Report: Investigation Into The Effects Of Microsecond Power Line Transients On Line-Connected Capacitors

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EXECUTIVE SUMMARY

An investigation was conducted into the effect of power-line transients on capacitors used by NASA and installed on platform primary power inputs to avionics. The purpose was to investigate whether capacitor voltage rating needs to be derated for expected spike potentials. Concerns had been voiced in the past by NASA suppliers that MIL-STD-461 CS06-like requirements were overly harsh and led to physically large capacitors.

The author had previously predicted that electrical-switching spike requirements representative of actual power-line transient potentials, durations and source impedance would require no derating. This investigation bore out that prediction. It was further determined that traditional low source impedance CS06-like transients also will not damage a capacitor, although the spikes themselves are not nearly as well filtered.

This report should be used to allay fears that CS06-like requirements drive capacitor voltage derating. Only that derating required by the relatively long duration transients in power quality specification need concern the equipment designer.

ACKNOWLEDGMENTS

The author wishes to thank Mr. Kurt Mikoleit of the Naval Surface Warfare Center, Dahlgren, Virginia for the long term loan of a Solar 7399-2 spike generator. This equipment, capable of delivering 8 MegaWatt pulses at 2 kV, was specially designed for the spike requirements of MIL-STD-1399 and is not standard equipment in the typical EMI test facility.

Mr. Robert Kapustka of the Marshall Space Flight Center suggested representative bulk capacitors he has employed as a designer of dc-dc converters. These were pulled from actual parts bins used for space applications. Mr. Kapustka has been with NASA since the Apollo program.

Mr. Mark Nave of Network Appliance suggested that an explosion container be built when using the Model 7399-2 to stress tantalum electrolytics, since the electrolyte is sulfuric acid. Given that evidence of explosive forces was found, this was a sound suggestion.

ACRONYMS

CS06	power-line spike susceptibility test requirement (MIL-STD-461/MIL-STD-462)
CUT	cable-under-test
DIP	dual in-line package (integrated circuit package)
EUT	equipment-under-test
FET	field-effect transistor
LISN	line impedance stabilization/simulation network
MSFC	(NASA) Marshall Space Flight Center
STS-1	switching transient simulator

1.0   Introduction

This report documents the results of a test in which capacitors were subjected to spiked potentials of varying amplitudes, durations, and source resistances. The work follows the development of special transient generators which simulate electrical power bus switching transients.[1] In addition to the use of these unique generators, two other generators which meet the requirements of MIL-STD-461 CS06 and MIL-STD-1399 were employed to stress the same capacitors subjected to switching transients earlier.

1.1   Purpose

The purpose of these tests is to demonstrate that capacitors connected across primary power inputs in avionics need not have their voltage rating derated for switching transient-like potential stresses. It will be shown that it is sufficient to derate capacitor voltage rating for power quality-related surges, which are lower in amplitude, but have longer durations.

1.2   Scope

Six capacitor configurations were evaluated. All capacitors were selected as representative of those used in spacecraft applications as hold-up or bulk energy storage or line-to-ground filters at the input to switching power supplies (dc/dc converters). Specifically, these capacitors were pulled from bins where power supply bulk capacitors are stored at MSFC. Capacitors used on 28 Vdc (Space Shuttle), 120 Vdc (Space Station), and 270 Vdc (X-33) were selected, as well as a capacitor rated for just 30 Vdc, which was just marginally rated to operate on 28 Vdc.

Cap.	Bus Type	Nomenclature	Cap Type	C μF	WVDC
A	28 Vdc	M39006/+ 22-0600	tantalum electrolytic	140	60
B	120 Vdc	M39006/ 25-0264H	tantalum electrolytic	82	125 [2]
C	120 Vdc	AVX 87106-157 9622A	ceramic	33.6	200
D	270 Vdc	AVX 87106-237 9726A	ceramic	15.6	500
E	<28 Vdc	M39006/ 22-0560	tantalum electrolytic	300	30
F	120 Vdc	Sprague LC filter	ceramic feedthrough	0.2	200

Spike sources were as follows:

Potential Volts	Source Impedance Ohms	Generator Name	Manufacturer
0 - 500	50	STS-1[3]	EMC Compliance
0 - 600	1.2	Model 8282-1	Solar
0-2500	0.25	Model 7399-2	Solar

1.3   Background

The Space Station program imposed a specially tailored CS06 spike (SSP 30237). The tailoring followed the practice of MIL-STD-461 of the spike potential being twice the nominal line potential, but ignored the 100 or 200 Volt limit. For Space Station, this resulted in a 240 Volt spike superimposed on a 120 Vdc bus. There were complaints from some equipment designers about the severity of this requirement. In 1994, the author presented a paper at the IEEE EMC

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[1]Reference NASA report: NASA/CR—1999—209574

[2] Two of these capacitors are used in series across the bus to get the proper derating. This results in 41 μF.

[3]Switching Transient Simulator - 1

symposium that was the result of investigations into this subject (the breadboard spike generator described therein was developed into stand-alone test equipment as described in the footnote 1 report). A 50 Ω spike source was developed which more accurately simulated switching transients.[4] It was demonstrated that a small capacitor could effectively filter a 50 Ω source impedance 1 μs spike, but could not filter a 10 μs, 1 Ω source impedance spike from a Solar Model 8282-1 spike generator, which is the usual test equipment employed for CS06.

This report extends that simple observation into a full investigation.

2.0   Applicable Documents

Number	Title
MIL-STD-461	Electromagnetic Interference Characteristics Requirements for Equipment
MIL-STD-462	Electromagnetic Interference Characteristics, Measurement of
MIL-STD-1399	Interface Standard for Shipboard Systems, Section 300A: Electric Power
SSP 30237	Electromagnetic Emission & Susceptibility Requirements for EMC
SSP 30238	Electromagnetic Techniques (Space Station)
NASA/CR-1999-209574	Specification, Measurement, and Control of Electrical Switching Transients

3.0   Results

Capacitors were tested as described above. Capacitance of each capacitor was measured prior to and after spike applications. Pass/fail criterion was the absence/presence of a change in capacity.

3.1   Summary

No bulk or hold-up capacitor failed at any spike potential generated by either the STS-1 1 μs, 50 Ω source or the Model 8282-1 10 μs, 1 Ω source. This included potentials of 500 V peak (spike plus dc bus) from the STS-1, and potentials of 600 Vdc superimposed on the bus potential (resulting in peak excursions of 600 Volts above nominal bus potential). Ceramic feedthrough capacitors were undamaged by the STS-1 generated transients, but failed at higher spike potentials from the Model 8282-1. These spike potentials were, however, above those normally imposed by NASA CS06 limits.

Capacitor E failed at a Solar Model 7399-2 spike source applied potential of 600 Volts for 20 μs. Amplitude was 1.32 kV into a 0.5 Ω resistor. The spike source impedance was 0.25 Ω. It took almost four hours to fail the capacitor, with spikes applied at a rate of two pulses per minute.

The original purpose of this investigation was to show that capacitors do not have to be derated for positive sense (turn-off) transients of microsecond duration if they are properly generated. This means a source impedance reflecting that of real transmission lines, as opposed to the Ohm or sub-Ohm source impedance of the Model 8282-1 CS06 spike source. The point here is that if a platform mission does not subject it to lightning attachments, a low impedance high potential transient on a power bus is difficult to explain.

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[4] 50 Ω was the source impedance for a positive going or turn-off transient. The negative-going or turn-on transient was low impedance.

This investigation amply demonstrates this is the case. All the bulk capacitors except capacitor E were able to load a 500 Volt (transient plus power bus) potential down to a level below their voltage rating. None of the capacitors showed any degradation either short or long term after such applications. In fact, the worst case application applied the 500 Volt spike to a 30 Vdc cap (capacitor E) biased at 28 Vdc (essentially no derating, even for dc) and caused no effect whatsoever after three hours of spikes at a repetition rate of one pulse per second.

But in addition to this fact, which it was the purpose of this investigation to demonstrate, it was also found that the CS06 spike caused no damage to any of the capacitors tested. This was a much more severe test, due to the low source impedance of the Model 8282-1 spike source. While the spikes were not as effectively filtered, they caused no lasting degradation. All the tantalum electrolytics got very hot, and capacitor E measured a higher capacitance just after the test than before the test or after it had cooled off, but this could not be considered an operational failure, since more capacitance would not cause a problem for a bulk capacitor function. Spike potentials generated by the Model 8282-1 were capable of damaging the capacitor of Filter F, but this occurred at potentials well in excess of normal CS06 limits (above 300 Volts spike potential).

Only a kiloAmp source was able to damage the other capacitors. Tantalum electrolytics failed at kiloVolt/kiloAmp spike levels (20 μs duration) after repeated spike applications at two pulses per minute (ppm). Ceramic bulk capacitors failed at the first kiloVolt/kiloAmp spike application.

3.2   Test Methods

Three different test techniques were utilized. They were implemented in order of increasing severity. The first tests used the EMC Compliance STS-1 switching transient simulators, which generated a 1 μs, 50 Ω source impedance spike. The next test applied spikes from the Solar Model 8282-1 CS06 transient generator. The last set of spikes were applied from a Solar Model 7399-2 borrowed from the Navy.

3.2.1   Application of Turn-Off Switching Transients

Capacitor value is measured prior to test start, and again at end of spike application. The test is diagrammed in Figure 1. In Figure 1, CUT refers to capacitor-under-test.
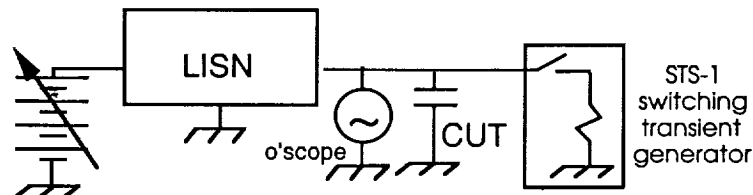
Figure 1: Schematic of switching transient test

The oscilloscope measures potential from line-to-ground at the LISN output. The nominal spike potential is measured without the capacitor in place, using a 1 or 10 MΩ oscilloscope probe. The spike is measured again with the capacitor in place. Spikes are imposed at a rate of at least 1 pps. Pictures of test set ups and capacitors are shown in Appendix A.

A characteristic of the STS-1 not previously discovered is that the switching FET has some kind of protection circuitry which clamps applied potential to just above 500 Volts peak. Regardless of switched load ($V_{spike} = 50 \, \Omega \cdot I_{switched}$) or nominal bus potential, V_{total} ($= V_{bus} + V_{spike}$) is bounded

by just over 500 Volts. Thus the spike applied to the 28 Vdc bus was about 500 Volts, but the spike applied to 120 Vdc was only a little over 400 Volts, and the spike applied to 270 Vdc was about 300 Volts.

In each case (for each capacitor at each bus potential), the initial spike potential applied was 100 Volts open circuit. The spike potential actually applied to the capacitor was much decreased in amplitude from the 100 Volts measured open circuit. This spike potential was applied for several minutes. The capacitor value was measured, found to be unchanged, and the spike potential increased to 200 Volts. The same process was reiterated until the maximum 500 Volt spike was applied. At this point, spikes were imposed at a rate of at least 1 pps for over one hour. At least 3600 spikes are thus applied at the maximum potential to which the capacitors are exposed and to which they are considered qualified. After this final application, the capacitance is again measured (and found to be unchanged in all cases). Test data is shown below for the final 500 Volt spike application for each type of capacitor and bus.

3.2.1.1 Test Data

Data 1-1 and 1-2 show the STS-1 50 Ω spike unloaded and loaded by a 140 µF, 60 V rated capacitor (cap A). This capacitor is typical of one used as a bulk capacitor at the input of a 28 Vdc dc/dc converter. The spike was generated by switching a 2 Ω load off the 28 Vdc line. A 14 Amp switched current should have resulted in a 700 Volt spike (14 A • 50 Ω), but protection circuitry limited overall (spike plus bus) potential to 516 Volts. The capacitor so loads the spike that peak spike amplitude (spike + nominal dc bus potential) is less than the dc rating of the capacitor. No capacitor failure is expected under such conditions. This is the case whenever the 50 Ω spike is generated across a capacitor. Therefore switching transient potentials should not be used to derate capacitor voltages. The switched spike amplitude will *not* appear across the capacitor. Demonstrating this was the major goal of this investigation.

In order to show just how benign the switching transient is, the same 500 Volt spike as of Data 1-1 was generated across a 300 µF tantalum electrolytic rated at 30 Vdc (Cap E), while it was biased at 28 Vdc. The resulting spike is presented in Data 1-3. It is almost identical to the spike of Data 1-2, except here the peak spike amplitude (spike plus nominal dc potential) exceeds the capacitor dc rating. Nevertheless, a three hour exposure at one pulse per second resulted in no observable change in capacitance, and no observed heating.

A 500 Volt spike (switched load = 20 Ω) was also imposed on capacitors B and C, which were typical of those used on 120 Vdc power. Capacitor B is two 82 µF, 125 Vdc electrolytics in series. Capacitor C is a 33.6 µF, 200 Vdc. Data 1-4 is an unloaded spike injected on 120 Vdc. Data 1-5 shows near complete filtering of Data 1-4 spike across capacitor B after over one hour of one pulse per second application. The same result was obtained when the Data 1-4 spike was injected into capacitor C for two hours at one pulse per second (Data 1-6).

