National Aeronautics and Space Administration

Qualification of Emerging Point-of-Load Regulators for Next Generation Power Systems

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Abstract

As demand for high-speed, on-board, digital-processing integrated circuits (ICs) on spacecraft increases (FPGAs and DSPs in particular), the need for the next generation point-of-load (POL) regulator becomes a prominent design issue. Shrinking process nodes have resulted in core rails dropping to values close to 1.0 V, drastically reducing margin to standard switching converters or regulators that power digital ICs. The objectives of this study are to first identify reliability issues or additional space reliability requirements that might not be addressed for commercial application of POL converters; second, to study the performances of existing or emerging POL converters (including linear regulators) within a practical two-stage power distribution architecture; and, finally, to identify points of failure at extreme temperatures (low and high) beyond specifications.

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1.0 INTRODUCTION

Most low-to-medium level power distribution systems in spacecraft use two to three stages of regulation with point-of-load (POL) mounted regulators fed by isolated DC-DC converters. These systems cause multiple sources of power dissipation resulting in an end-to-end efficiency that can be as low as 30%, depending on the commercial parts selected.

There is also a growing demand for high-speed, onboard digital integrated circuits (ICs) on spacecraft, including field-programmable gate arrays (FPGAs), digital signal processors (DSPs) and other application-specific integrated circuits (ASICs) built with aggressively scaled technologies. As shown in Figure 1, increasing reduction in effective device lengths has resulted in core voltage rails dropping to values close to 1 V as opposed to 2.5 V about ten years ago. This drastically reduces margin (ripple, transient response, and efficiency) to standard switching converters or regulators that power digital ICs.

As a result, there is an increasing need for flexible, small footprint, high-performing (i.e., tight regulation and highly efficient) POL regulators. Next-generation power distribution schemes will need new strategies to respond to sub-micron technologies and will require more design flexibility and better fault management. In addition, most space-use DC-DC converters or linear regulators are hybrid converters and, due to the lack of information regarding the process technology, it is often quite difficult to assess their reliability and radiation hardness. Their qualification cost is also often very high. Several NASA missions have had anomalies with hybrid switching converters, in particular related to radiation effects and single-event transient (SET) effects. SET represents a major threat for power systems. Converter transient responses are dependent on load conditions as well as temperature. Ion strikes on a sensitive area of a conventional pulse-width modulated switching converter or a linear regulator can result in an unacceptably large transient pulse of several volts of amplitude and several hundreds of μs at their output. Recently, several stability issues tied to the ESR output capacitor for hybrid linear regulators have been reported. As a result, evaluating the reliability and radiation response for space applications is very critical and not always readily available for manufacturers, since testing under high reliability space conditions is often left by the users.

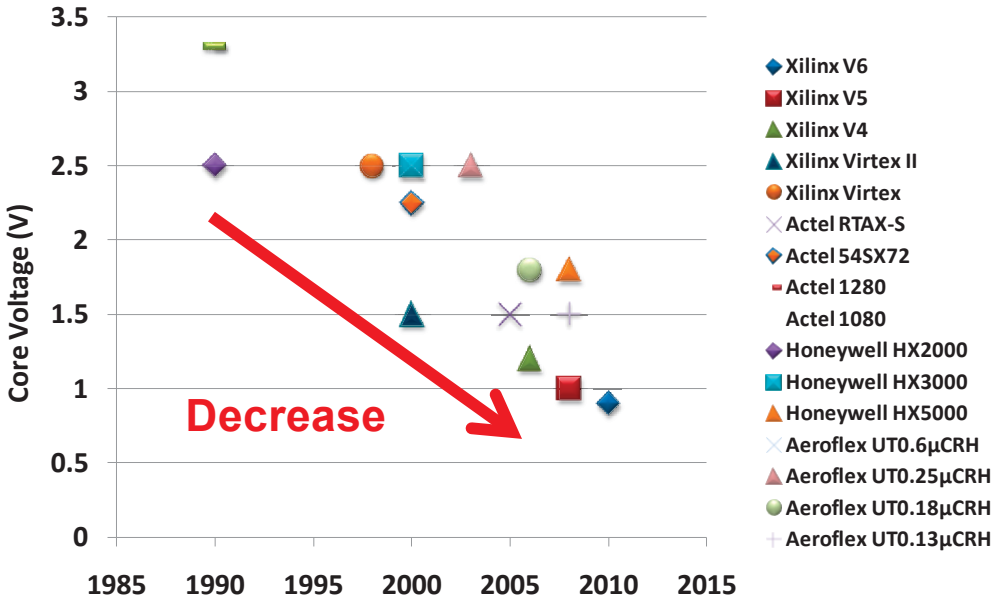

Figure 1. FPGAs and ASICs core voltage roadmap.

Table 1 summarizes the different converters that are considered for this study. It includes both linear dropout (LDO) regulators and point-of-load (POL) switching converters. While switching regulators provides regulation at a higher efficiency, and has less known radiation issues, linear regulators are extensively used on many programs, including Mars Science Landers (MSL). Indeed, the performance of LDO regulators is acceptable for low loads and remains a good choice in applications where the extra circuitry of buck regulators would make them less effective for small load.

In this report, we present experimental results from several evaluations performed on several emerging POL and linear regulators. Those assessments include:

1. Characterizing POL devices at low temperature (beyond specifications). Results from FY10 indicated the MSK5810RH failed to start up and perform basic functions at or below -25 C. MSK did provide another evaluation board with some design modifications so that another evaluation at low temperature could be performed. The Intersil ISL7001RH was also tested at low temperature.
2. Evaluating the stability of linear regulators with respect to their equivalent series resistance (ESR) recommendations.
3. An evaluation of the behavior of emerging POLs (Crane MFP0507S, Peregrine P9915X, and Intersil ISL7001RH) implemented within a two-stage power distribution architecture. Results about dynamic loading and end-to-end efficiency are presented. It should be noted that companies such as Aeroflex, 3D plus, BAE, and Texas Instruments are currently developing POL devices, and contacts have been made to get devices for evaluation in FY12.

Table 1. List of POL regulators that are currently available for evaluation.

Part Number	Manufacturer	Assurance level	Device type	Input Voltage	Output Voltage	Output Current
MSK5920-2.5RH	MS Kennedy	Radhard	LVDO	2.9 to 6.5 V	2.5 V	3 A
MSK5900RH	MS Kennedy	Radhard	LVDO	2.9 to 7.5 V	Vdo = 0.3 V	4 A
TPS79133	Texas Instruments	COTS	LVDO	-3 to 6 V	3.3 V	0.1 A
ISL70001SRH	Intersil	Radhard	Buck regulator	3V to 5.5V	Adjustable down to 0.8 V	6 A
MSK5810RH	MS Kennedy	Radhard	LVDO	2 - 7.5 V	Adjustable down to 1.5V	5 A
MSK5059RH	MS Kennedy	Radhard	Buck regulator	16 V	Adjustable down to 1.8 V	4.5 A
PE9915X	Peregrine	Radhard	Buck regulator	5 V	3.3 V and 1.8 V	10 A (3.3 V) 2 A (1.8 V), 6A (2.5)
MFP0507S	Interpoint	Radhard	DC/DC converter	6 V	3.3 V and 0.8 V	7 A (3.3 V) 5 A (0.8 V)
TPS7A4901	Texas Instruments	COTS	LVDO	3 to 36 V	1.2 V	0.15 A
SBB503R3S	International Rectifier	Radhard	DC/DC converter	4.5 to 5.5 V	3.3 V	9.1 A

2.0 EQUIPMENT USED

The following is a list of calibrated equipment used for those evaluations. It should be noted that parameters evaluated such as turn-on, transient step load changes, efficiency, stability, etc., were performed following the same testing procedure described in the FY10 report.

- HP 6060B 3-60V and 0-60A-300W electronic load(s)
- HP 6654A DC power supply
- Temperature controller (data acquisition switch unit) Agilent 34970A
- FLUKE 77 Series II multi-meter (only for monitoring)
- Switch (mercury) and small power supplies as needed for switch (only for turn-on tests)
- Oscilloscope: Tektronix TDS 3014B (for startup, synchronization, and load transient response tests)
- Precision resistors (as needed)
- Heat sinks and thermocouple (to regulate and monitor temperature)
- Thermal chamber to perform measurements at -55°C and at 125°C
- Current probe: Tektronix (AM 503 current probe amplifier)

3.0 RESULTS AND DISCUSSION

3.1 Equivalent Series Resistance (ESR) Evaluation on Linear Regulators' Instabilities

3.1.1 Theory

It is well known that the output capacitor of a linear regulator can make it oscillate if the capacitor is not correctly selected. Indeed, every real capacitor contains unwanted parasitic elements that degrade its electrical performance. The most important elements are the Equivalent Series Resistance (ESR) and the Effective Series Inductance (ESL). While the ESL tends to limit the capacitor effectiveness at high frequencies, the ESR is the primary cause of regulator loop instabilities. The loop response of a typical regulator is shown in Figure 2. The most important point is that for a stable loop, the gain must cross below 0 dB before the phase angle reaches 180°. A phase angle of 180° means that the signal being fed back around the loop is actually positive feedback and will cause oscillations to occur. In a linear regulator, the output capacitor is required to force the gain to roll off fast enough to meet the stability requirements. If the ESR value is not adequately selected, the "zero frequency" can get low enough to cause the instability. Typically, manufacturers provide a range of values to ensure stabilities of their devices.

