortion of the incident wave disregarded. With no losses in the system, 200 watts of source power would provide the desired electric fields over a radiated area 8 square cm. Thus reaching the desired field strength was feasible if a transverse electromagnetic (TEM) cell was used to provide the test volume; however, the resultant mismatch probably would have been too severe for the amplifiers, which were being operated at full power. Thus, this method was not used.
2. The shield could have been removed from the USOP and the incident power lowered by an amount equivalent to the measured shielding effectiveness. This was also feasible; however, the primary coupling path would have been changed from the connector pins to the wires on the circuit boards. Understanding the coupling mechanisms was not straight forward; therefore, this method was not used.
3. The final method used direct drive of the connector pins. Since the transfer function of a free-field wave to the pins inside the backshell (see Section 2.1.1) had been measured, the signal from the source could be adjusted so that the proper coupling was achieved. This method was used for these tests. The test sequence is shown below.

Test Sequence Four

The RF source cable was connected directly between pin M and ground with as short a connector lead as possible. The USOP utilizes only four of the connectors pins and one of these is the ground connection. The primary pin of interest was pin M, the clock input pin. First, the direct drive parameter, S_{21} , was measured for pin M, then pin M was directly driven with both cw and pulsed RF.

The objective was to couple power from an RF source, through connecting leads, to the pins of the USOP at power levels which are similar to those induced by a 10-kV/m free-field signal. Thus the problem involved two measured transfer functions, the one from the test covered in Section 2.1.1, and a new transfer function which identified the mismatch of the coupling connection. The test configuration is shown in Figure 5. Note that the network analyzer records a transfer function (with low power input) in exactly the same transmission line configuration as that required for the high-power test. The following steps were used in test sequence four to determine the direct drive power levels:

1. Evaluate $\log(\sigma)$

$$\text{where } \sigma = P_{d1} / S$$

as defined above in Section 2.1.1. The direct drive coupling cross section data is shown later, in Figure 13a.

2. Evaluate P_{dth} , the power delivered to the chip by either a 10-kV/m, 1- μ s microwave pulse, or by a 500-V/m cw signal. For example, in the pulsed case the power density that results from 10 kV/m is $S = 26.5 \text{ watts/cm}^2$, thus

$$P_{dth} = \sigma[26.5] \text{ watts.}$$

P_{dth} is plotted in Figure 13b.

Figure 5. High-Power Test Configuration

3. Evaluate the direct drive transfer function. The objective was to use a smaller power source for this test than would have been required for the free field, high-power illumination of the USOP. By connecting the source directly between pin M of the connector and the connector shell, the energy was delivered to the USOP internal chip more efficiently. The transfer function of interest in the direct drive case is S_{21} , the scattering matrix parameter (see Figure 13c). It is defined as:

$$S_{21} = P_{out} / P_{in}$$

where,

P_{out} = power out of the cujac voltage monitor

P_{in} = power driven into pin M of the connector.

4. Evaluate the direct drive power level, P_s , which resulted in P_{dth} being delivered to the chip. Since

$$P_s = P_{dth} / S_{21}$$

P_s may be formed by subtracting the two appropriate transfer functions as follows:

$$10 \log(P_s) = 10 \log(P_{dth}) - 10 \log(S_{21})$$

After P_s is plotted (Figure 13d), one refers to that plot to obtain the required direct drive power.

One additional piece of information may be obtained from step 2 above. The energy that is delivered to pin M by a 1- μ s pulse can also be plotted (see Figure 14). This plot illustrates the safety margin in the design of the USOP. It may be observed that the safety margin is largest below 2 GHz, and smallest above 5 GHz.

The direct drive of the USOP with the higher level signals is a pass/fail test. If the USOP has not been damaged, it passes. If it fails, the shielding may need to be improved.

3. TEST METHOD FOR PHASE TWO TESTS

Phase two testing included both pulsed and cw tests in a free-field environment. This approach was pursued because the newly available, 1-kilowatt, Space Systems microwave amplifiers are capable of providing an environment of up to 6,000 V/m. This field strength was adequate for testing the USOPs.