A more visible spike appears in Data 1-7, which is the spike of Data 1-4 injected into filter F, a Sprague threaded LC filter with capacitor value of 0.2 µF. The capacitor was facing the LISN in this test. Spike amplitude clearly exceeded the capacitor rating of 200 Vdc, but the spike was applied for two hours at greater than one pulse per second with no change in capacitance.
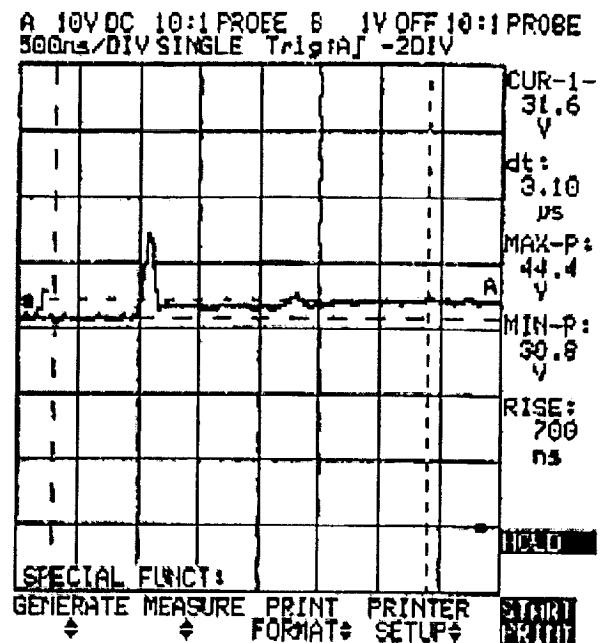
Data 1-8 shows the 500 V, 50 Ω spike injected onto 270 Vdc. This same spike was injected over one and one-half hour (at one pulse per second) into capacitor D, a 15.6 µF, 500 Vdc rated
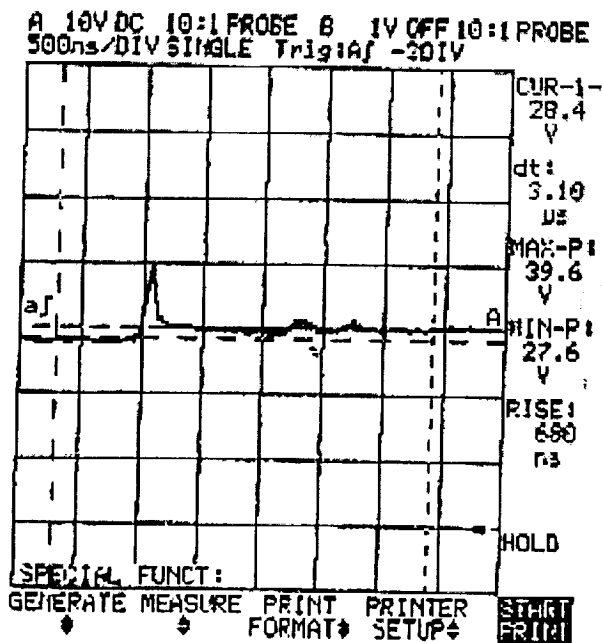
ceramic. No visible spike was generated or recorded. Note that in any case, the unloaded switching transient barely exceeds the capacitor D dc rating.
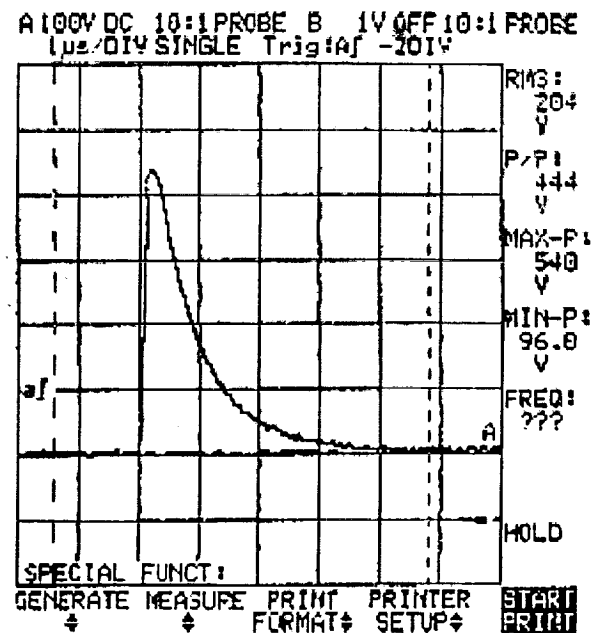

Data 1-1: 500 V spike injected on 28 Vdc
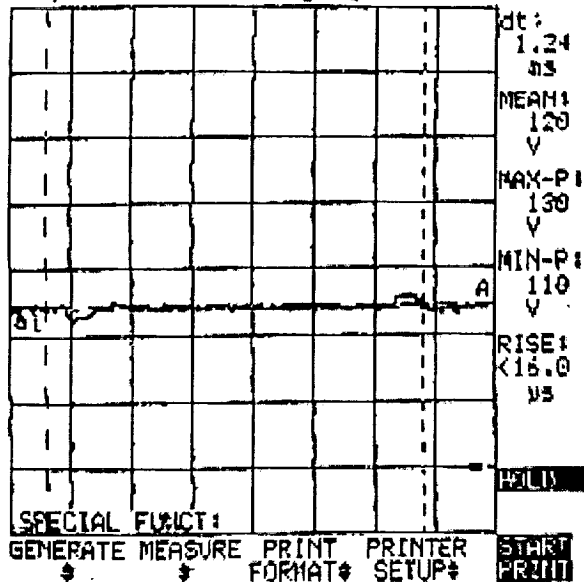

Data 1-2: Spike of Data 1-1 on capacitor A

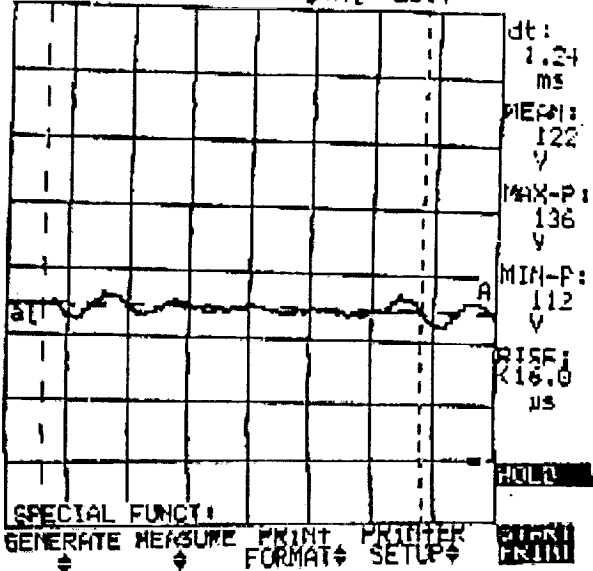Data 1-3: Spike of Data 1-1 on capacitor E

Data 1-4: 500 Volt spike injected on 120 Vdc

A 50V DC 10:1 PROBE B 1V OFF 10:1 PROBE
200ua/DIV SINGLE Trig:A[-7DIV

dt:
1.24
ms

MEAN:
120
V

MAX-P:
130
V

MIN-P:
110
V

RISE:
<16.0
us

HOLD

SPECIAL FUNCT:
GENERATE MEASURE PRINT PRINTER START
FORMAT♦ SETUP♦ PRINT

A 50V DC 10:1 PROBE B 1V OFF 10:1 PROBE
200ua/DIV SINGLE Trig:A[-2DIV

dt:
1.24
ms

MEAN:
122
V

MAX-P:
136
V

MIN-P:
112
V

RISE:
<16.0
us

HOLD

SPECIAL FUNCT:
GENERATE MEASURE PRINT PRINTER START
FORMAT♦ SETUP♦ PRINT

Data 1-5: Spike of Data 1-4 injected into cap B   Data 1-6: Spike of Data 1-4 injected into cap C

A 50V DC 10:1 PROBE B 1V OFF 10:1 PROBE
20us/DIV SINGLE Trig:A[-2DIV

dt:
124
us

MEAN:
120
V

MAX-P:
236
V

MIN-P:
56.0
V

RISE:
<1.60
us

HOLD

SPECIAL FUNCT:
GENERATE MEASURE PRINT PRINTER START
FORMAT♦ SETUP♦ PRINT

A 100V DC 10:1 PROBE B 1V OFF 10:1 PROBE
1us/DIV SINGLE Trig:A[-2DIV

dt:
6.20
us

MEAN:
304
V

MAX-P:
564
V

MIN-P:
260
V

RISE:
<60.0
ns

HOLD

SPECIAL FUNCT:
GENERATE MEASURE PRINT PRINTER START
FORMAT♦ SETUP♦ PRINT
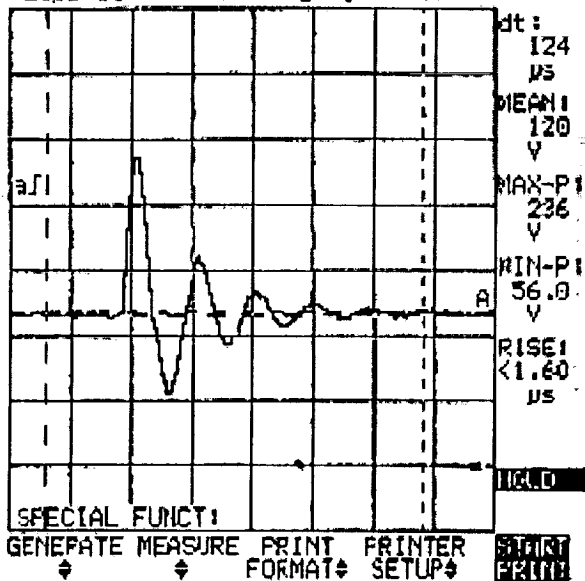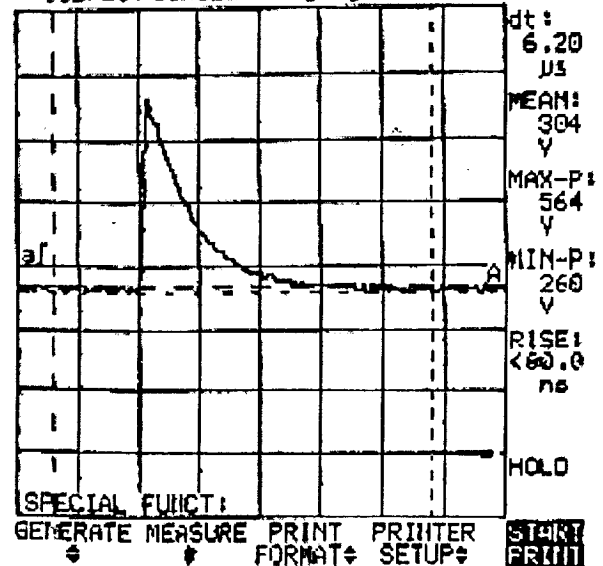
Data 1-7: Spike of Data 1-4 injected into cap F   Data 1-8: 500 Volt spike injected on 270 Vdc

3.2.2   Application of CS06 - Like Positive Transients

The Solar Model 8282-1 Transient Pulse Generator was used in a MIL-STD-462 CS06-like parallel injection technique (as diagrammed in Figure 2) to inject up to 600 Volt pulses into the test capacitors. The 10 μs spike source impedance was very near 1 Ω. Data 2-1 and 2-2 show spike waveforms into 5 Ω and 1 Ω loads respectively. Spike source resistance is given by:

$$R_{source} = \frac{R_1 R_2 (V_1 - V_2)}{V_2 R_1 - V_1 R_2} = \frac{5\Omega \cdot 1\Omega (600V - 340V)}{340V \cdot 5\Omega - 600V \cdot 1\Omega} = 1.2 \ \Omega$$

An unloaded source potential of about 700 Volts may also be deduced from this data. The test set up was identical to CS06 parallel injection with two differences. A MIL-STD-462D LISN was used in lieu of the MIL-STD-462 suggested 20 µH coil, and the EUT (capacitor) was connected directly to the Model 8282-1 parallel output banana jacks. Lead lengths were thus minimized. Pictures of test set up may be viewed in Appendix A.
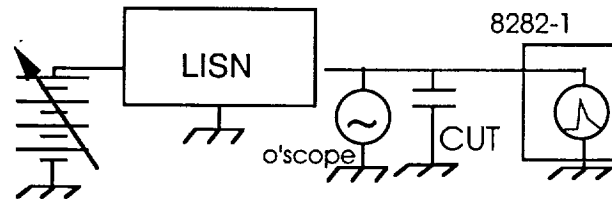
Figure 2: Test set up of CS06-like parallel spike injection

3.2.2.1 Test Data

The 600 V, 10 µs spike of Data 2-1 was injected on to capacitors B through E, with no test failures. All tantalum electrolytics got very hot during this test. These tests were run for at least one hour at one pulse per second. The ceramics were run at 2 pps with no noticeable heating. One tantalum electrolytic, capacitor E, read 386 µF immediately at test end (very hot), but 316 µF after returning to ambient temperature. This was not deemed a failure.

The most important result here is Data 2-3. This is the induced spike across the 300 µF, 30 Vdc rated capacitor (E) biased at 28 Vdc. With absolutely no headroom to spare, this capacitor still did not fail when the 600 Volt spike was injected. Note that about 600 Amps was flowing at the peak of the spike waveform in order to result in an applied spike amplitude of 114 Volts (greater than 700 Volts source potential loaded through 1 Ω source resistance down to approximately 100 V). It is quite reasonable to extrapolate from this result that no properly derated tantalum electrolytic bulk capacitor will be damaged by any low duty cycle CS06 - like spike application.