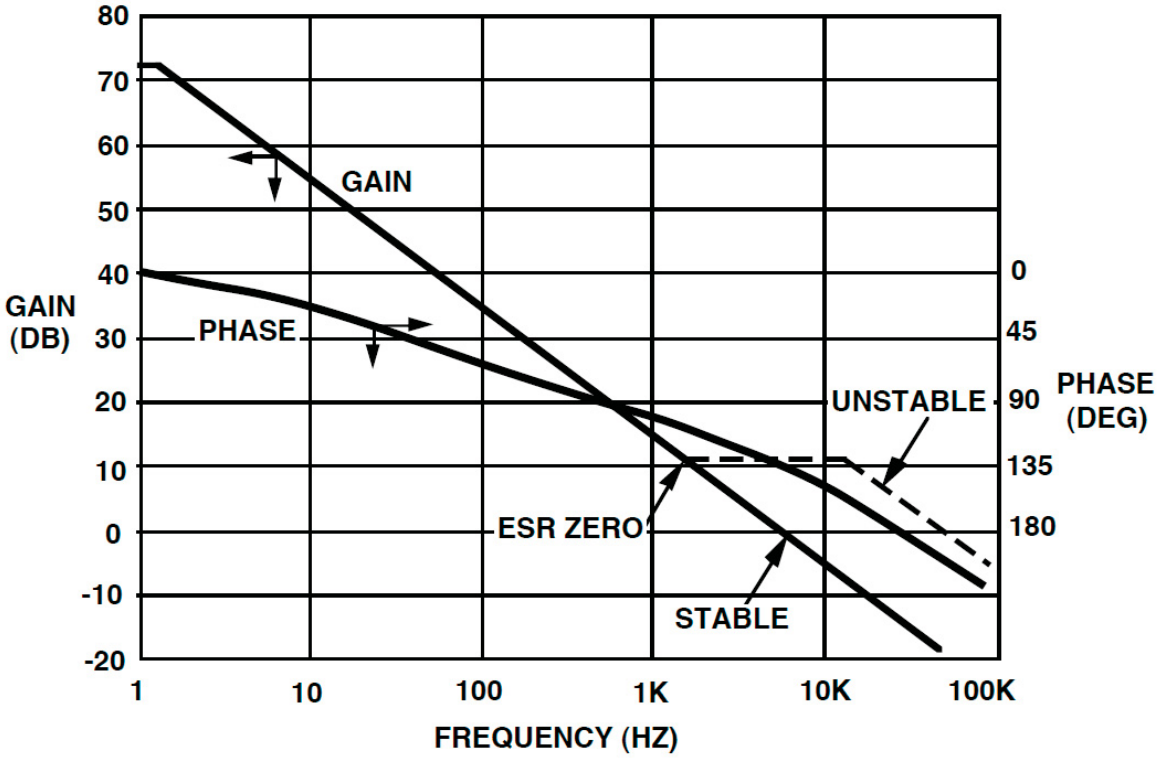

Figure 2. Example of loop gain plot for a regulator.

3.1.2 Evaluation of the MSK5920 with Respect to ESR

The MSK5920RH part is an ultra-Low Dropout (LDO) positive linear regulator. As shown above, LDO regulators (also called single PNP regulator) rely on the ESR of the output filter capacitor to ensure stability. The LDO regulator output has high output impedance that results in the RC load behaving as a dominant pole to the frequency loop. To obtain stable operation, it is essential to obtain an output capacitor with the ESR value within the determined range provided by the manufacturer and to pay close

attention to the layout to minimize unwanted parasitic elements. A common practice to evaluate the stability of a converter is to perform a turn-on test. This is particularly necessary when standard loop gain and phase measurements are not accessible within the devices. Figure 3 illustrates two extreme cases: one when the regulator is stable after a turn-on test and one that is unstable, meaning that the LDO output exhibits some unacceptable oscillation (400 mV Pk-Pk) due to the wrong ESR capacitor value used.

For the MSK5920, M.S. Kennedy made recommendations for output capacitor with selected ESR. Values are summarized in Table 2. In this table, MSK did revise their recommendations for output capacitor selection. Revision O recommended using a 220 uF tantalum output capacitor, while in revision P this recommendation was changed to four low ESR 220 uF capacitors, specifically of the type CWR29FB227 from AVX, screened to an ESR of 57 mOhm maximum. The change in recommendation was initiated based on stability analysis performed by one of their customers. (Note that while the analysis was performed for the MSK5820, this device can be considered identical in electrical performance to the MSK5920, the only difference being in the passivation of the internal IC.) This change has been a concern for most NASA programs because these modifications could lead to instabilities in their design.

For these reasons, part of the work was to evaluate the MSK5920 stability with respect to the rev. H/O and rev. P recommendations. The stability was investigated with turn-on/turn-off tests. For this purpose, the circuit's boards were carefully designed to reduce parasitic elements, and each capacitor was serialized and its ESR recorded according to the MIL-PRF-55365 standard. Table 3 gives a summary of the parts available, and Figures 4 and 5 show images of the 1.5 and 2.5 V versions of the MSK5920.

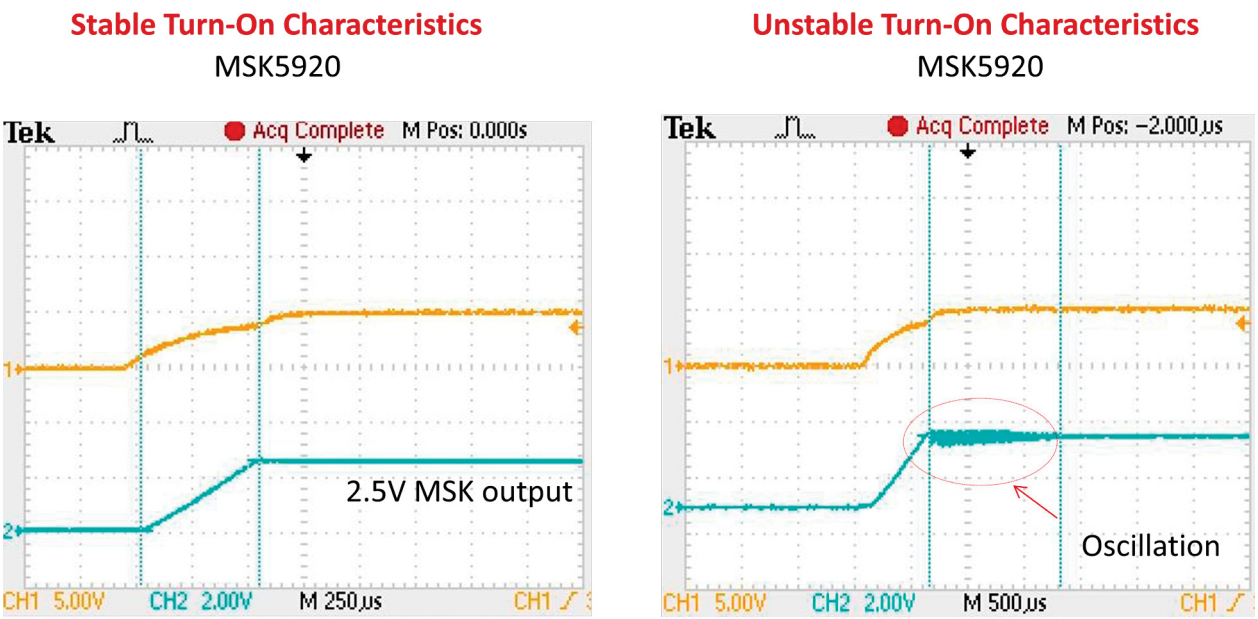

Figure 3. Illustration of a stable and unstable turn-on test for the MSK5920. For this particular case, a value 220 uF capacitor with an ESR > 100 mOhm was used. The peak-to-peak amplitude of the oscillation was over 200 mV.

Table 2. MSK output capacitor/ESR recommendations for stabilities.

Rev.	Capacitor Recommendation	ESR Recommendation	Comments
H	One 220 uF surface mount tantalum	0.1 to 1.0 Ohm	CWR19, 10V, meets this recommendation
O	One 220 uF surface mount tantalum	None	
P	Four 220 uF surface mount tantalum CWR29FB227 (AVX p/n TAZH227K010L)	< 57 mOhm	CWR29 must be screened to meet lower ESR

Table 3. MSK parts tested.

Qty	Generic Number	Procurement P/N	D/C	MFR	Package
1 ea.	MSK5920-1.5 MSK5920-2.5	MSK5920-1.5 MSK5920-2.5	0635 0703	MSK	5 pin metal FP

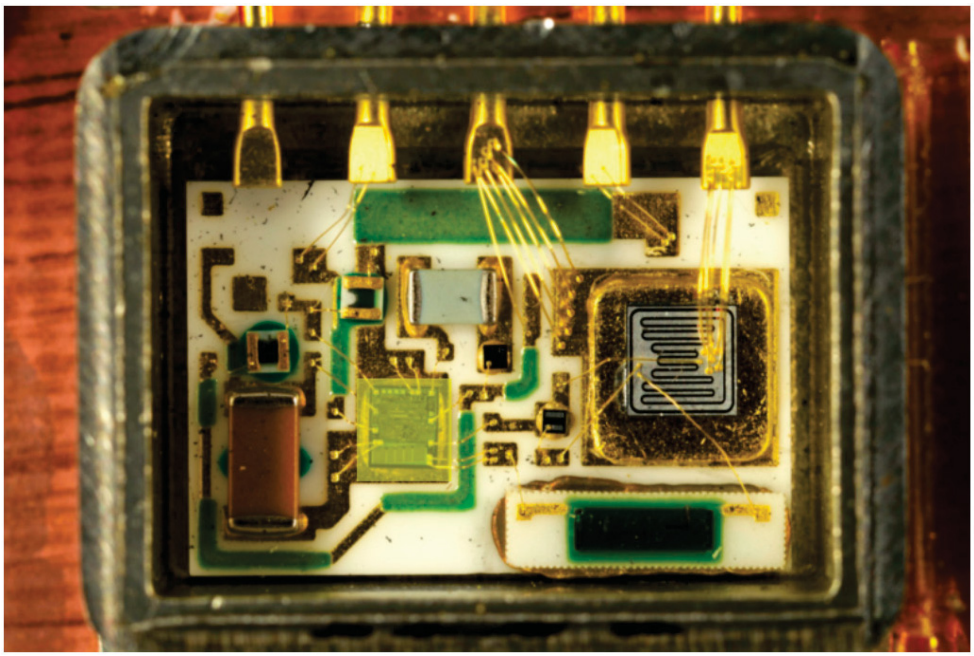

Figure 4. Photograph of the 2.5V MSK5920 LDO. Mainly two dies are incorporated: the RH1573 and the large PNP bipolar transistor.