3.1 Free-field Pulsed Tests

The pulsed free-field tests were designed to expose the USOP to electric field strengths of 4,000 and 6,000 V/m while it was positioned in a "worst-case" orientation. Because the Prototype 2 USOP construction was similar to that used for the Prototype 1 USOP, the "worst-case" orientation is believed to be the same as was defined in the Phase One tests. Thus the "worst-case" orientation positioned the USOP connector cross section in a plane parallel to the plane of incidence and had the electric field radial from pin M to the connector backshell (see Figure 1a).

This test sequence had three basic parts. These were

- evaluate the incident electric field,
- expose the USOP, and
- evaluate USOP health.

The evaluation of the electric field included a determination of the polarity, free-field impedance, pulse full-width-half-maximum (FWHM), and electric field magnitude at a point in space. Because the amplifier and antenna gains are not constant with frequency, a portion of this procedure was repeated for every data point.

Evaluating the Incident Electric Field

The following steps were used to calculate the radius from the source antenna at which the electric field equaled the desired value.

1. Selecting a source antenna.

The available power, 1 kilowatt, was barely adequate to provide the desired field strengths of 6,000 V/m. To maximize the radiated power, larger antennas were required for the lower frequencies (i.e., better source-to-antenna impedance match). However, the desire to keep the USOP in the antenna free-field requires that the USOP be placed no closer to the source antenna than $D^2/4\lambda$, where D is the larger of the antennas dimensions. Since these were conflicting requirements, three antennas were used over the frequency span so that the proper separation between USOP and antenna could be maintained while reaching the desired electric field levels. These antennas and the distance required for keeping the USOP in the far field are shown in Table 1.

Table 1. Antennas Used in Pulsed Free-Field Test

SOURCE ANTENNAS						
ANTENNA	FREQUENCY <i>GHz</i>	APERTURE <i>cm</i>	$D^2/4\lambda$ <i>cm</i>			
			<i>f</i> = 1 GHz	<i>f</i> = 4 GHz	<i>f</i> = 8 GHz	<i>f</i> = 10 GHz
AEL H1479	1-12.4	31.5	8	33	66	83
AEL H5201	4-10	10.5	N/A	4	7	9
Syston Donner	4-10	7.3	N/A	N/A	4	5

2. Selecting a field measurement sensor.

A TLB-3 B-dot sensor (manufactured by EMF) was used to measure the free-field power density. The TLB-3 was chosen because of its small physical cross section, 0.4 cm², and its bandwidth, 10 GHz. The voltage output of a B-dot sensor is

$$V_o = \omega \mu H A_{eq}$$

where

$$\omega = 2\pi(\text{frequency})$$

$$\mu = \text{magnetic permeability}$$

$$= 4\pi \times 10^{-9} \text{ henrys/cm}$$

$$H = \text{magnetic field intensity in amps/cm}$$

$$A_{eq} = \text{sensor equivalent area}$$

$$= 0.125 \text{ cm}^2.$$

When the USOP is placed a distance of $D^2/4\lambda$ (see Table 1) from the transmitting antenna, a free space environment can be assumed. In free space the electric field, E, and magnetic field are related by the relationship

$$Z_o = E/H$$

$$= 377 \text{ ohms.}$$

Thus in free space the electric field may be derived from the B-dot output voltage into a 50-ohm load as

$$E = (377/\omega\mu A_{eq})(50P_o)^{1/2}$$

where

$$\begin{aligned} P_o &= \text{B-dot output power} \\ &= V_o^2/50. \end{aligned}$$

A plot of B-dot output power versus frequency for various electric field intensities is shown in Figure 6.

3. Measuring the Pulse Width.

The Space Systems power amplifiers provide for internal modulation with a user selected repetition rate and pulse FWHM. Unfortunately, these amplifiers can only operate with repetitive pulses; they cannot supply the desired single pulse. The difference between a repetitive pulse and a single pulse must be examined for a test object such as a semiconductor. When the pulse repetition rate delivers the energy to a semiconductor faster than the thermal equilibrium of the semiconductor, multiple pulses can increase the temperature and result in damage/degradation at lower power levels than for single pulse application. Thermal equilibrium times have been shown [Ref. 2] to be on the order of tens of microseconds. Thus, a pulse repetition rate of 150 Hz is significantly slower than the thermal equilibrium time and will provide the same results as a single pulse. Because the amplifiers cannot operate in a single pulse mode, the pulse repetition rate was therefore set to 150 Hz for all the pulse tests.