Because traditional CS06 test procedures mention spike repetition rates of 1 - 10 pps, spike testing was also performed at 10 pps. An initial trial placed a 600 Volt spike setting across capacitor A. The Model 8282-1 amplitude was turned all the way clockwise (maximum output). This yields a spike potential of greater than 600 Volts into 5 Ω. Data 2-7 shows the resultant spike across capacitor A. Spike amplitude actually dropped over the course of an hour long test to a peak of 96 Volts. This was attributed to an increase in capacitance due to electrolytic fluid heating. Capacitor A, nominally 140 µF, rated at 60 Vdc, measured 168 µF cold. After one hour of 600 Volt spike application at 10 pps, the capacitor case was extremely hot and the capacitance measured 320 µF. This returned to the pre-test value of 168 µF in about four minutes. Figure 3 shows measured post-test capacitance as a function of time, with a superimposed exponential decrease. Close correlation shows that capacitance decreases exponentially with time:

$$C(t) = C_0 (1 + e^{-t}), \ C = \text{capacitance}, \ C_0 = \text{initial pre-test capacitance}, \ t = \text{time}.$$

which is a solution to Newton's Law of Cooling:

$$\frac{\partial T}{\partial t} = T, \ T = \text{temperature}, \ t = \text{time}.$$

Strong correlation between capacitance and predicted temperature as a function of time indicates a very high probability of a causal relationship between electrolyte temperature and capacitance.
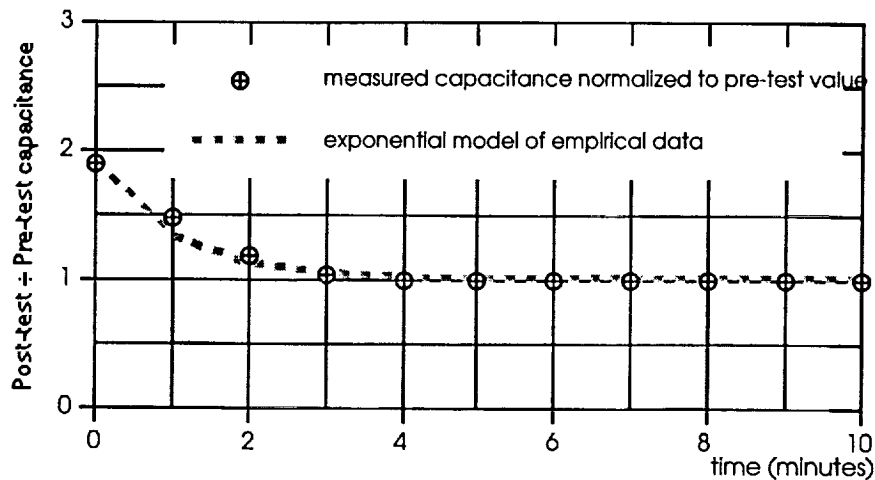
Figure 3: Capacitance as a function of post-test time

Having completed a one hour application of a 10 pps 600 V, 10 μs spike to a 60 Vdc rated capacitor (A), an identical test was performed on a 30 Vdc rated capacitor (E). Data 2-8 shows the spike applied to capacitor E (recall that Model 8282-1 amplitude is at maximum, yielding over 600 Volts peak into 5 Ω). Both capacitors A and E were biased at 28 Vdc for these tests. Capacitor E gave similar results to A post test, but hot capacitance exceeded the capacitance meter's range and could not be measured until it was nearly room temperature. Post-test, the clear plastic coating of both capacitors was discolored by the extreme heating. It is possible that if the case of such a capacitor were in contact with a printed circuit board (PCB), that damage to the board could result. However, recall that the applied spike in the above cases was 600 Volts peak. No CS06-like specification calls out such a spike at such repetition rates for an hour.

The same test was performed on capacitor B, the two series tantalums. Capacitor B was biased at 120 Vdc (Space Station). The applied spike is shown in Data 2-9. Over two hours the capacitors did not overheat, and immediate post-test capacitance was equal to the pre-test value.

When the 600 Volt, 10 μs, 10 pps spike was applied to ceramic capacitor C, biased at 120 Vdc, there was no effect. The test was repeated with the bias at 190 Vdc to most severely stress the capacitor. There was no effect, other than mild temperature rise after a two hour application. Data 2-10 shows the applied stress to a 5 Ω load at 10 pps, while Data 2-11 shows the actual stress across capacitor C.

The above tests on the tantalum capacitors established a significant safety margin between typical CS06 requirements and any resultant damage to bulk capacitors. However, the heating issue may cause concern with respect to nearby circuit elements, including the PCB. Therefore the above tests were rerun with a 240 Volt spike. This is the highest CS06 spike potential yet levied on a NASA program. Data 2-12 shows the 240 Volt spike applied to a 5 Ω load. Data 2-13 shows the result when the same spike generator setting as for Data 2-12 is applied to capacitor E (300 μF, rated at 30 Vdc, biased at 28 Vdc). After one hour of a 10 pps application, the capacitor was warm, but not too hot to handle. Initial post-test capacitance measured 380 μF, not much different than nominal 315 μF.

Filter F was an L-filter rather than a discrete capacitor. Line-to-ground cap value is 0.2 μF, other specifications, taken from the RFI™ catalog, are given below.

SUBMINIATURE FILTERS
M28861/5 200VDC 125VAC 400HZ

.070 ± .010
2 PLACES

1/4-28 UNF - 2A

.125
.100

.410
MAX

.190
.100

.190
.100

.210
.190

A

.793
MAX

SPECIFICATIONS

OPERATING TEMPERATURE -55° TO +125°C
DIELECTRIC TEST: 2.5 TIMES RATED VOLTAGE
INSULATION RESISTANCE: 1000 MEGOHMS
MIN.@25°C
CONFORMS TO THE APPLICABLE
REQUIREMENTS OF MIL-F-23861
FILTER SUPPLIED WITH LOCKWASHER & HEX NUT
FINISH: HOT SOLDER DIP

M28861/5 DASH#	RFI PART#	CKT	AMP	RATING DCV	ACV	A±.010	MAX V DROP	MINIMUM INSERTION LOSS IN DB CIRFLS MIL-STD-220A (FULL LOAD)					
								100KHz	150KHz	300KHz	1MHz	10MHz	1GHz
0001	RF6905-1	L₁	.25	200	125	.187	.375	22	28	40	60	60	70
0002	RF6905-2	L₂	.25	200	125	.187	.375	22	28	40	60	60	70

No manufacturer specifies filter series inductance, so this had to be measured. A series insertion loss technique was used. The filter was placed in series between a 50 Ω signal source and a 50 Ω spectrum analyzer. No connection whatsoever was made to the filter case, so the capacitor had no effect on the measurement. A baseline measurement was made without the filter in line, so that insertion loss could be ascertained. The equation which predicts the insertion loss is:

$$\text{Insertion Loss (dB)} = 20 \log \left(\frac{50}{\sqrt{2500+(2\pi fL)^2}} \right)$$

Test set-up schematic and equation is plotted below for L = 400 μH, over a 100 to 1100 kHz range. Test data shows excellent agreement with theoretical insertion loss for 400 μH. Test data upper trace A is a baseline measurement without the filter in the test circuit. The lower trace B is due to the insertion of the inductor in series between signal source and receiver.

choke-under-test

PSG 1000

SSA-1000A

50 Ω

50 Ω

Linear Frequency (1 Div = 100.00kHz)
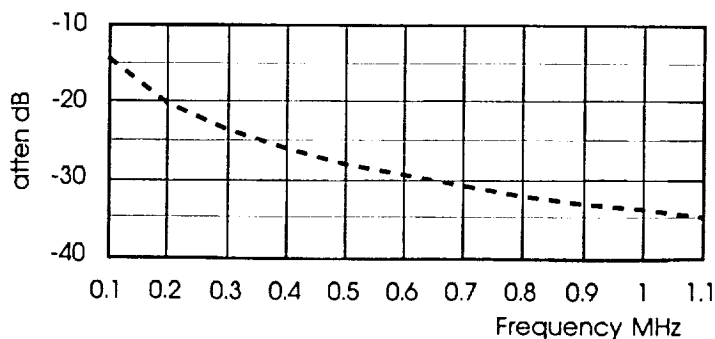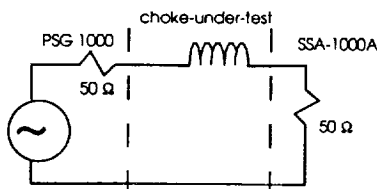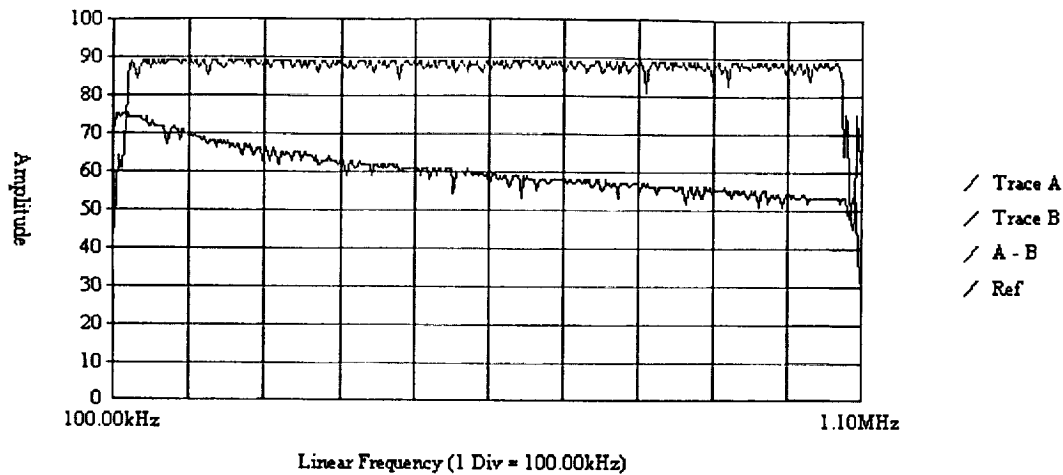
The table below shows the response of the filter to CS06-like spikes. Filter F failed from a single 5 or 10 μs at about 450 V spike applied to the inductor end, when biased at 120 Vdc. It could take the SSP 30237 10 μs 240 Volt pike at 10 pps indefinitely. It failed within two minutes of 350 V 10 μs spike 10 pps applications on the capacitor end. When spike duration was reduced from 10 μs to 5 μs, damage threshold at 10 pps injection increased from 350 to 420 Volts (it took 2 minutes to fail at the same rep rate at 420 Volts).