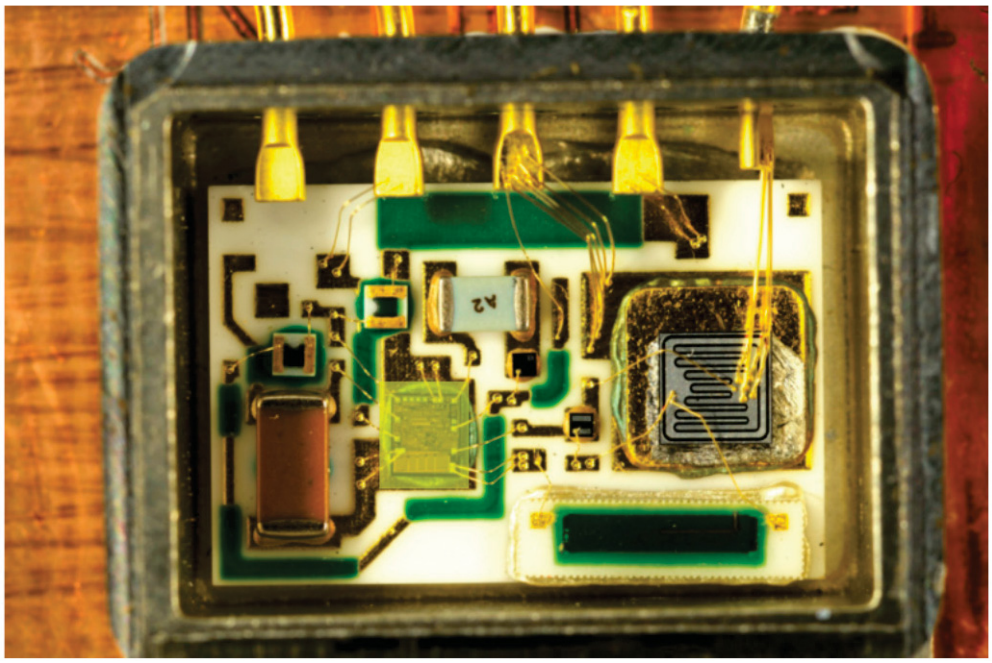

Figure 5. Photograph of the 1.5V MSK5920 LDO. Mainly two dies are incorporated: the RH1573 and the large PNP bipolar transistor.

Capacitors were located as close to the device as possible. ESR of tantalum capacitors was measured and recorded prior to assembly. All components were soldered directly to the board. Tantalum capacitors were as specified in Table 4. The circuit shown in Figure 6 was used. The testing procedure was the following: a) verify component values and that known ESR value capacitors are used; b) perform turn-on test with minimum load (Table 4); record and verify waveform; and c) perform step load test with maximum load (Table 4) and record and verify waveform.

Table 4. Information about input voltage, capacitors, and respective ESR for stability test.

LOT	Generic Number	Vin	Input Capacitor	Output Capacitor	ESR (mOhm)	Series Res (Ohm)	Load Current
0635	MSK5920-1.5	5V	47uF CWR29	220uV 10V CWR19	338	0	10 and 500 mA
0635	MSK5920-1.5	5V	47uF CWR29	220uV 10V CWR29	51	0, 0.1, 0.3, 0.5	10 and 500 mA
0703	MSK5920-2.5	5V	47uF CWR29	220uV 10V CWR19	413	0	10 and 500 mA
0703	MSK5920-2.5	5V	47uF CWR29	220uV 10V CWR29	40	0, 0.1, 0.3, 0.5	10 and 500 mA

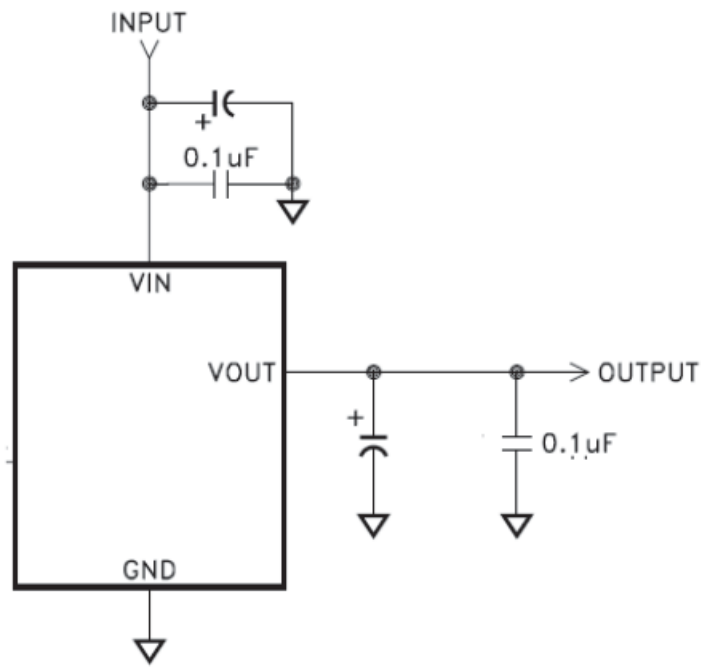

Figure 6. Circuit configuration used for the stability test.

The figures in Appendix A show the power-on and step-load change measurements; results are outlined in Table 5. Four cases were considered, as follows:

- Damped indicates a damped oscillation was observed.
- Driven indicates the observed oscillation was sustained.
- Pass indicates no recordable oscillations were observed.
- Fail indicates the regulator failed to regulate.

Table 5. Summary of findings about stability studies with turn-on and step-load test.

Generic Number	Vin	Input Capacitor	ESR (mOhm)	Output Capacitor	ESR (mOhm)	Series Res (Ohm)	Turn On (min Load)	Load Switching (min to max)
MSK5920-1.5	5V	47uF CWR29	125	220uV 10V CWR19	338	0	Damped	Driven
MSK5920-1.5	5V	47uF CWR29	125	220uV 10V CWR29	40	0	Pass	Pass
MSK5920-1.5	5V	47uF CWR29	125	220uV 10V CWR29	40	0.1	Damped	Pass
MSK5920-1.5	5V	47uF CWR29	125	220uV 10V CWR29	40	0.5	Pass	Fail
MSK5920-2.5	5V	47uF CWR29	112	220uV 10V CWR29	413	0	Damped	Driven
MSK5920-2.5	5V	47uF CWR29	112	220uV 10V CWR19	51	0	Pass	Pass
MSK5920-2.5	5V	47uF CWR29	112	220uV 10V CWR19	51	0.1	Pass	Pass
MSK5920-2.5	5V	47uF CWR29	112	220uV 10V CWR19	51	0.5	Pass	Fail

3.1.3 Conclusion

In agreement with other studies performed at JPL by the power systems group for several projects, the following recommendations and observations could be concluded with respect to the rev. H/O and rev. P recommendations:

- Both configurations appeared to be stable.
- Oscillations in the four 220uF configuration were observed but were attributed to the added inductance of the stacked capacitor configuration used. (Later tests confirmed that with proper layout no oscillation is observed.)
- A single capacitor with ESR < 0.1 Ohm exhibited oscillations.

Note that, while these tests roughly validate the rev. K and rev. P recommendations, stability of low dropout regulators is dependent on many factors specific to a circuit, e.g., layout, actual dynamic load, and stray inductance/capacitance/impedance. Optimally, for any given circuit application, a good design practice would include determination/validation of adequate phase and gain margin. However, with this particular device, it is not possible to do this by direct test due to a feedback loop internal to the device. Further, this cannot be obtained by simulation without a detailed model of the internal LT1573 controller.

For new designs using the MSK5820 or 5920, it is recommended that the manufacturer's current output capacitor configuration recommendations (MSK5920 rev. P) be followed. This does not preclude use of heritage designs that do not follow the current recommendations. For heritage designs following the MSK5820 rev. K output capacitor configuration, recommendation is to use as is. In all other cases, a stability test is recommended.

3.2 Low Temperature Evaluations

3.2.1 Devices Tested

Two parts were evaluated at low temperature. The first was the MSK5810RH linear dropout regulator from MS Kennedy (see Figure 7). This device was selected because it is extensively used as well as similar regulators in different flight missions, particularly the Mars Science Landers (MSL). It is an adjustable output dropout positive linear regulator that has been shown to be radiation tolerant up to 450

krad(Si). It can deliver up to 5 A output current and an output voltage that can be adjusted from 1.5 V to 7 V. The second was the ISL70001 switching POL converter from Intersil. Figure 8 shows the ISL70001 device with the manufacturer-supplied application board. The ISL70001SRH is a radiation hardened monolithic synchronous buck regulator capable of converting an input voltage 3V to 5.5V to an output that is adjustable from 0.8V to 85% of the input voltage with a high efficiency (~ up to 89%). The output load current capacity is 6 A at a junction temperature up to +125 C. The nominal switching frequency is 1 MHz.

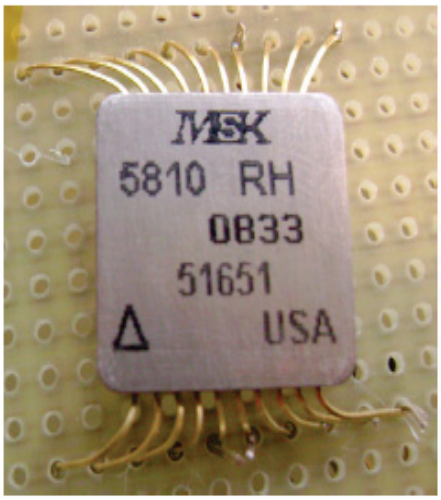

Figure 7. Photograph of the MSK5810RH linear regulator inserted in board. The application board was made per the instructions and diagram provided by the datasheet for this device. The surface shown with markings was pressed against the heat sink; the thermocouple was placed between the two surfaces.