Figure 6. Plot of B-dot Output Power Versus Frequency

Having determined that a repetitive pulse would be used, the measurement circuit (configuration A) shown in Figure 7 was used to set the pulse FWHM. The Hewlett Packard coaxial detector has a bandwidth of 0.01 to 26.5 GHz and required an input power level of 0 dBm to provide a measurable output of 10 mV. The diode output was connected to the oscilloscope and the pulse FWHM was viewed directly. The Space Systems modulator was then adjusted for the proper pulse FWHM.

4. Verifying Meter Calibration.

The Hewlett Packard peak power meter, model HP890D was used to measure the pulse peak power. The proper operation of the meter was verified by a cw comparison of results with the Boonton power meter.

5. Configuration for Field Measurement.

The circuit in Figure 7 also depicts the test equipment configuration for the measurement of the free-field power (configuration B). The goal of this step was to determine the distance from the source antenna where the electric field was the desired level (i.e., either 4,000 or 6000 V/m). For each exposure it was necessary to calculate the desired B-dot output power, reduce it by the attenuation of the output cable (see Figure 8), adjust the actual power level to the desired power level by moving the B-dot position with respect to the source antenna, and measure the pulse peak power on the HP890D. The position of the sensor was changed to adjust the measured peak power to the calculated value.

Pulsed Exposure of the USOP

After the free-space location for the proper electric field strength had been determined, the source was then shut off and the B-dot was replaced with the properly oriented USOP. The source was turned on for 5 seconds, exposing the USOP to the selected frequency. Between exposures the frequency was changed and step 5 above was repeated. Thus on each exposure, the USOP was exposed to a 5 second burst of 150 pulses-per-second, 1- μ s FWHM, rf envelope of the appropriate frequency.

In the Phase One tests the coupling cross section was shown to vary dramatically with frequency. Since each USOP exposure was conducted at a discrete frequency it is possible that all test frequencies were inadvertently selected at frequencies which had very low coupling cross sections. Increasing the number of frequencies checked reduces this probability. This potential problem is enhanced because the low power test data indicates that the USOP is most susceptible over a subset of the test frequencies. Therefore, for the most susceptible frequency range, above 6 GHz, it is possible that all eight of the selected discrete frequencies resulted in low coupling to the vulnerable component. To assure that this was not the case, a final test was performed after the discrete frequency testing was concluded. The power amplifier was turned on and left on while the Systron Donner rf source was varied continuously from 8 to 12 GHz. This test was conducted in approximately 20 seconds and provided a pulse train in which each pulse had a slightly higher frequency than the preceding pulse. Thus, for this frequency range, essentially all frequencies were tested, and the probability of having tested only at frequencies with very low coupling cross section has been reduced to a very low value.

Figure 7. Equipment Configuration for Measuring Free-Field Power

Figure 8. Output Cable Attenuation

USOP Health Check

After each exposure the USOP was powered up and all essential functions were checked.

3.2 Free-Field Continuous Wave Tests

The continuous-wave (cw) tests of the USOP were designed to expose the USOP to electric field strengths of 200, 300, and 400 V/m while it was positioned in a "worst-case" orientation. These tests were similar to the pulsed tests; however, measurements of a cw signal is less complex than measurement of a rf pulse. The test sequence again contained three basic parts. These were

- evaluate the incident field,
- expose the USOP, and
- evaluate USOP health.

Evaluation of the Incident Electric Field

The evaluation of the electric field included a determination of the electric field magnitude at a point in space. Because the 200-watt Logimetrics amplifiers provided adequate power for the desired electric field levels, a single antenna, the AEL H1479, was used. The measurements were all conducted in the free-field where the polarization and the relationship between E and H were clearly understood.

The test configuration is shown in Figure 9. The TLB-3 was used to measure the incident magnetic field. The measured value of sensor power is equal to the power reading plus the loss in the output cable. Thus P_o , the output power is

$$P_o = P_{\text{meter}} * 10^{-(\text{db atten}/10)}$$

where the dB attenuation is the measured loss in the output cable. The measured value was then converted to the electric field using the relationship $E = 377H$.