spike duration μs	single pulse failure point Volts	10 pps, 2 minute failure point Volts
5	464	420
10	450	350
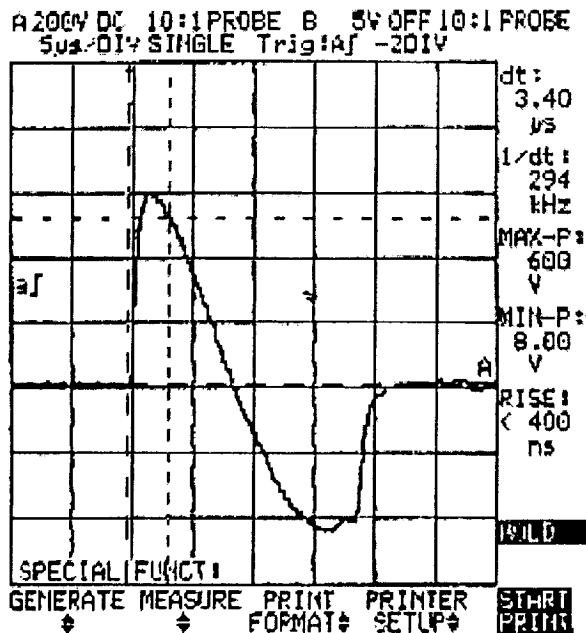
Data 2-1: 600 V spike across 5 Ω
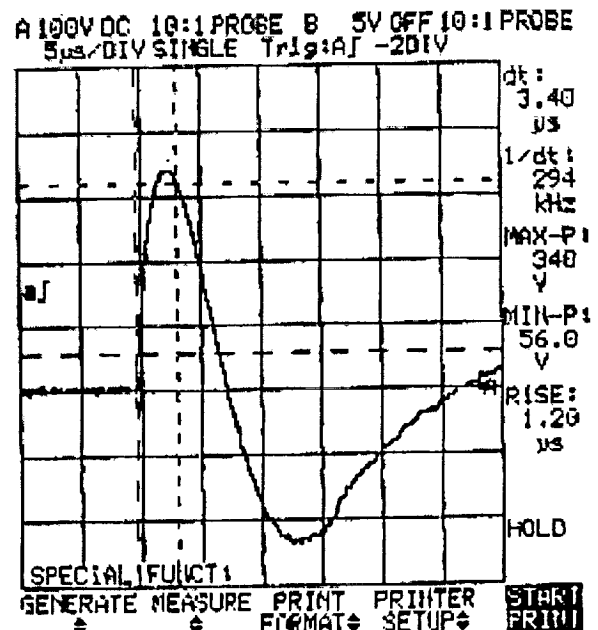
Data 2-2: Data 2-1 generator setting develops this spike across 1 Ω
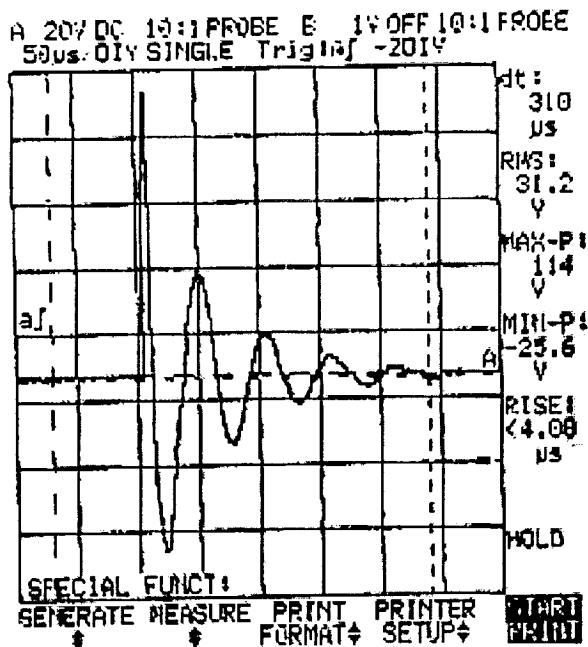
Data 2-3: Data 2-1 generator setting develops this spike across capacitor E
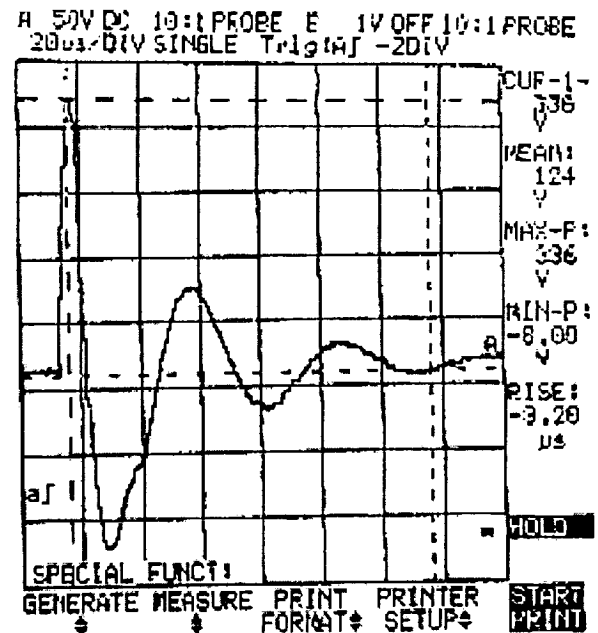
Data 2-4: Data 2-1 generator setting develops this spike across capacitor B
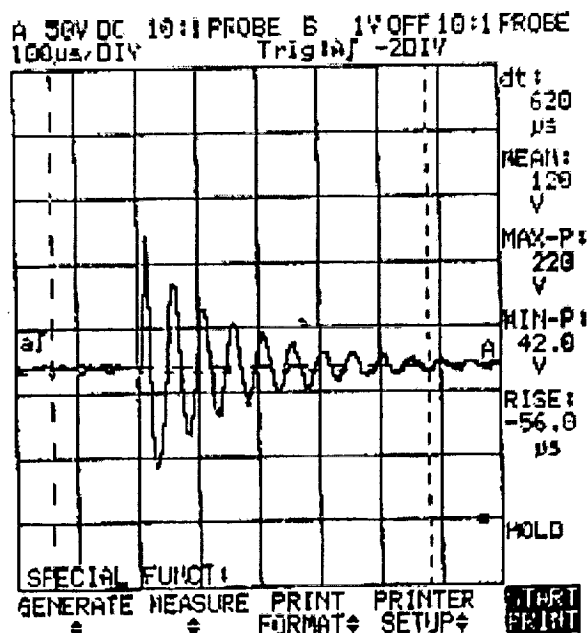
Data 2-5: Data 2-1 generator setting develops this spike across capacitor C
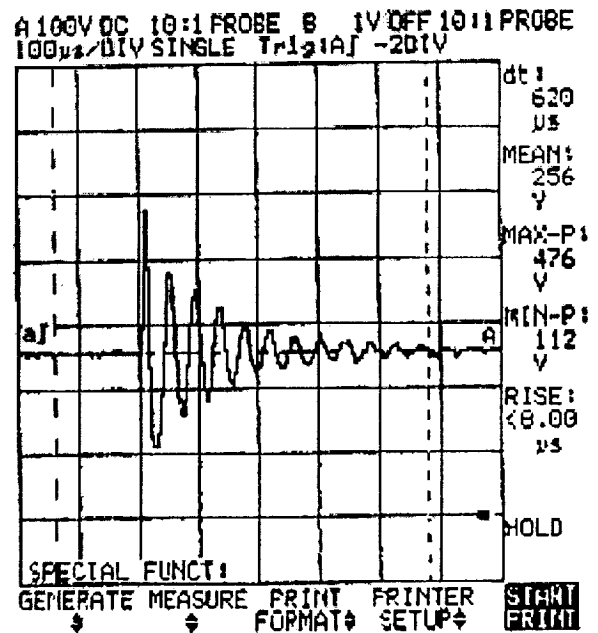
Data 2-6: Data 2-1 generator setting develops this spike across capacitor D
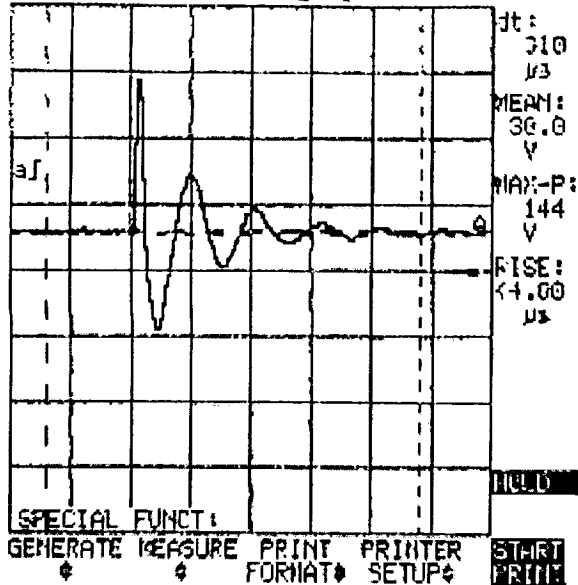
Data 2-7: Maximum generator setting develops this spike across capacitor A at 10 pps
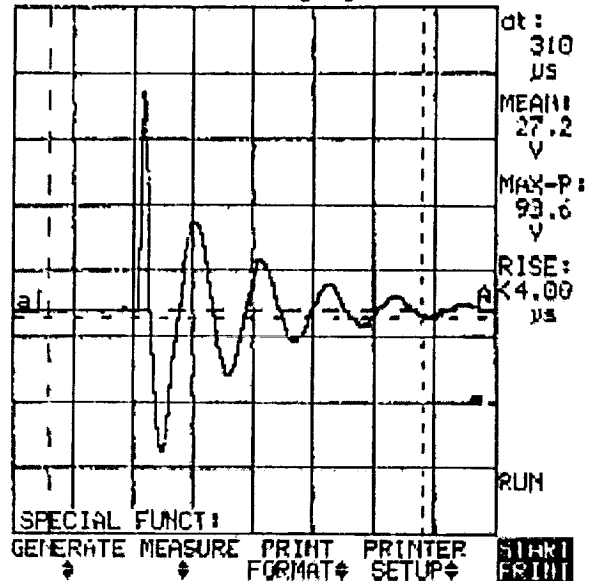
Data 2-8: Maximum generator setting develops this spike across capacitor E at 10 pps
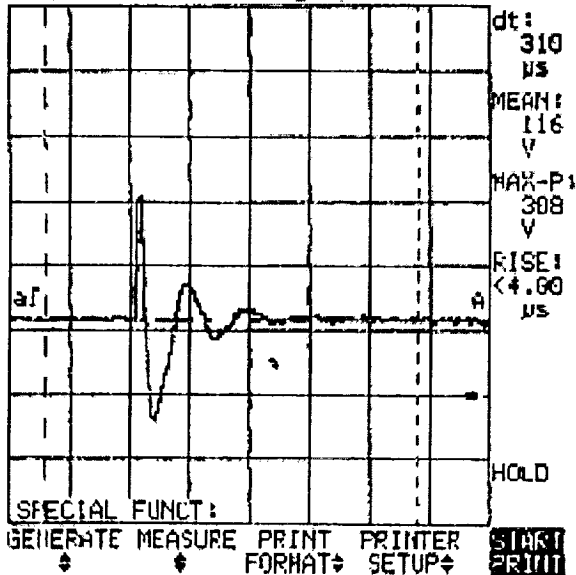
Data 2-9: Maximum generator setting develops this spike across capacitor B at 10 pps
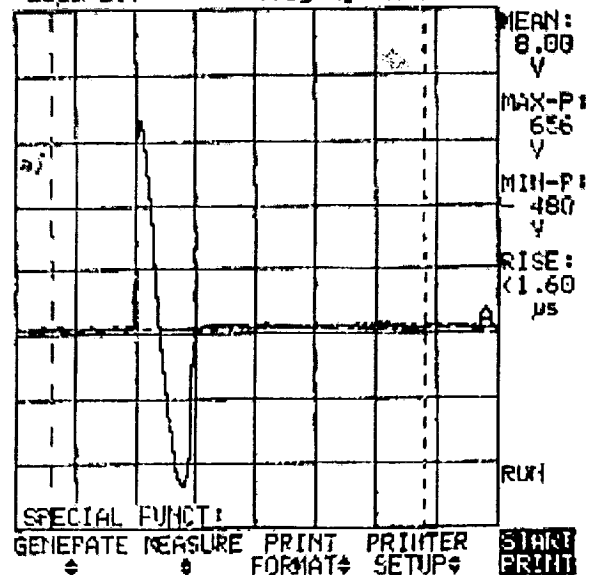
Data 2-10: Maximum generator setting develops 650 V spike across 5 Ω at 10 pps
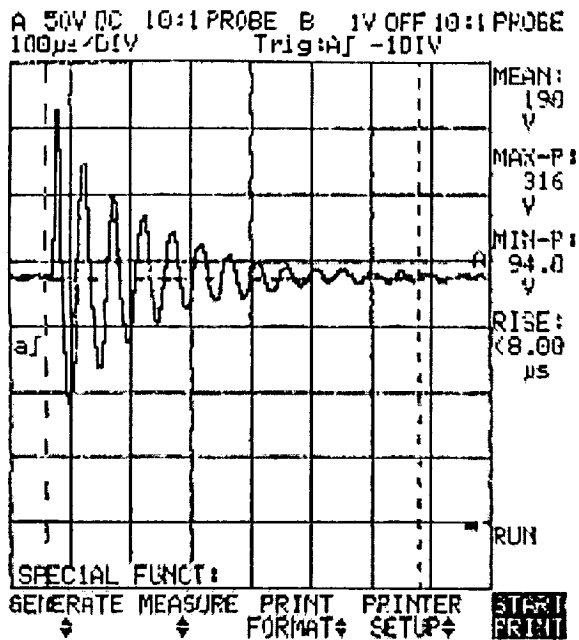
Data 2-11: Data 2-10 setting delivers this spike across capacitor C at 10 pps
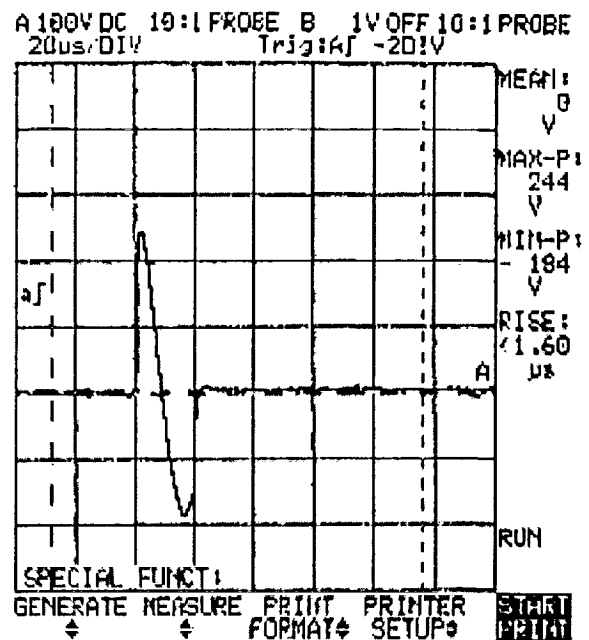
Data 2-12: Model 8282-1 generator set to develop 240 spike across 5 Ω at 10 pps
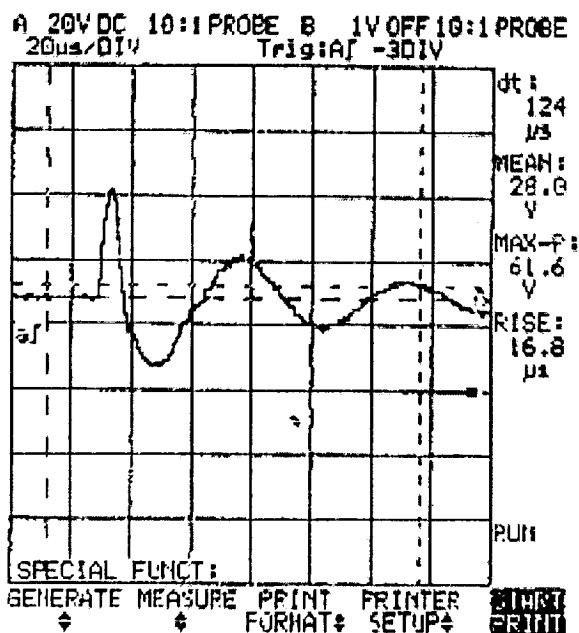
Data 2-13: Data 2-12 setting delivers this spike across capacitor E at 10 pps
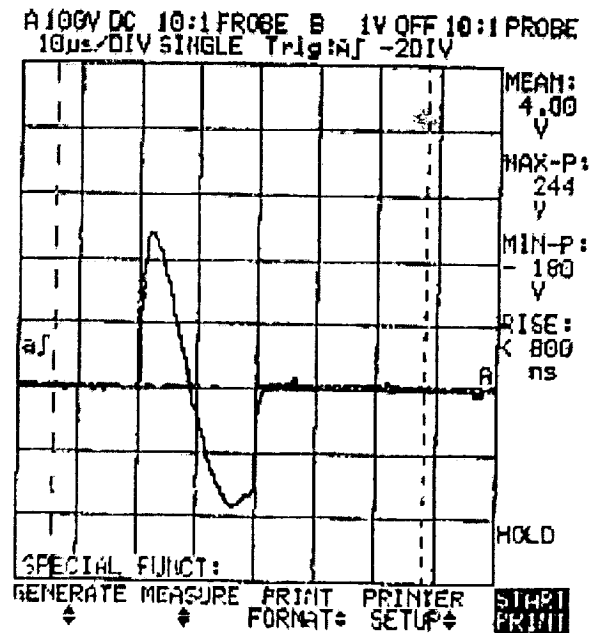
Data 2-14: Model 8282-1 generates a 240 Volt spike (SSP 30237 CS06) into 5 Ω
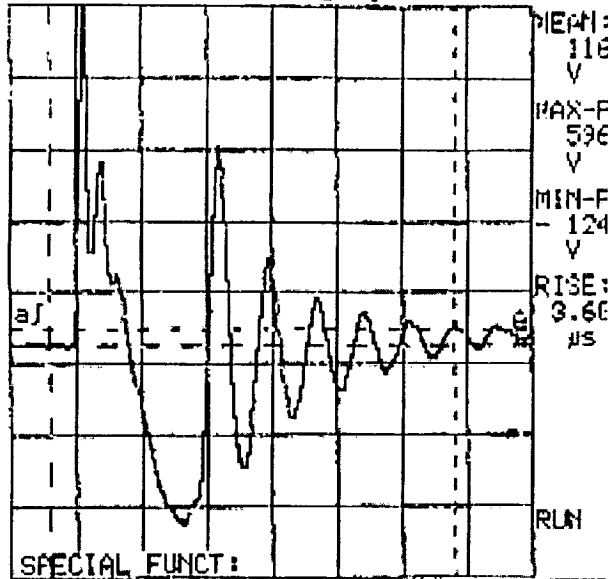
Data 2-15: Filter F response to Data 2-14 spike injected into capacitor side
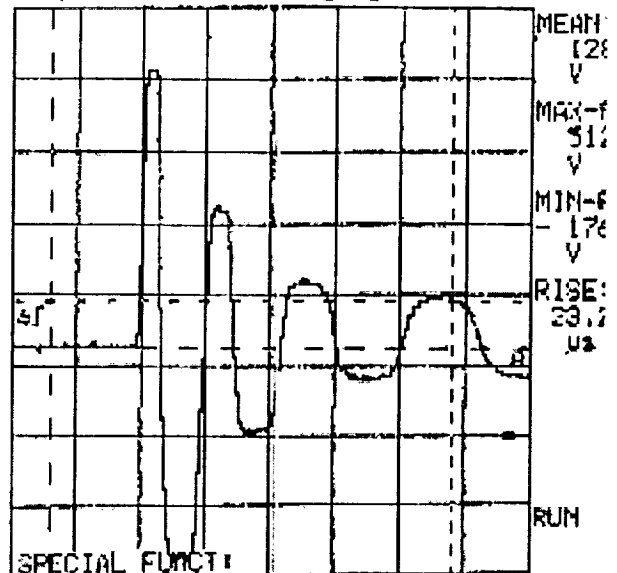
Data 2-16: Filter F response to Data 2-14 spike injected into inductor side (measured across capacitor