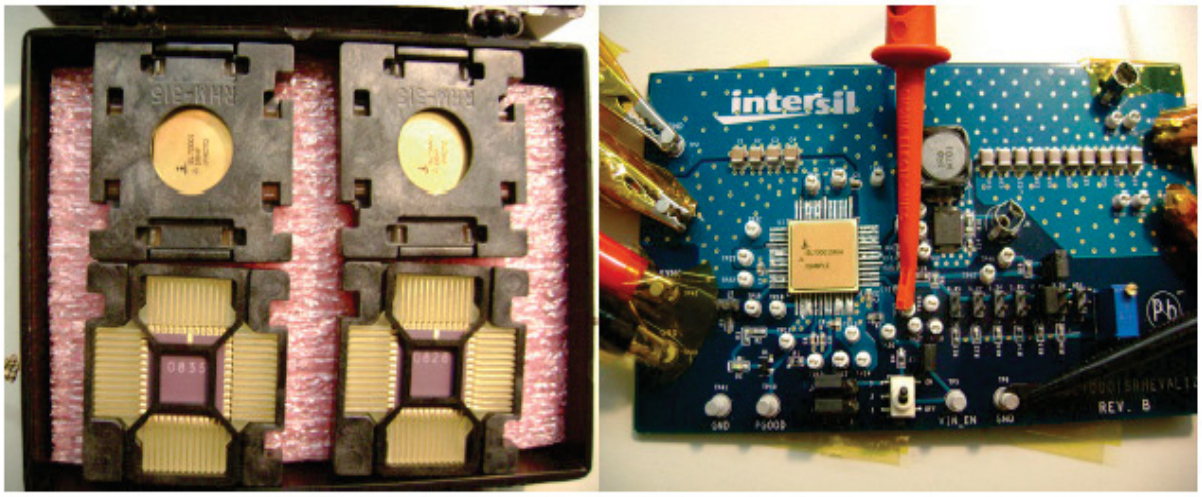

Figure 8. Optical photographs of ISL70001 buck regulators. The front and back of the devices in the ESD safe box are shown on the left; the regulator mounted on the manufacturer-supplied application board is shown on the right.

3.2.2 Temperature Control and Monitoring

The POL regulators were tested at room and low temperatures using a finned heat sink. A small fan was also used to lower the temperature when the regulators were fully powered up. The thermocouples used were T-type. They were mounted on thermal tape between the heat sink and the regulators with a plate bolted on the regulators to make good thermal contact. Figure 9 shows photos of the low temperature set-up, including the thermal chamber used for the various temperature tests. When tests are performed at temperatures other than room temperature (i.e., -40°C, -55°C, below -55°C, +85°C, and at 125°C), a Sigma Systems M30 computer controllable thermal chamber is used. The system's testing capabilities include both cycling and static temperature testing at extreme temperatures from -150°C to 250°C. With small thermal masses, the chamber achieved a ramp rate between temperatures above 10°C/min. Inert atmosphere testing was achieved through a built-in gas purge (using nitrogen). Adjustable, fail-safe, over-temperature and under-temperature protection was built into the system and is active in both manual operation and remote operation. The test chamber is 33 cm (L) × 25 cm (W) × 33 cm (H) and has eight 7.6 cm 1.3 cm door feed troughs and one 5 cm side port. Figure 9 shows the chamber both closed and with a regulator on a heat sink inside ready for tests. Manual control was used in these tests for greater temperature accuracy. A thermocouple was placed very close to the converter devices; this is the reading that was used, rather than the chamber thermocouple reading. At full load, there was sometimes a small discrepancy, so the chamber temperature was adjusted accordingly.

Figure 9. Thermal chamber used in all DC/DC converter tests at -55 oC (and below) and 125 oC. Tests were also performed at room temperature before closing the chamber and bringing it to temperature to ensure measurements were as expected.

3.2.3 Experimental Results

In FY10, results from experiments at low temperature on the MSK585810RH indicated that the device failed to turn on or perform basic function at -25°C and below. Figure 10 highlights some results about some transient step-load changes that were performed at both room and -30°C. The load step was from 1.5 A to 3 A. The input voltage was 3 V and the output was 1.7 V. The regulator oscillates for part of the duty cycle. It warmed up rapidly and was turned off as soon as scope traces were captured. It was diagnosed that possible issues with ESR of output capacitor at low temperature could induce these types of stabilities. As a result, MSK provided another application board with a better capacitor and better layout and requested that we perform additional testing.

Those additional experiments were performed in FY11 and results are presented below. The device shows proper functionality for different input voltages and load conditions down to -55°C. Figure 11 shows illustrative plots of a turn-on test and transient step-load change (0.2–2 A) at -55°C for a Vin of 3.3 V. It should be noted that various conditions were tested, and the device operated properly.

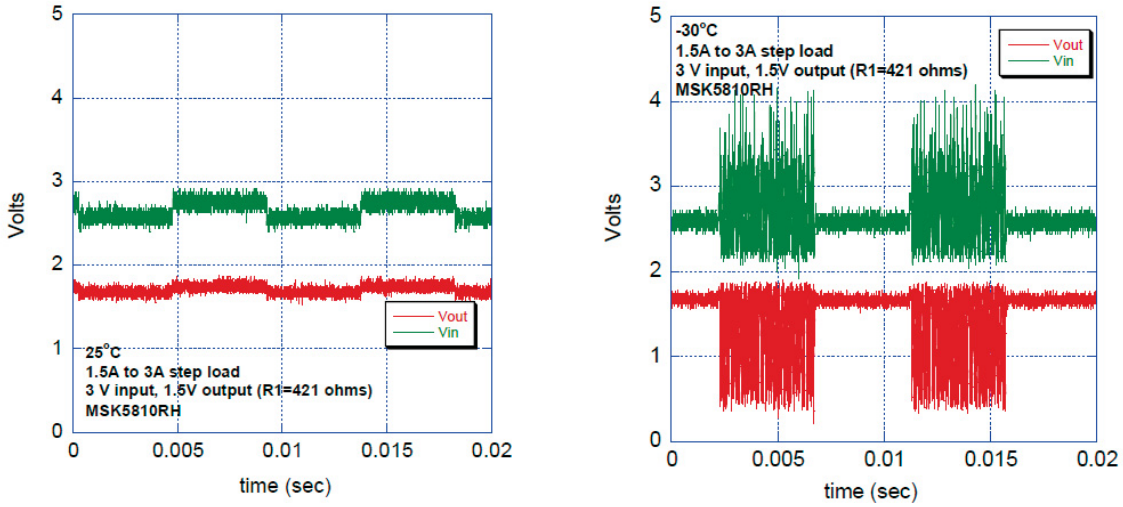

Figure 10. Load transient response test at 25°C for the linear regulator MSK5810RH. The load step was from 1.5 A to 3 A. The input voltage was 3 V and the output was 1.7 V.

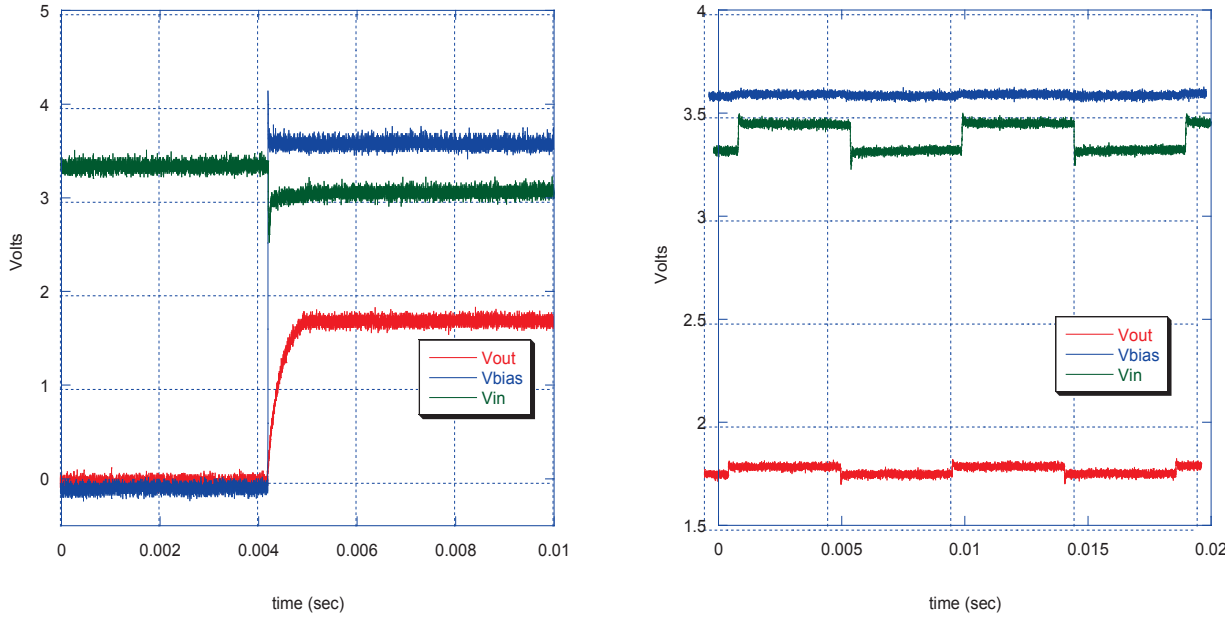

Figure 11. Bounceless switch turn-on test done at -55°C for MSK5810RH. V_{in} was 3.3 V and the load current (4 A) (100%) (left) and load transient response test at -55°C for MSK5810RH. V_{in} was 3.3V and the load step was 0.2-2 amps (right). MSK5810RH tested with new application board: good performance at -55°C.

Similar testing was performed at -78°C at full load. Results are presented in Figure 12. Experiments show that at -78°C the device shows basic functionality. However, the turn-on behavior at low input voltage has different response. The turn-on is slower for lower V_{in}, and the desired output is not reached.

Similar testing was performed at -100°C at full load and half load. Results are presented in Figure 13. Experiments show that at -100°C the device shows basic functionality only at 50% load. At 100% load, the device fails to reach the desired output voltage even at low input voltage.