Figure 9. Test Configuration for Continuous Wave Tests

The 200-watt amplifiers were all computer controlled. A rough estimate of the free-field power density at a given radius is directly available from the computer. The measurements were used to provide a more accurate value of E as a function of radius.

Continuous Wave Exposure of the USOP

The cw exposures were made for 30 seconds. Thus for each of the selected frequencies, the USOP was exposed to 30 seconds of a cw signal which was adjusted to a single frequency. Again, there is the potential for inadvertently selecting frequencies for which the coupling is low.

Therefore, after the successful conclusion of the point by point testing the rf source was continuously varied between 8 and 12 GHz to ensure that an adequate number of frequencies were included in the test.

USOP Health Check

After each exposure the USOP was powered up and all essential functions were checked.

4. DISCUSSION OF TEST RESULTS

4.1 Executive Overview

Two prototype designs were tested during this test program. Prototype 1 was tested in the Phase One tests and Prototype 2 was tested in the Phase Two tests. Because 1 kilowatt microwave amplifiers were not available, the Phase One tests did not include the free-field testing of a full assembly. They did include a variety of coupling and high-power direct drive tests. The coupling tests provided insight into design approaches and the level of shielding afforded by the USOP case. The direct-drive test provided information related to USOP susceptibility. There was one USOP failure, at a very high drive level, in the direct-drive tests.

The Phase Two testing consisted of free-field USOP illumination only. The data from the Phase One testing was used as a basis for selecting the method of attaching the shield cover to the case and for selecting a "worst case" orientation. There were no USOP failures in any of the free-field tests.

Overview of Phase One Test Results

The USOP was tested with direct-drive levels that resulted in stresses that were equivalent to, or greater than, a radiated free field, electromagnetic field of a 10-kV/m pulse with a 1- μ s width. The USOP was not damaged at the direct-drive levels that corresponded to 10 kV/m; however, it was damaged at levels that were just above 10 kV/m and which were at frequencies above 2 GHz. During the Phase One high power tests, the USOP health checks were performed at a remote location. Consequently, the USOP was exposed to several frequencies at each power increment and the exact frequency at which damage occurred is not known. Because the USOP was damaged during the pulsed, high-power tests, it was not exposed to the cw threat levels during the Phase One testing.

The low power test results did show that the disconnected, passive-USOP is hardest below 2.5 GHz, a factor of ten less hard between 2.5 GHz and 5.5 GHz, and most susceptible above

5.5 GHz. The epoxy proved to be a marginally better shield than the set screws; however the epoxy was brittle and did break off the cujac measurement lead. Below 5.5 GHz, all of the USOPs produced a larger coupling cross section when the electric field was oriented in the axial direction. This indicated that the predominate coupling mechanism, below 5 GHz, results from the coupling through the backshell-to-connector mating arrangement. Above 5.5 GHz the predominate coupling path is through the connector opening itself.

It thus follows that additional hardening of the backshell-to-connector interface would improve the overall electromagnetic hardness of the USOP below 5.5 GHz. A suggested improvement would make this a threaded, mating interface. To improve hardness above 5.5 GHz, it will be necessary to address the connector pins themselves. They could be covered with a protective metal or lossy dielectric cap, or the connector could be redesigned so that the pins are hidden behind a perforated electrostatic shield.

Overview of Phase Two Test Results

During the Phase Two pulsed tests the USOP was exposed to a free-field exposure of a 1- μ s-wide pulse with a 4,000-V/m amplitude at all selected test frequencies and 6,000-V/m amplitude at test frequencies below 7.5 GHz. Additionally, it was exposed to cw free-field illumination with field strengths of 400 V/m at selected frequencies from 1 to 12 GHz. No failures or degradation in performance were observed.

4.2 Phase One Test Results

4.2.1 Free-Field and Direct-Drive Low-Power Tests. The results of the low-power tests, which are summarized in Figures 10 through 13, are

1. Identification of the principal leakage paths,
2. Quantitative data concerning the shielding effectiveness of two methods for attaching the backshell to the connector.
3. Measurement of σ for USOP 2, and
4. Measurement of the direct-drive transfer function.