Filter F provides the best example of how correctly defining a switching transient provides design relief. Data 1-7 is filter F response to a 50 Ω spike of total (spike plus line potential) 540 Volts (Data 1-4). The applied spike measured 420 Volts (540 - 120 V) open circuit, and would have measured 210 Volts into 50 Ω. Spike amplitude in Data 1-7 is only 116 Volts (236 V - 120 V). Filter capacitor succeeds in loading the transient potential sufficiently that no damage is done. Contrast this filter efficiency with what happens when a Model 8282-1 spike is applied to the same filter F, as shown in Figure 3. Data 2-14 shows a 240 spike (from SSP 30237 CS06) developed across 5 Ω. Data 2-15 shows the same spike applied to the capacitor side of filter F.

The peak potential has increased from that shown in Data 2-14 because the capacitor is a higher impedance than 5 Ω. If the filter is turned around so that the inductor bears the brunt of the spike, the potential across the capacitor is shown in Data 2-16. Spike potential is reduced from that measured when injected directly into the capacitor, but it still exceeds the potential the Model 8282-1 can deliver into 5 Ω. The inductor is incapable of significantly filtering the spike.
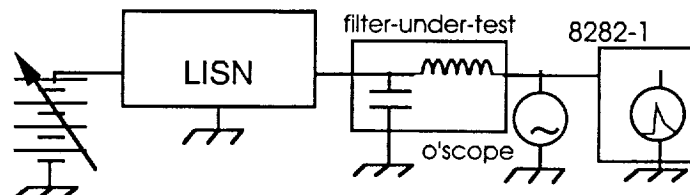
Figure 3: Test set up of CS06-like parallel spike injection for single filter F. (Either cap side or inductor side face the spike source.)

However, the test set-up of Figure 3 harkens back to the days when a MIL-F-15733 type filter was installed in just such a line-to-ground configuration because power current was returned

through metallic platform structure. Nowadays it is much more common to return current on a dedicated wire, at least until return current exits the equipment enclosure. The test set-up of Figure 4 is a better model of modern power bus and filter topology.
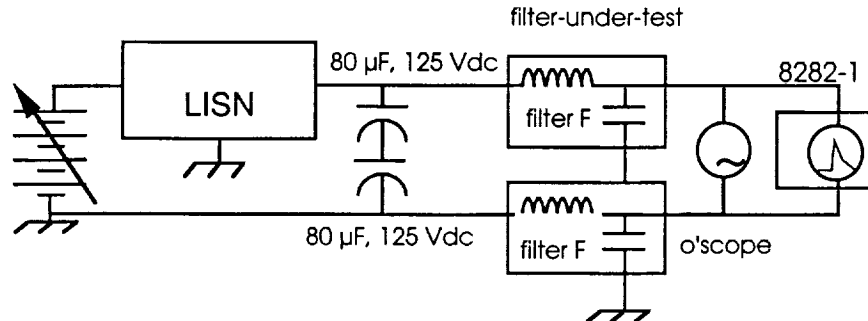
Figure 4:　　　Test set up of CS06-like parallel spike injection for two filters F in modern power bus topology.

In Figure 4, the filters F are paralleled by 40 μF of bulk capacitance. This should help to lower the spike potential across capacitors in filter F, but filter F inductors interfere with that function. Data 2-17 shows a 450 Volt spike calibrated across 5 Ω. This is the potential at which a single application destroyed a stand-alone filter F. Data 2-18 shows the spike potential when the setting resulting in Data 2-17 is applied as in Figure 4. For comparison, Data 2-19 shows spike potential between filters F and the bulk capacitors. Almost the entire spike potential is dropped across filters F. However in this test configuration the 450 Volt spike did not affect the filters F, even applied at a rate of 10 pps for several minutes. When the spike potential was increased to 500 Volts (at a rate of 10 pps) it caused filter F capacitor failure in less than one minute.
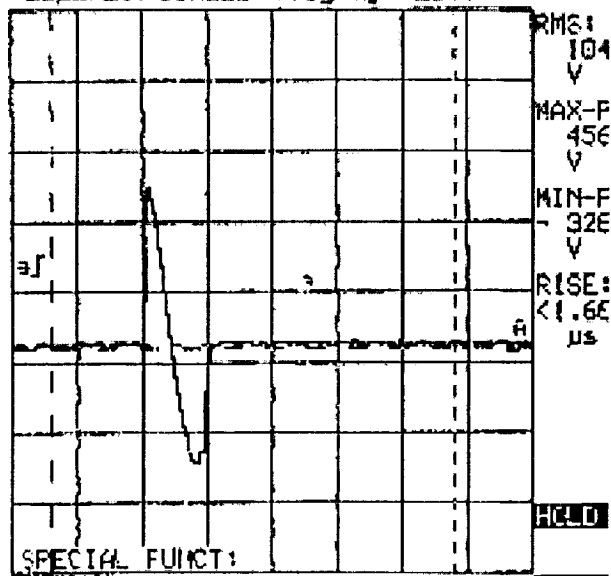
Data 2-17: 450 V spike across 5 Ω
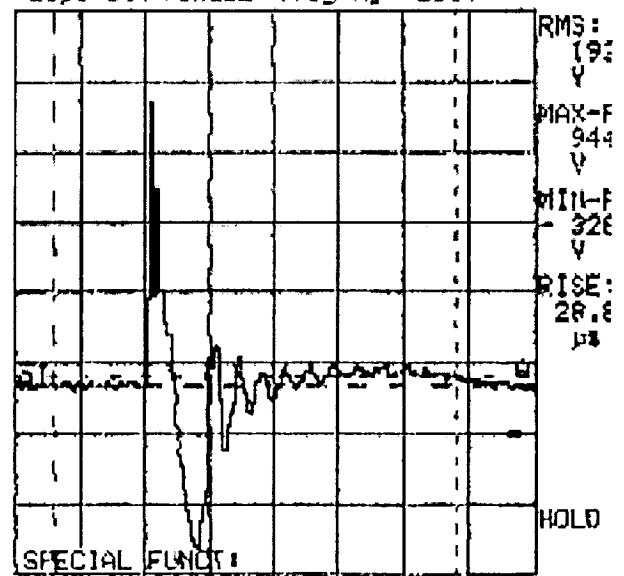
Data 2-18: Data 2-17 generator setting develops this spike across filters F in Fig. 4 configuration
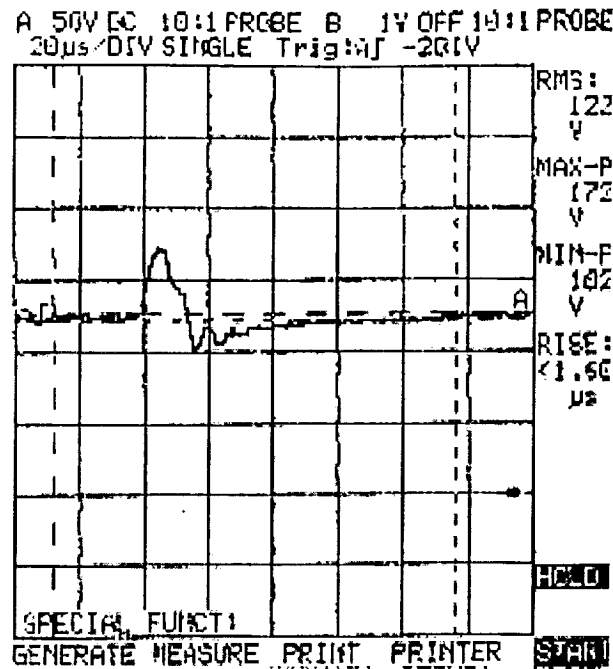
Data 2-19: portion of Data 2-18 spike potential dropped across bulk capacitors

3.2.3 Application of MIL-STD-1399 - Like Positive Transients

The Solar Model 7399-2 Transient Pulse Generator was used in a MIL-STD-462 CS06-like series injection technique (as diagrammed in Figure 5) to inject up to 2000 Volt pulses into the test capacitors. The source impedance of this generator was measured to be 0.25 Ω (for the 17.5 μs waveform). Data 3-1 and 3-2 show 17.5 μs spike waveforms into 10 Ω and 0.5 Ω loads respectively. The equation which gives the spike source resistance is:

$$R_{source/17.5} = \frac{R_1 R_2 (V_1 - V_2)}{V_2 R_1 - V_1 R_2} = \frac{10\Omega \cdot 0.5\Omega (1940V - 1320V)}{1320V \cdot 10\Omega - 1920V \cdot 0.5\Omega} = 0.25 \ \Omega$$

$$R_{source63} = \frac{R_1 R_2 (V_1 - V_2)}{V_2 R_1 - V_1 R_2} = \frac{10 \cdot 0.5 (2460-2000)}{2000 \cdot 10 - 2460 \cdot 0.5} = 0.1225$$

An unloaded source potential of about 2000 Volts may also be deduced from this data. The test set up was identical to CS06 series injection with only the 7399-2 replacing the Model 8282-1. The capacitor under test was placed in an explosion chamber in case it failed catastrophically. Pictures of test set up may be viewed in Appendix A.
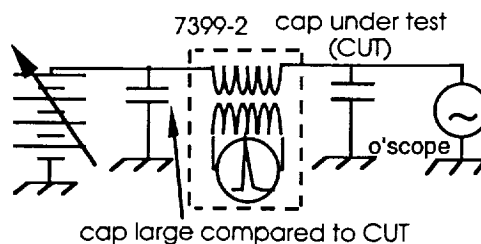
Figure 5:   Test set up of CS06-like series spike injection

3.2.3.1 Test Data

The 1320 V spike of Data 3-2 was injected on to capacitor E. Capacitor E is 300 µF, rated for 30 Vdc. The power source bypass capacitor was 3300 µF in order to force the series injected spike potential to drop mainly across capacitor E. Data 3-3 shows the spike potential as measured across capacitor E. Note that it is very close to half the potential of the same spike source applied to 0.5 Ω. Capacitor E presents a 0.25 Ω load impedance. In turn, this implies a peak current flow of 5.2 kA in capacitor E. The spike potential of data 3-3 was applied for three hours (at two pulses per minute, the maximum rate achievable with the 7399-2) with no failure. At 3:40 into the test, a very large popping sound was heard, the applied spike was very large, and capacitor E now only measured 1.5 µF. It measured 1.5 µF a day later as well. The hot side of the tubular capacitor was blackened from arcing. The ground side has a domed characteristic, as opposed to the healthy capacitor whose flat end cap is that of a cylinder. This is evidence of high pressure developed in the capacitor. A picture in Appendix A shows capacitor E along side a "healthy" capacitor A. Although heating must have occurred in order to generate the pressure, at no time did capacitor E become hot or even warm to the touch, in contrast to the CS06-like spike application, which injected much less current (600 A), but did so 30 to 60 times as often.