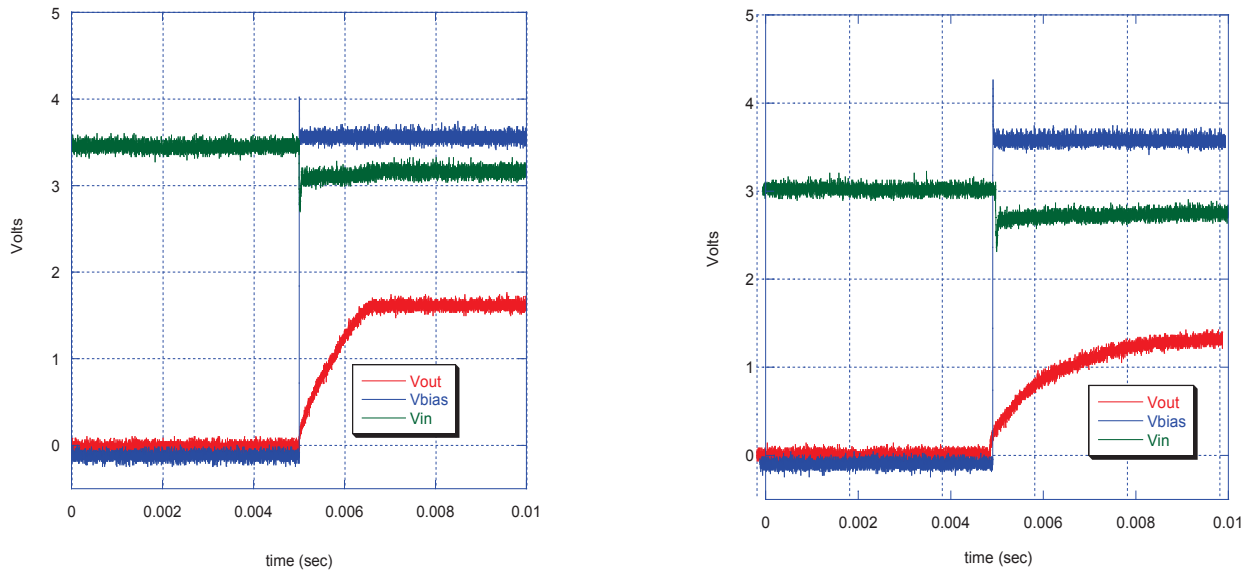

Figure 12. Bounceless switch turn-on test at -78°C for MSK5810RH. The input voltage was 3.1 V and the load 4 amps (100%) (left). Bounceless switch turn-on test at -78°C for MSK5810RH. V_{in} was 2.7 V and the load 4A (100%) (right).

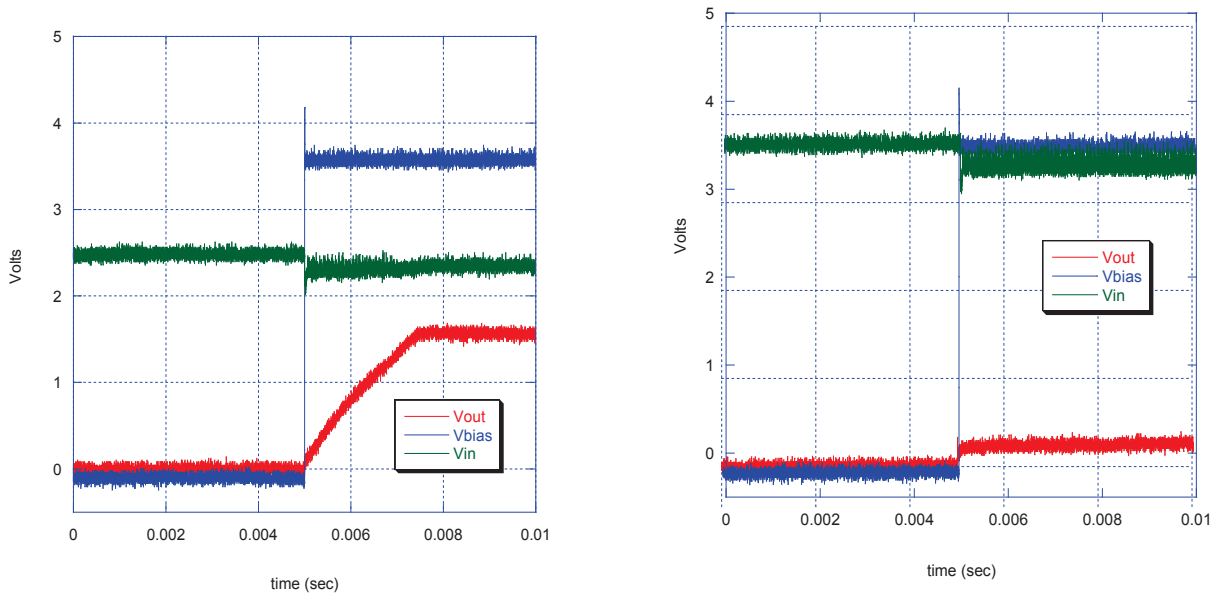

Figure 13. Bounceless switch turn-on test at -100°C for MSK5810RH. The input voltage was 2.2 V and the load 2 amps (50%) (left). Bounceless switch turn-on test at -100°C. The input voltage was 3.2 V and the load 4 amps (100%) (right). Tests down to -100°C show basic functionality if only using 50% load.

The ISL7001 regulator was also evaluated at low temperature. The device operation was not affected at a temperature of -55°C. Because evaluating the performance at very low temperature can be really helpful when selecting commercial regulators that can be used in flight application where cryogenic temperatures are unavoidable, further experiments were conducted at -125°C and -135°C. The ISL70001 shows acceptable performance down to -125°C at all loads. As shown in Figure 14, at -135°C, as long as less than the full load is used, the device was able to start. Change in the voltage reference behavior at -135°C would be indicative of the behavior observed.

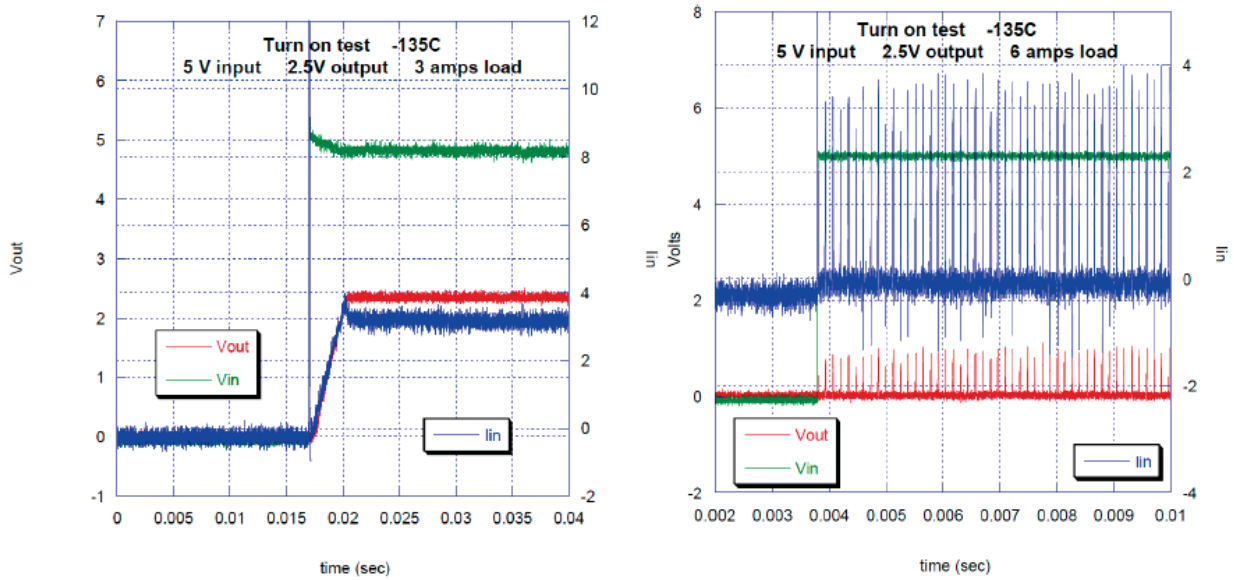

Figure 14. Turn-on test for ISL70001 regulator at -135°C with 5 V input and 2.5 V output. The load was 3 amps, which is 50% of the maximum load (left). Turn-on test for ISL70001 regulator at -135°C with 5 V input and 2.5 V output. The load was 6 amps or a full load (right).

3.3 Dynamic Loading Evaluation and Two-Stage Power Architecture Implementations

3.3.1 Power System Architecture

All POL switching converters or linear regulators are operating within a two- to three-stage power distribution scheme. The main reason is that it is impossible to convert a 28 V bus input voltage down to 1 V with a single device. Operating two converters in series is not a trivial task because there are many sources of power dissipation that can result in a poor end-to-end efficiency. Many sources of malfunctions, such as instability or overshoot, and often additional circuitry, such as over-voltage protection or other fault management circuitry is needed to provide a reliable system. In addition, when operating in a flight application, the load at the POL output within the architecture is typically not fixed, and ensuring proper functionality of the POL when dynamic loading occurs is critical.

As a result, experiments were conducted to assess the behavior of several POLs available within a typical two-stage power architecture. The most common bias scheme was selected for this study, i.e., a 28 V input down to an intermediate voltage of approximating 5 V and then a conversion to lower voltages between 0.8 V and 3.3 V, depending on the POL capabilities. Basic operation, efficiency, and transient step load change were evaluated for those different implementations.

Within two-stage architecture, the first stage converter is typically an isolated converter that can convert 28 V down to 5 V. We selected the M3G2805SR from international rectifier. This buck converter is well suitable for space application and has been flown on several programs. It is a radiation-hardened, high-reliability buck converter that incorporates fixed-frequency, single-ended forward topology with magnetic feedback and an internal EMI filter that utilizes multi-layer ceramic capacitors for optimum reliability.

Some of the features are: total dose hardness > 200 krad(Si), 18 to 50 V input range, up to 40 W output power and single and dual output models 3.3, 5, 12, 15 V. The converter was first tested separately to check proper functionality with respect to the datasheet specification. The single M3G2805SR test set-up is shown on Figure 15.

Three candidate point-of-load regulators were selected for this study: the ISL70001 switching POL from Intersil, the crane MFP0507S from Interpoint, and the PE99153 from Peregrine. The crane MFP0507S is a single-output, non-isolated POL regulator that can supply any voltages between 0.8 VDC and 3.3 VDC. The rated output current is 7 A at 0.8 V and 5 A at 3.3 V. The input voltage range is from 3.3 V to 6 V; however, the selected output voltage should not exceed 80% of the input voltage. Its maximum output power of 16.5 W is with output set for 3.3 V and 5 A. Maximum output power with the output voltage set for 0.8 V and 7 Amp is 5.6 W. The Peregrine PE99153 is a non-isolated POL regulator delivering high efficiency at VIN = 5 V (4.5–6.0) and output current up to 6 A continuous. The output voltage ranges from 1.0 V to 3.3 V.