The transfer functions for the three angles of orientation are shown in Figures 10, 11 and 12. As previously mentioned, when the source frequency was below 5.5 GHz, the coupling was largest for axial orientation. Above 5.5 GHz, the cylinder of the connector (diameter = 2 cm) coupled the energy more efficiently and the response for this aperture began to dominate the measured response. Additionally, the epoxy was shown to be a marginally better shield than the setscrews. The backshell-to-connector slot was driven most strongly when the electric field was in the axial orientation (Figure 10) and thus that data showed the relative merit of these two shielding methods. As the frequency increased, the set screws were less effective as shields. This resulted from the fact that the uniformly spaced set screws created a slot antenna which resonated at 3.75 GHz, and for both subharmonics, such as 1.8 GHz, and higher order harmonics. For these resonant frequencies the shield was notably degraded.

Figure 10. USOPs 1, 2, and 3, Axial Orientation

Figure 11. USOPs 1, 2, and 3, 45° Orientation

Figure 12. USOPs 1, 2, and 3, Radial Orientation

Figure 13. USOP 2 Test Data

For all orientations and over most of the frequency ranges, the coupling cross section to the chip was significantly larger than it was for a single pin. This resulted from the fact that the circuitry, which included the chip, provided a much larger antenna for coupling. For USOP 2 the results of varying orientation are shown most clearly in Figure 13. This data clearly shows (see Figure 13a) the predominance, below 5.5 GHz, of the axial exposure over the radial (end-on) exposure for USOP 2. Figure 13b depicts the pin power levels which may be expected with an incident 10-kV/m field. The value of S_{21} is shown in Figure 13c. Because this measurement was extremely sensitive to position, the sharp dips in S_{21} at 1.3 and 7 GHz should not be interpreted literally. The dips result in peaks in the calculation of the direct-drive power (Figure 13d) which resulted in an over estimate of the direct-drive power level. In retrospect, the largest value of direct-drive power for which the USOP should have been expected to survive would be 27 dBW (i.e., 500 watts) instead of the 30 dBW (i.e., 1 kilowatt) that was applied. The 30 dBW was on overtest, especially below 5 GHz. What this data does imply is that the USOP is likely to fail when exposed to electric free-field illumination of 20 kV/m at frequencies between 5 and 10 GHz. Because the issue of survivability involves statistical data from a large number of data points, it would be improper to assume survivability between 10 and 20 kV/m.

Figure 14 extrapolates the energy for a 10-kV, 1- μ s pulse. When semiconductors are exposed to pulses of energy which are short with respect to thermal time constants, the semiconductor junction temperature can rise very quickly and thus cause damage. In general, the pulsed data apply to all pulse widths which are shorter than the semiconductor thermal equilibrium time. For chips of this type, this implies that Figure 14 applies to all pulse widths that are less than 10 μ s. Previous measurements [Ref. 2] have shown that at least 100 microjoules is required for damage of integrated circuits and that microwave diodes can be damaged with 10 microjoules incident energy. These two levels are noted in Figure 14, which is a plot of the energy delivered to the chip from an incident electric free-field of 10 kV/m. From these two reference points it can be observed that for a 10-kV/m incident wave, damage to the USOP is definitely not expected at frequencies below 2.5 GHz. At frequencies between 2.5 GHz and 5.5 GHz damage is still not expected; the safety margin is approximately a factor of ten. Finally, at frequencies above 5 GHz, the threshold level for damage is being approached. The reader is cautioned that actual piece-part tests on the SA3727 tests have not been conducted; such tests are necessary to arrive at a conclusive determination of USOP hardness. Based on past experience, however, the values shown in Figure 14 are very likely to be worst-case estimates for pulsed exposure. That is, for pulses with widths below 10 μ s, the USOP is at least as hard as shown in Figure 14. Thus, one may infer that the USOP is not susceptible to a 10-kV/m, 1- μ s pulse at frequencies below 5 GHz, and is approaching the damage threshold at frequencies above 5 GHz.