A single application of the same spike destroyed capacitor C while biased at 120 Vdc. A picture and description of the damage is shown in Appendix A. Single applications of the 63 µs spike were applied with successively greater amplitudes to capacitor A. Starting at 500 Volts (as calibrated into a 0.5 Ω load) superimposed on 28 Vdc, with 100 Volt increments up to 1 kV, and 200 Volt steps thereafter, it was determined that the single application threshold of damage occurred at 1400 Volts. At this potential, the post-test capacitance decreased to 1 µF or less (nominal was 140 µF, pre-test). In case the step-by-step incremental testing had weakened the capacitor, a fresh capacitor A was also subjected to 1400 Volts, and also failed. Test data 3-6 through 3-15 show samples of calibrated and applied spikes.
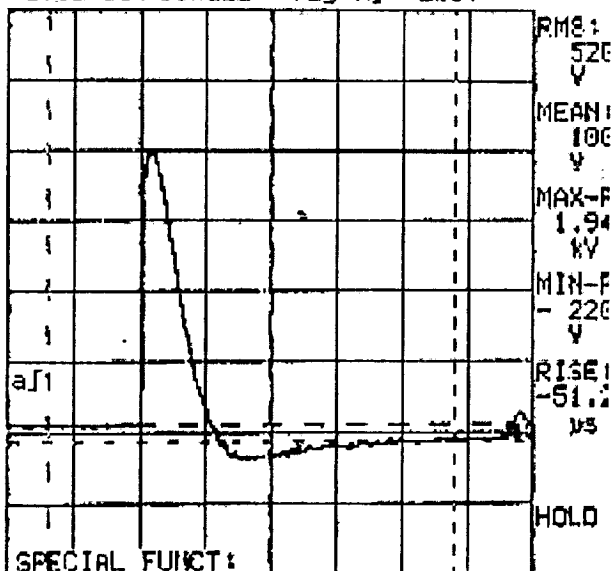
Data 3-1: 1940 V, 17 µs spike across 10 Ω
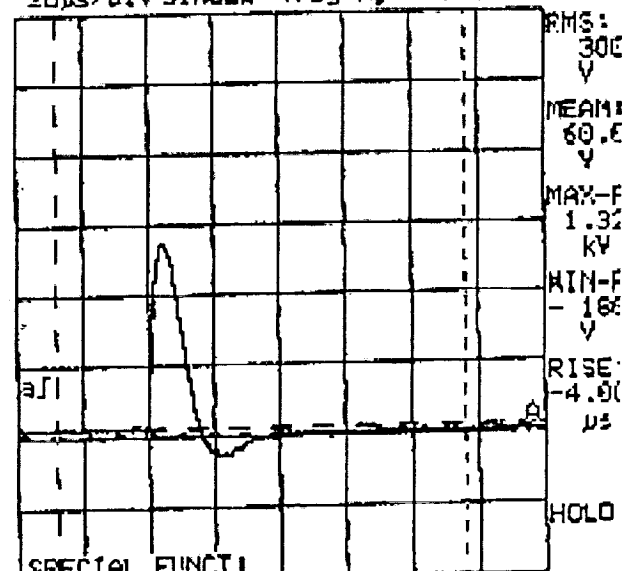
Data 3-2: Data 3-1 generator setting develops this spike across 0.5 Ω

A 500V DC 10:1 PROBE B   1V OFF 10:1 PROBE
20µs/DIV SINGLE Trig:AJ -2DIV

dt:
124
µs

MEAN:
746
V

MAX-F
2.46
kV

RISE:
126
µs

HOLD

SPECIAL FUNCT:
GENERATE MEASURE PRINT PRINTER

Data 3-3: 2460 V, 63 µs spike across 10 Ω

A 500V DC 10:1 PROBE B   1V OFF 10:1 PROBE
20µs/DIV SINGLE Trig:AJ -2DIV

dt:
124
µs

MEAN:
426
V

MAX-F
2.06
kV

RISE:
-16.6
µs

HOLD

SPECIAL FUNCT:
GENERATE MEASURE PRINT PRINTER
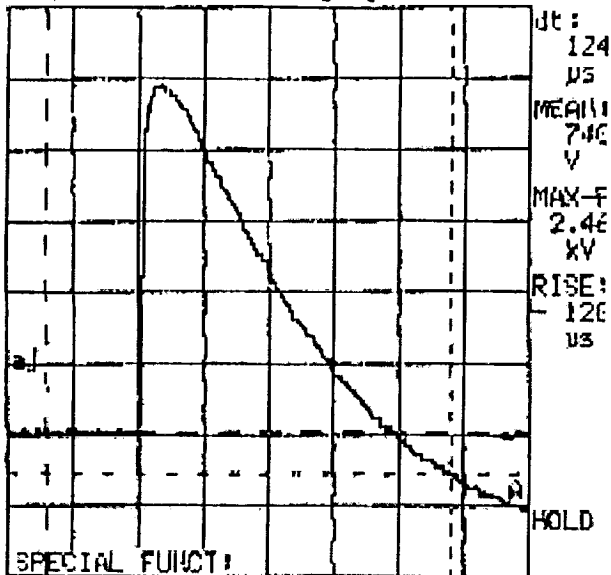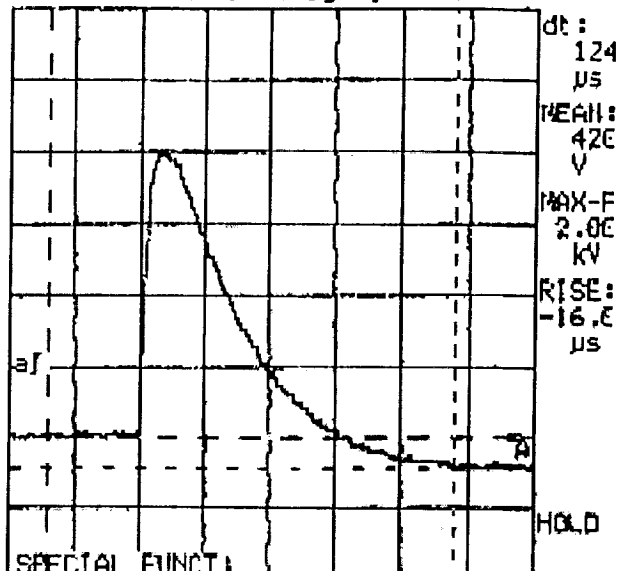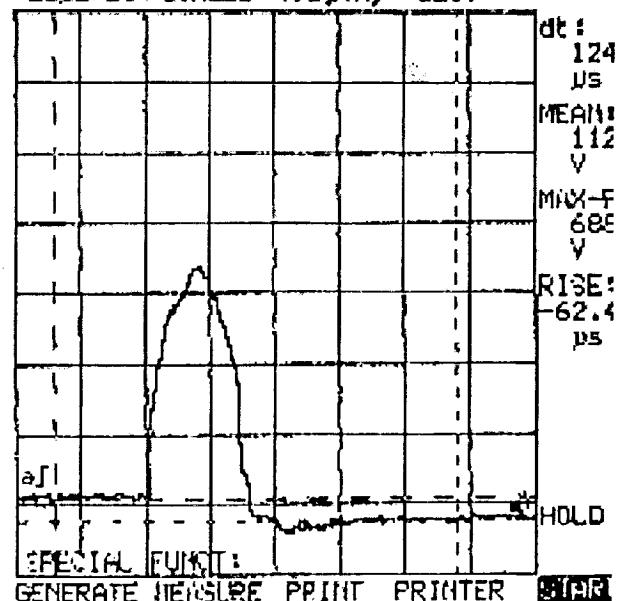
Data 3-4: Data 3-3 generator setting develops this spike across 0.5 Ω

A 200V DC 10:1 PROBE B   1V OFF 10:1 PROBE
20µs/DIV SINGLE Trig:AJ -2DIV

RMS:
192
V

MEAN:
48.6
V

MAX-F
686
V

MIN-P
-328
V

RISE:
-16.8
µs

HOLD

SPECIAL FUNCT:
GENERATE MEASURE PRINT PRINTER
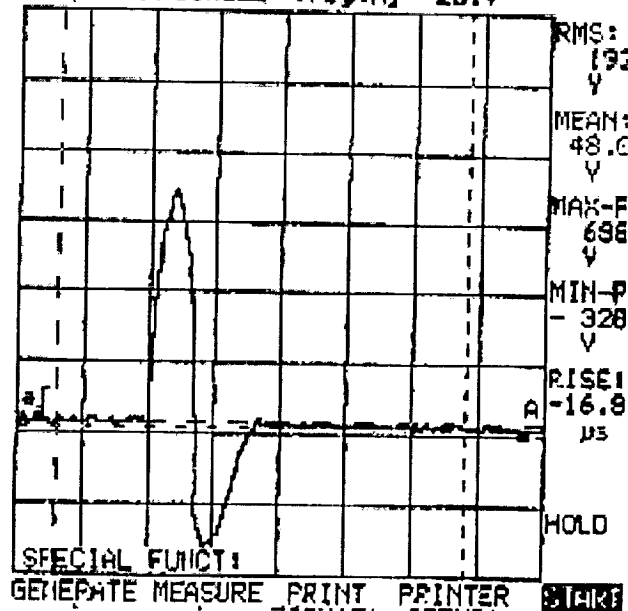
Data 3-5: Data 3-1 generator setting develops this spike across capacitor E, which caused eventual failure
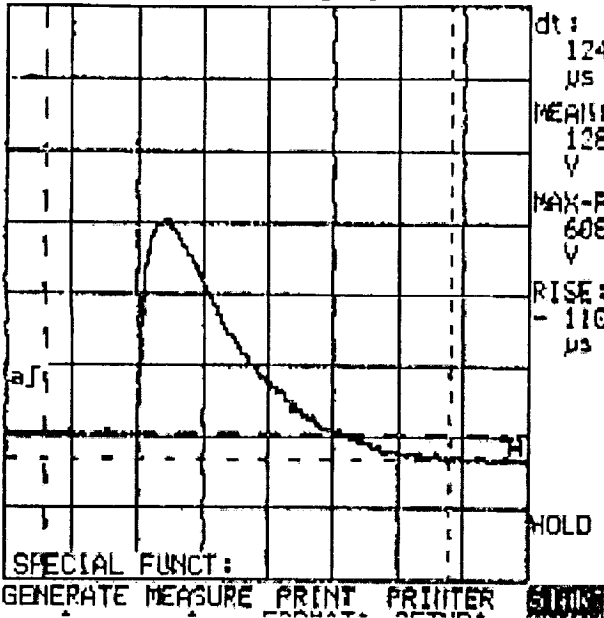
Data 3-6: 600 V 63 μs spike across 0.5 Ω
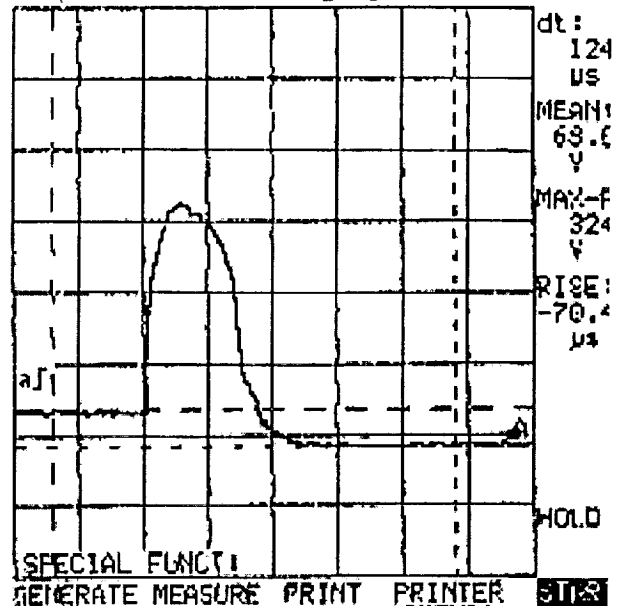
Data 3-7: Data 3-6 generator setting develops this spike across capacitor A
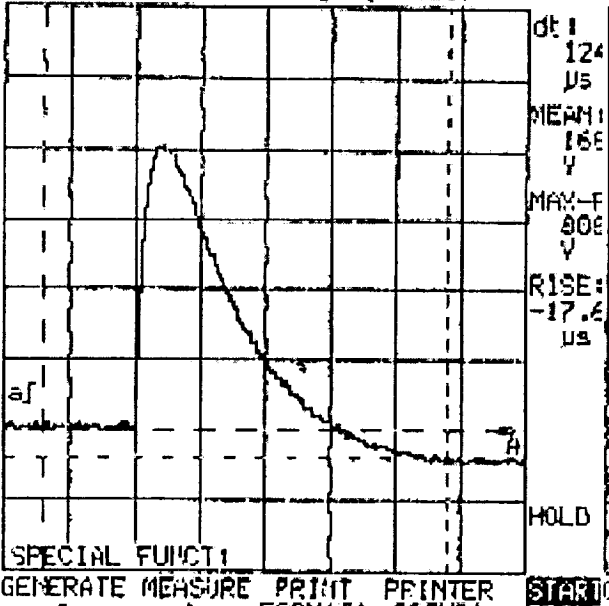
Data 3-8: 800 V 63 μs spike across 0.5 Ω
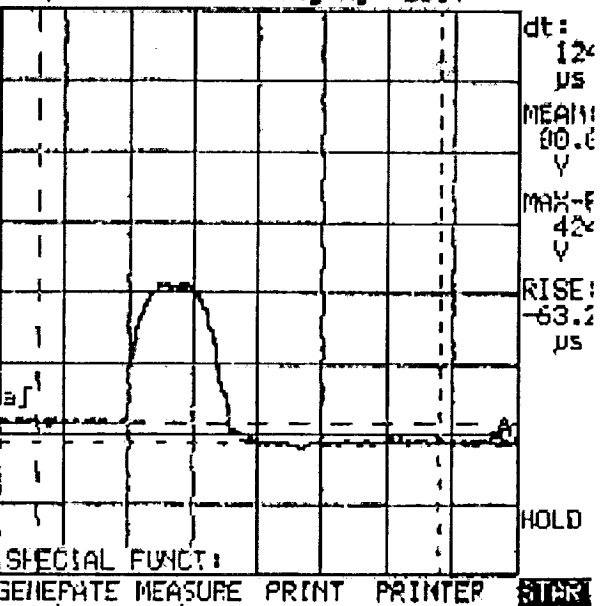
Data 3-9: Data 3-8 generator setting develops this spike across capacitor A
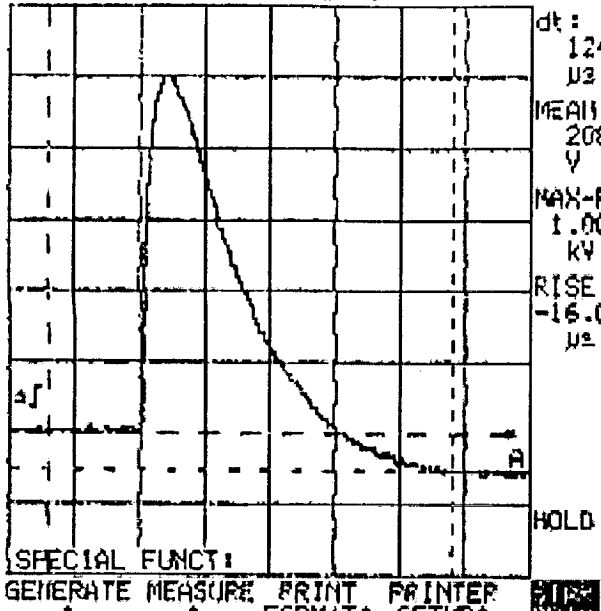
Data 3-10: 1 kV 63 μs spike across 0.5 Ω