The end goal of this study is to evaluate various POLs in combination with single isolated hybrid converters used in the industry and establish some guidelines summarizing which combinations are better suited in terms of performance, transient response, dynamic loading response, and temperature range of operation. In addition, as shown in Figure 16, with respect to a real application, those combinations can also be evaluated when powering digital devices such as FPGAs. This study will be pursued in 2012.

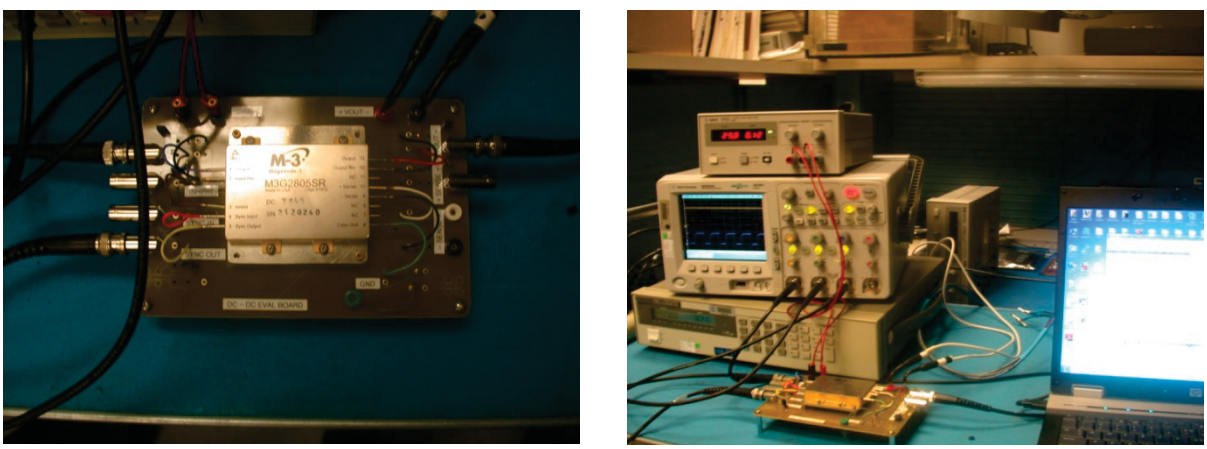

Figure 15. Test set-up and application board representation for the hybrid M3G2805SR buck converter characterization.

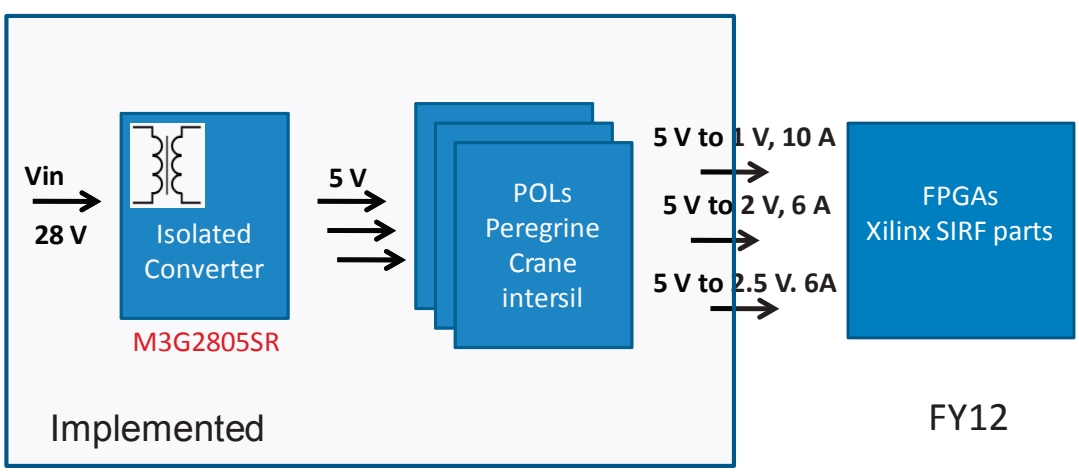

Figure 16. Prototype two stages implementation considered to study the impact of dynamic loading and test the capabilities of the available POLs

3.3.2 Results

Preliminary evaluations of the three candidate parts have shown promising results. The three architectures were implemented and operated properly through various input voltages and load conditions. The first dataset shown in this section relates to the end-to-end efficiency of the three architectures proposed for different output voltages and load conditions. It should be noted that no instabilities or oscillations have been observed for the different architecture proposed through to full range of loads. Figure 17 shows an efficiency plot when using the combination MG32805SR + ISL70001 for two output voltages, 1.2 V and 3.3 V. The maximum efficiency recorded was close to 65% for a wide range of load conditions. As expected, the efficiency dropped significantly when lowering the output voltage and the performances at low load degraded quite a bit. These results indicate that linear regulator can be competitive at low load.

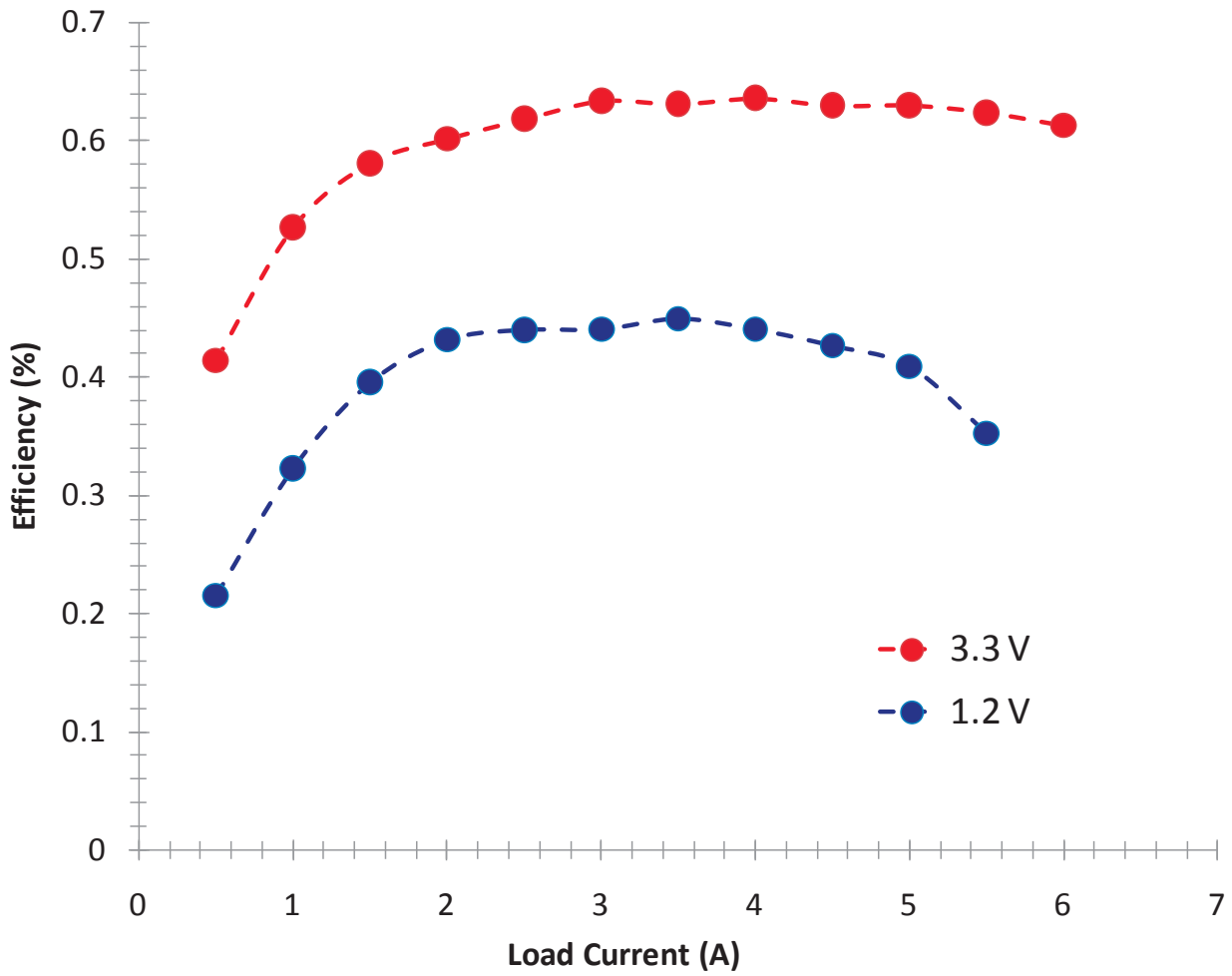

Figure 17. End-to-end efficiency plot that uses the combination of IR MG32805SR with Intersil ISL70001. The conditions were 28 V input, 5 V intermediate voltage, and 2.5 V output for various load conditions.

Figure 18 shows an efficiency plot when using the combination MG32805SR + MFP0507S for two output voltages, 0.8 V and 3.3 V. The maximum efficiency recorded was close to 70% for a wide range of load conditions. As expected, the efficiency dropped significantly when lowering the output voltage, and the performances at low load degraded quite a bit. However, it looks like this combination might be the most efficient of the three implementations considered here.