Finally, Figure 15 depicts the pin power levels which may be expected with an incident field of 500 V/m. Since the chip quickly reaches thermal equilibrium for cw illumination, energy deposited in the junction is not a relevant parameter. Instead, one can simply compare the power levels shown in Figure 15 to the rated power levels for the SA3727 chip. If these levels are small with respect to the rated values, the chip will be safe. The data from Figures 13d and 15 were used as inputs for the high power tests.

Figure 14. Energy (joules) at Chip Due to 10-kV/m, 1- μ s Pulse

Figure 15. Direct Drive Power (watts) at Chip, which compares to a 500-V/m Continuous Wave Field

4.2.2 Mode-Stirred Chamber Tests. The mode-stirred chamber (MSC) test confirmed that no pathological combination of polarizations could result in a high coupling to the USOP electronics. The plot of sigma for the MSC is displayed in Figure 16. The MSC data is plotted over the free field transfer function. The fact that the MSC data does not jump above the free-field transfer functions confirms that the worst-case orientations were selected.

4.2.3 High-Power Tests. The direct drive high-power tests were designed to apply a stress to the SA3727 chip that is equivalent to the stress from one of two free-field radiated signals. The first is a 10-kV/m pulse with a 1- μ s width, and the second is a 500-V/m cw signal. The data from Figures 13 and 15 are used to determine the values of the direct-drive power. The test configuration was outlined in Figure 5. The direct drive microwave pulses had a 1- μ s full-width half maximum. The test data points are shown in Figure 17. Here the direct-drive power that corresponds to the power coupled from a 10 kV/m electric free-field is shown for two orientations. The squares, which are superimposed on these previously shown transfer functions, are the high-power test points. It may be observed that the chip was tested at levels that were above 10 kV/m for several frequencies. The USOP was damaged when the set of pulses which had a direct-drive power level of 1 kW were applied to the test configuration (Figure 5b). As was previously noted, this corresponds to an electric free-field of approximately 20 kV/m. Since several frequencies were tested at each power level, the exact frequency at which the system failed is not known; however, it was between 2.5 and 8 GHz. Because the USOP was damaged in the high-power pulsed test series, no high-power cw tests were performed.

4.3 Phase Two Test Results

Based on the results of the Phase One testing no failures were expected at the field strengths used in the Phase Two tests and none were observed. A summary of Phase Two exposure levels is shown in Tables 2 and 3. As noted in Sections 3.1 and 3.2, after the tests listed in Tables 2 and 3 were completed, the USOP was further exposed to a continuum of pulses, each of which had a slightly higher frequency than its predecessor. This was accomplished by tuning the rf source from 8 to 12 GHz while the microwave amplifier was left energized. These additional pulses add significant confidence that the USOP was tested at all significant pulses. In conclusion, the USOP did not fail or show signs of degradation for 4,000 V/m pulses or for 400 V/m cw electric free fields. Additionally, there were no observed effects for pulses of 6,000 V/m for frequencies below 7 GHz.

Figure 16. Mode-Stirred Chamber Results

Figure 17. Pulsed High-Power Levels (1- μ s FWHM)

Table 2. Pulsed Free-Field Exposure of the USOP Prototype 2

frequency in GHz	exposure level #1 (V/m)	exposure level #2 (V/m)
1.0	4,000	6,000
1.5	4,000	6,000
2.4	4,000	6,000
2.8	4,000	
3.5	4,000	6,000
4.0	4,000	6,000
4.5	4,000	6,000
5.0	4,000	6,000
6.0	4,000	6,000
6.5	4,000	6,000
7.0	4,000	6,000
7.5	4,000	
8.0	4,000	
8.5	4,000	
9.0	4,000	
9.5	4,000	
10.0	4,000	

-source not able to provide 6000 V/m in X band
-cw source dialed through 8-12 GHz with maximum
available output of approximately 4000 V/m.

Table 3. Continuous Wave Free-Field Exposure of the USOP Prototype 2

frequency(GHz)	level #1(V/m)	level #2(V/m)	level #3(V/m)
1.0	200	300	400
2.0	200	300	400
3.0	200	300	400
4.0	200	300	400
5.0	200	300	400
6.0	200	300	400
7.0	200	300	400
7.9	200	300	400
9.0	200	300	400
10.0	200	300	400
11.0			400
12.0			400

stepped continuously from 8 to 12 GHz at 400 V/m

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