Data 3-11: Data 3-10 generator setting develops this spike across capacitor A
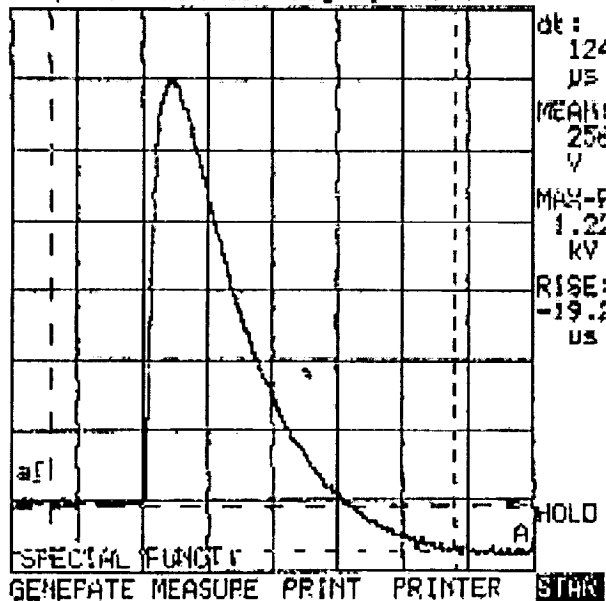
Data 3-12: 1.2 kV 63 μs spike across 0.5 Ω

Data 3-13: Data 3-12 generator setting develps this spike across capacitor A
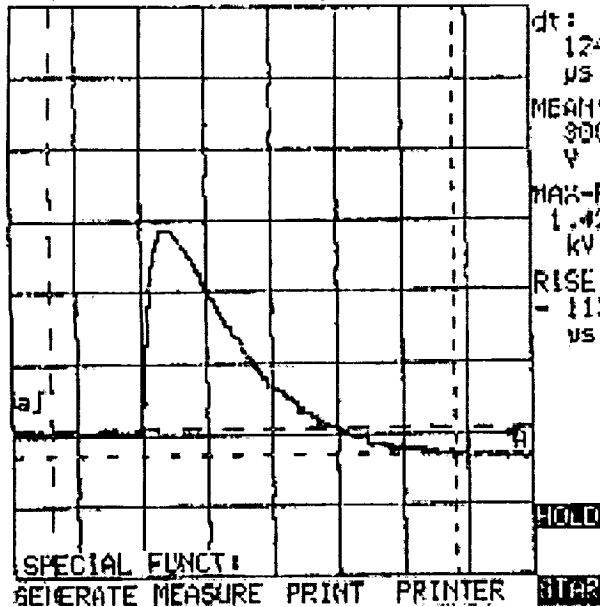
Data 3-14: 1.4 kV 63 µs spike across 0.5 Ω

Data 3-15: Data 3-14 generator setting develops this spike across capacitor A.*

* Note that whereas at lower potentials the capacitor A spike potential was roughly half of the potential applied to 0.5 Ω, here the capacitor potential has risen to about 70% of the 0.5 Ω potential. This was indicative of the onset of capacitor failure. After application of this spike, the pre-test nominal capacitance of 140 µF was reduced to 1 µF.
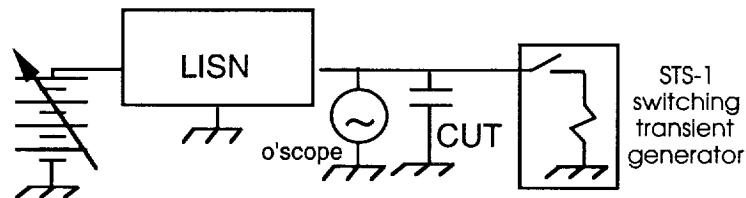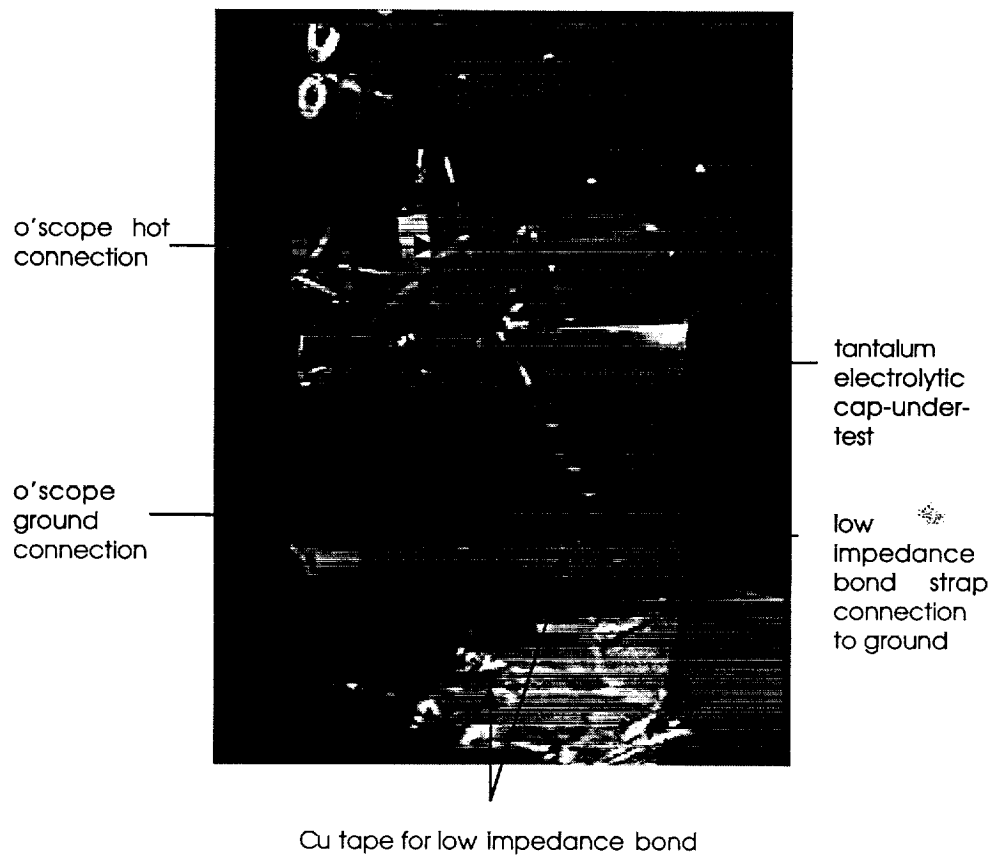
Appendix A
Test Setup Pictures
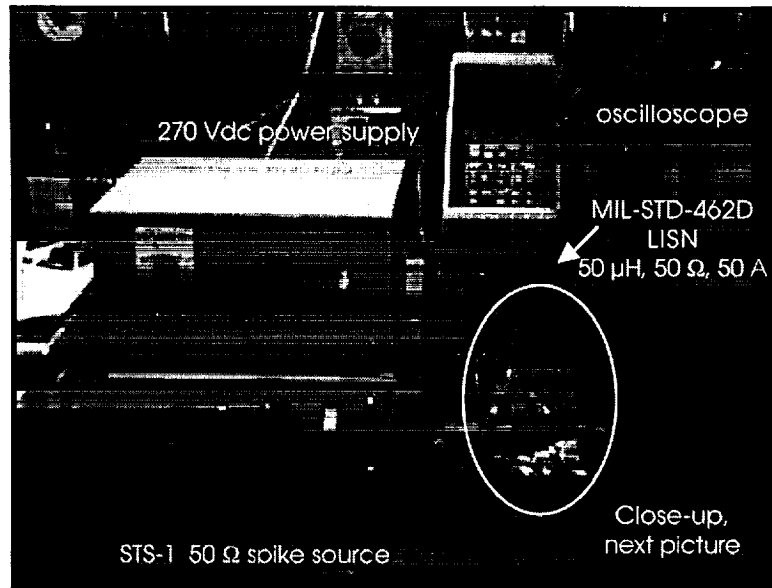
Picture 1:   50 Ω spike source test set up. Capacitor is connected to LISN power output and brass bond strap to minimize potential drop across capacitor leads and connections. The power supply hot output is connected to the back side (power input side) of LISN. A large capacitor also bypasses the LISN power input to ground, to provide local energy storage. Switched current is high in magnitude relative to what the power supply can deliver (also there is inductance/resistance in leads between the supply and LISN). The electrolytic capacitor (on the order of mF) has its high side connected to the LISN power input connector using a solder wick bond strap less than one inch long, and a sheet of thin brass stock from the low side of the capacitor to the ground plane, providing less than 3:1 length-to-width ratio in the ground path.

The picture above is schematically depicted below (Figure 1 from section 3.2.1):

o'scope hot
connection

o'scope
ground
connection

tantalum
electrolytic
cap-under-
test

low
impedance
bond strap
connection
to ground

Cu tape for low impedance bond

Picture 2:   Close up of tantalum capacitor connection to LISN output in 50 Ω spike test set up. Capacitor lead length has been minimized by close connection to LISN port and use of brass bond strap extension of ground plane.