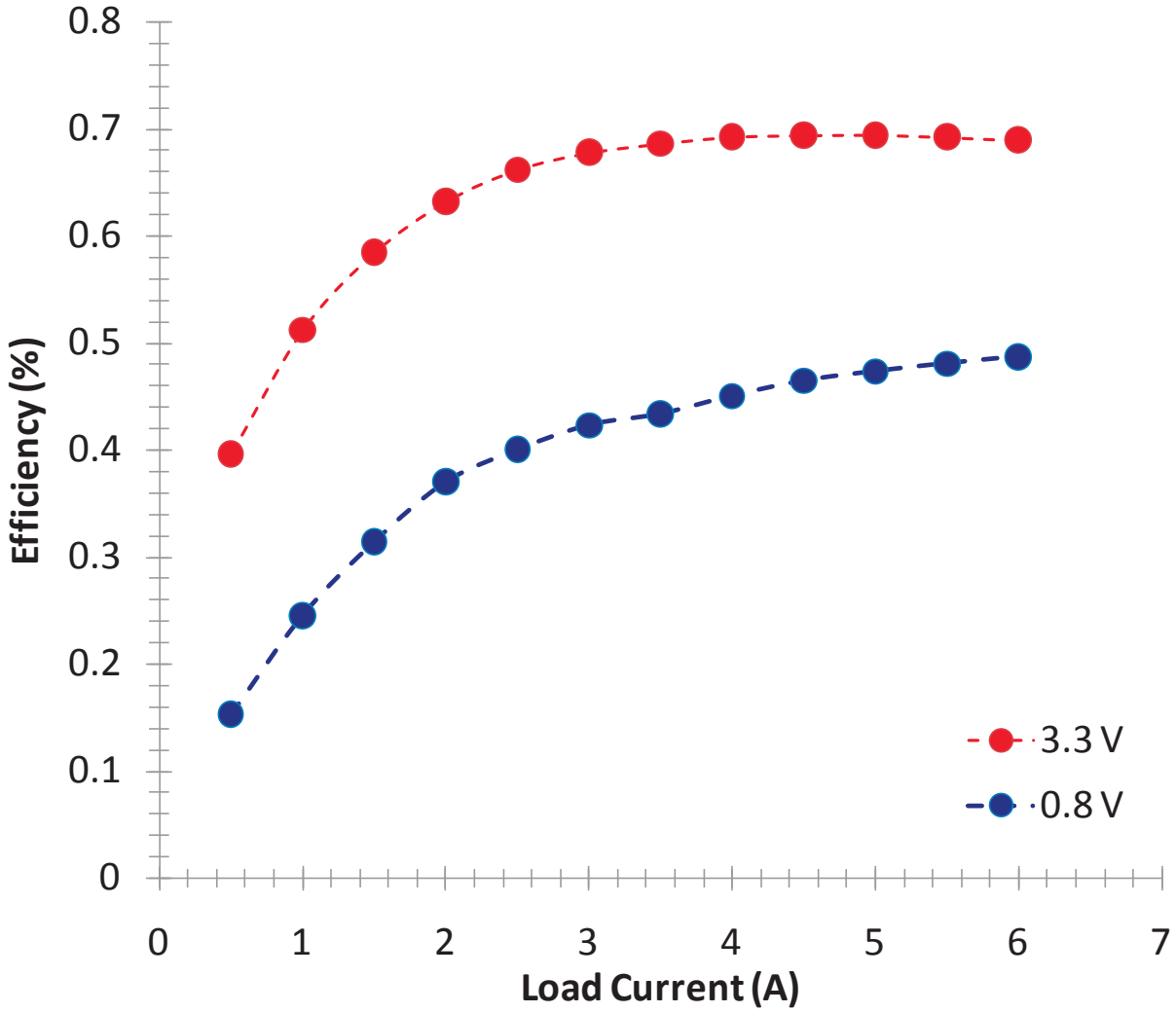

Figure 18. End-to-end efficiency plot that uses the combination of IR MG32805SR with the Crane MFP0507S. The conditions were 28 V input, 5 V intermediate voltage, and 2.5 V output for various load conditions.

Figure 19 shows an efficiency plot when using the combination MG32805SR + PE99153 for a single output voltage, 2.5 V. This voltage was the only voltage available in the application board provided by Peregrine. Some modifications need to be made on the evaluation board to change the output voltage. The maximum efficiency recorded was close to 65% for a wide range of load conditions. As expected, the efficiency dropped significantly when lowering the output load. However, this combination seems to operate better at low load.

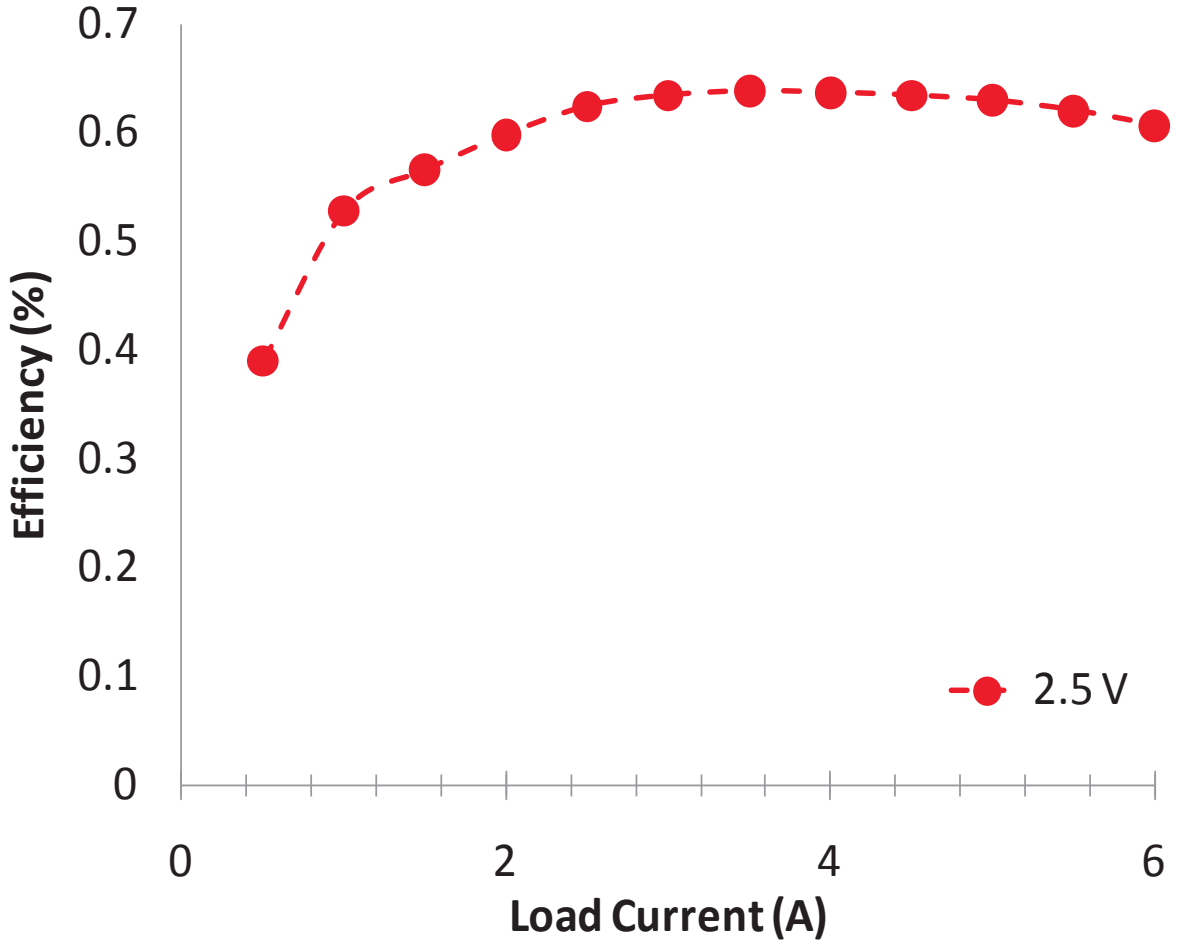

Figure 19. End-to-end efficiency plot that uses the combination of IR MG32805SR with the Peregrine PE99153. The conditions were 28 V input, 5 V intermediate voltage, and 2.5 V output for various load conditions.

Additional results are shown below, illustrating the good behavior of the two-stage implementations with respect to dynamic loading. The test consisted of monitoring the output voltage and intermediate voltage to check the ripple and regulation window, applying a transient step load change (20% to 80%), and checking the intermediate voltage as well as output. Figures 20 and 21 illustrate the good behavior of the two-stage architecture using the combination M3G2805SR + MFP0507S. In both figures, the intermediate voltage is the top curve and the bottom is the output voltage. Figure 20 shows a nice and clean ripple for a 3.3 V output (20 mV Pk-Pk). Figures 21and 22 show a nice transient step load change without any oscillations and amplitude and recovery within specification. Similar results were obtained for the PE9953 and ISL70001, and data are plotted in Figure 23.

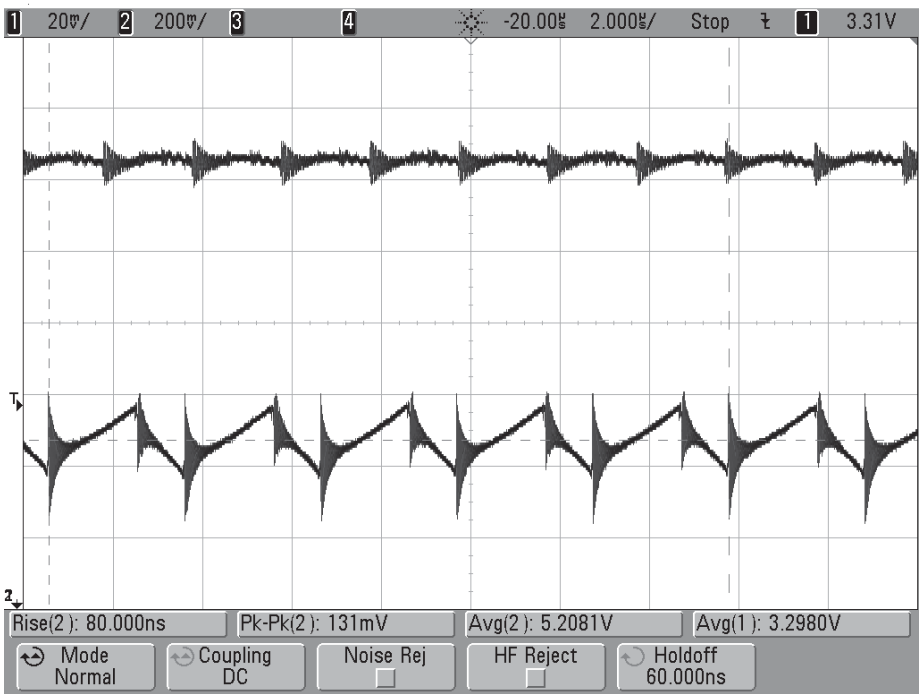

Figure 20. Two-stage results using the combination MG32805SR + MFP0507S. The top curve is the intermediate voltage, and the bottom curve is the crane converter output (20 mV ripple)