MIL-STD-462D LISN 50 µH, 50
Ω, 50 A (used as power
supply protection filter only)
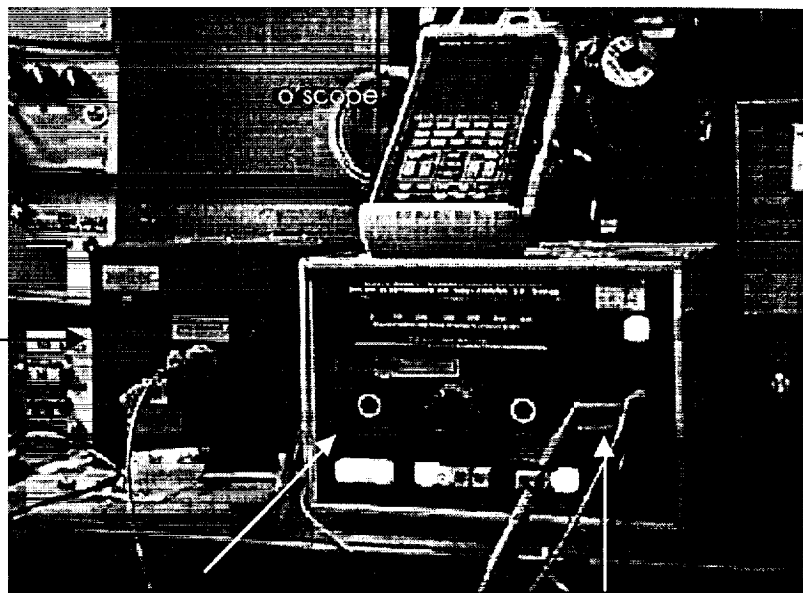
Solar Model 8282-1   ceramic DIP cap-under-test
CS06 spike source

Picture 3:   CS06 parallel injection test set up. The LISN here is a filter protecting the power supply output from the CS06 spike. Note that capacitor under test is connected directly to Model 8282-1 parallel output jacks to minimize lead impedance. Figure 2 (from section 3.2.2) below is a schematic of above test set up:
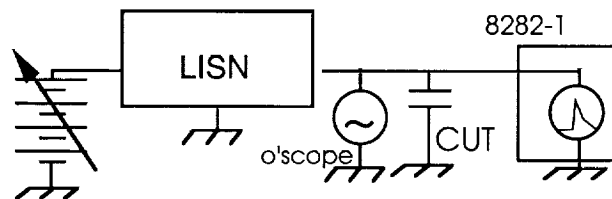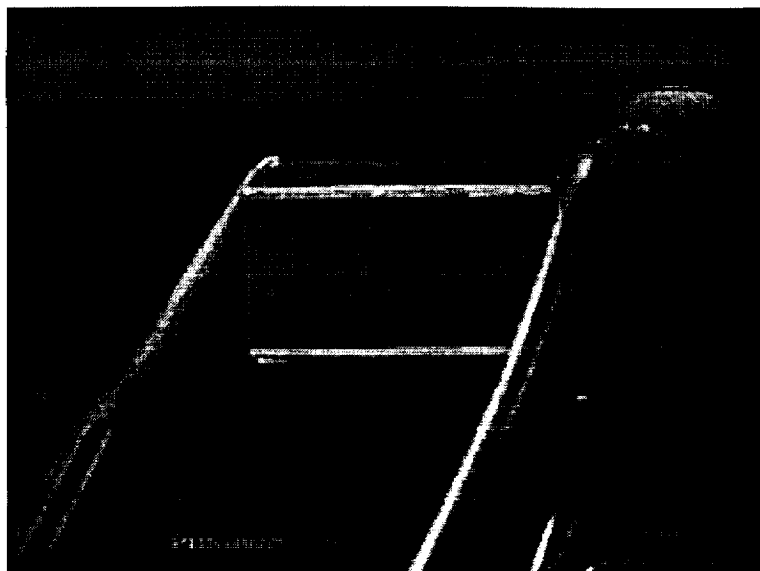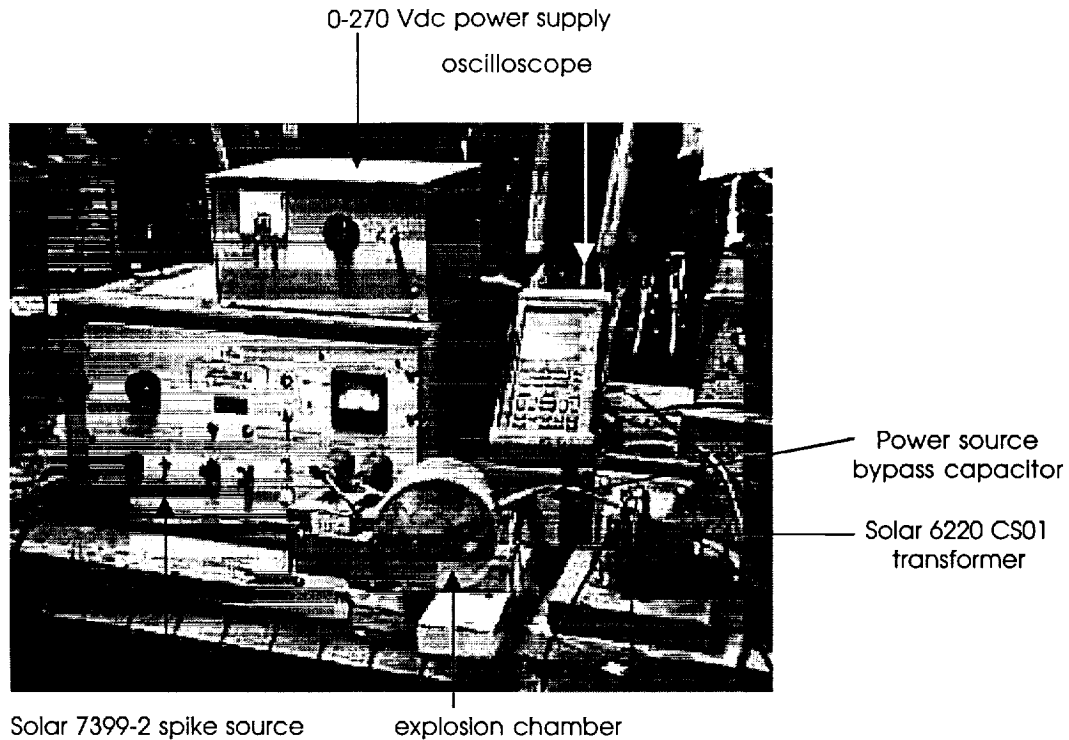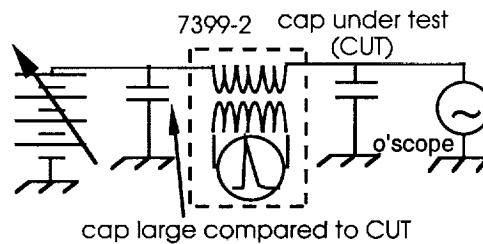
Picture 4:   Close up of ceramic capacitor under CS06 spike parallel injection. Minimized lead length is apparent. Note that ceramic capacitor is configured as a DIP, but all leads on one side are common. These were interwoven with solder wick and EMI tape to provide very short, low impedance leads for connection to either LISN terminal and brass bond strap (50 Ω spike test) or Model 8282-1 parallel output jacks.
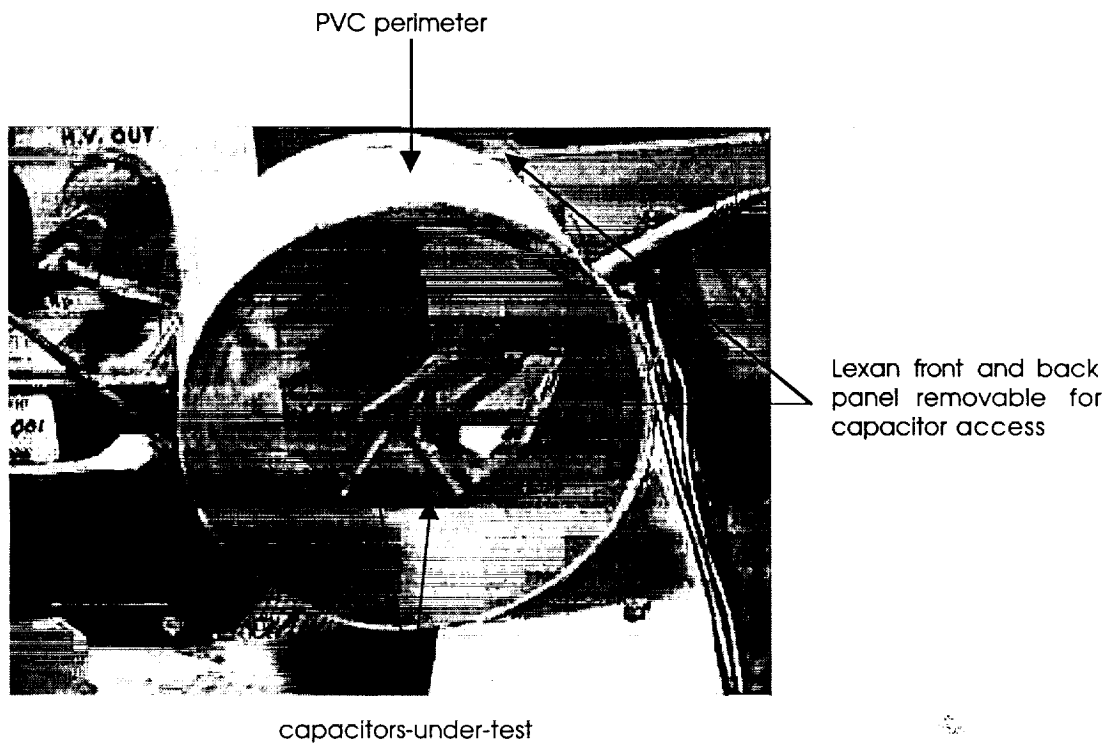
0-270 Vdc power supply

oscilloscope

Power source
bypass capacitor

Solar 6220 CS01
transformer

Solar 7399-2 spike source   explosion chamber

Picture 5:   MIL-STD-1399 series injection test set up.   Explosion chamber holds capacitor under test. Solar transformer is extra protection for power supply, recommended by Solar 7399-2 instruction manual. For clarity, it is not shown in schematic below (Figure 5 of section 3.2.3):
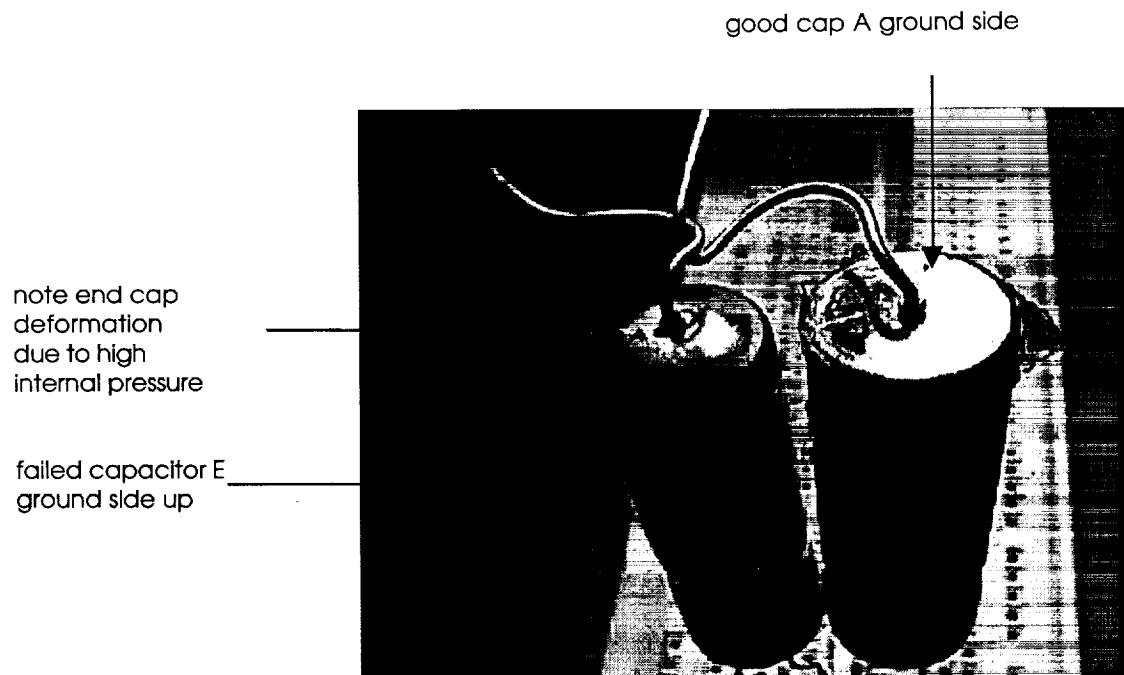
7399-2   cap under test
(CUT)

o'scope

cap large compared to CUT

PVC perimeter

Lexan front and back
panel removable for
capacitor access

capacitors-under-test

Picture 6: Close up of explosion chamber with capacitor B (two series 125 Vdc rated capacitors ganged for Space Station power bus derating) installed.

good cap A ground side

note end cap
deformation
due to high
internal pressure

failed capacitor E
ground side up

Picture 7:   End view comparison of failed capacitor E with good capacitor A (same package). Capacitor E is seen to have undergone explosive compression, which, however, was contained by its case.   Capacitor failed open; its failure would not have directly caused other circuit malfunction, except by its failure to perform its original function.
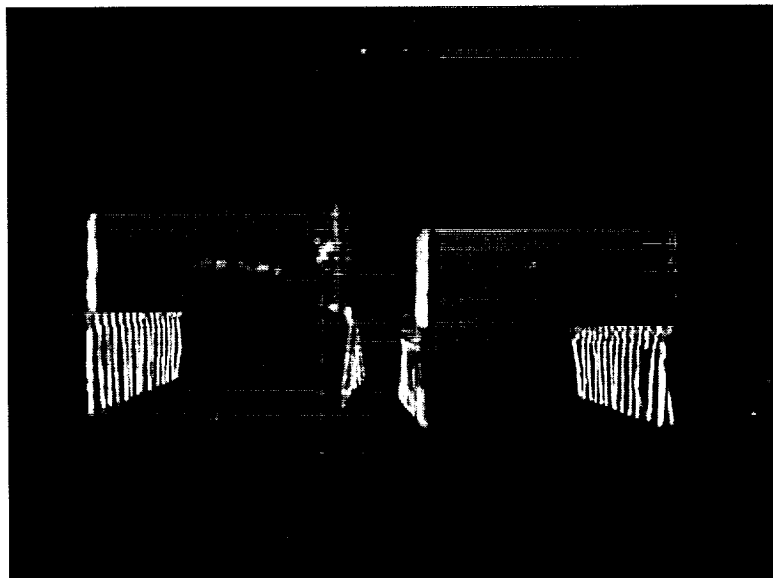
Picture 8:   End view comparison of failed ceramic DIP capacitor C with good capacitor. Capacitor C dielectric has broken into pieces. Capacitor failed short, blowing a 1 Amp fuse in the power supply.