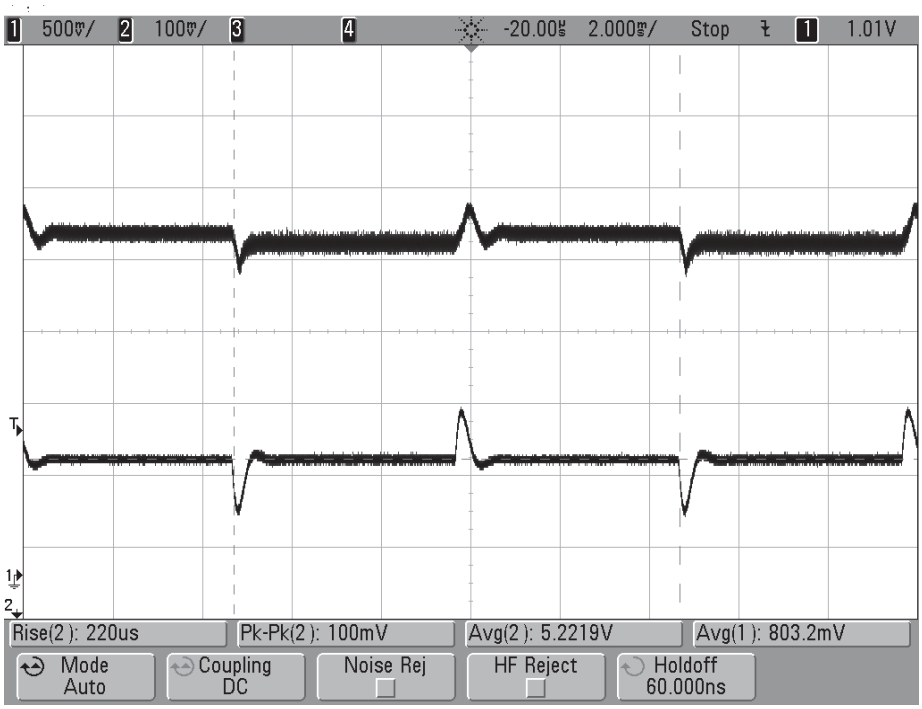

Figure 21. Transient step load change (20% to 80%) for the two-stage combination MG32805SR + MFP0507S. The top curve is the intermediate voltage, and the bottom curve is the crane converter output. Bias conditions were 28 V, 5 V, and 0.8 V output.

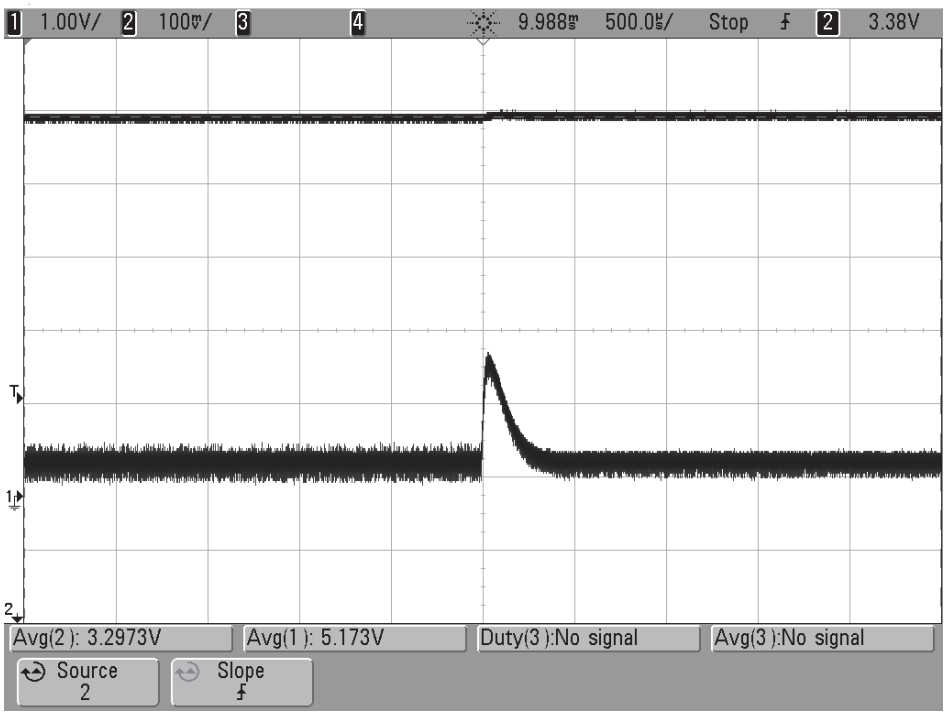

Figure 22. Transient step load change (20% to 80%) for the two-stage combination MG32805SR + MFP0507S. The top curve is the intermediate voltage, and the bottom curve is the crane converter output. Bias conditions were 28 V, 5 V, and 3.3 V output.

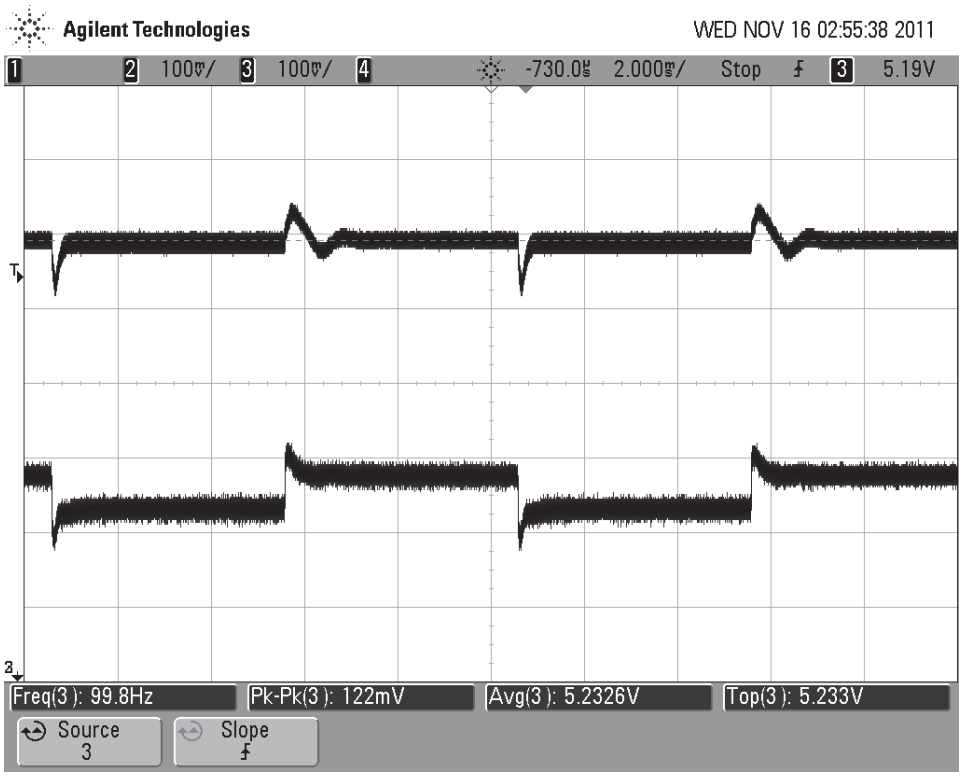

Figure 23. Transient step load change (0.2 A to 3A) for the two stage combination MG32805SR + PE99153). The top curve is the intermediate voltage, and the bottom curve is the crane converter output. Bias conditions were 28 V, 5 V and 2.5 V output.

4.0 CONCLUSION

Characterizing POL devices at low temperature (beyond specifications)

Results from FY10 indicated the MSK5810RH failed to start up and perform basic functions at or below -25°C. MSK provided another evaluation board with some design modifications so that another evaluation at low temperature could be performed. It was shown in this report that the MSK5810RH shows proper functionality for different input voltages and load conditions down to -55°C. The device shows basic functionality down to -78°C. However, the turn-on behavior at low input voltage had different a response, and the desired output was not reached. At -100°C, the device showed basic functionality only at 50% load. At 100% load, the device failed to reach the desired output voltage even at low input voltage. The ISL70001 shows acceptable performance down to -125°C at all loads. At -135°C, as long as less than the full load is used, the device was able to start. Change in the voltage reference behavior at -135°C would be indicative of the behavior observed.

Evaluating the stability of linear regulators with respect to their equivalent series resistance (ESR) recommendations: Case study MSK5920

In agreements with other studies performed at JPL by the power systems group for several projects, the following recommendations based on ESR measurements could lead to the following conclusions, with respect to the rev. H/O and rev. P recommendations:

- Both configurations appeared to be stable.
- Oscillations in the four 220uF configuration were observed but were attributed to the added inductance of the stacked capacitor configuration used. (Later tests confirmed that with proper layout, no oscillation is observed.)
- A single capacitor with ESR < 0.1 Ohm exhibited oscillations.

For new designs using the MSK5820 or 5920, it is recommended that the manufacturer's current output capacitor configuration recommendations (MSK5920 rev. P) be followed. This does not preclude use of heritage designs that do not follow the current recommendations. For heritage designs following the MSK5820 rev. K output capacitor configuration, the recommendation is to use as is. In all other cases, a stability test is recommended.

Evaluation of the electrical behavior of emerging POLs (Crane MFP0507S, Peregrine P9915X and Intersil ISL7001RH) within a two-stage power distribution architecture

For the three devices evaluated, the combination with the international rectifier M3G2805SR show some promising results. The dynamic loading response was acceptable for the three POLs tested. No instabilities were observed for the full range of load conditions and for various input voltage. As expected, for all devices, the end-to-end efficiency drops quite a bit for low output voltage and even more load, making the use of linear regulator a viable solution at low load.

Plan for FY12

We will continue perform standard measurements to evaluate the basic performance of emerging POL switching converters and LDOs.

We will continue the study at the extreme range of temperature to compare the performances of manufacturers beyond specifications. It should be noted that three devices from three different manufacturers are expected for FY12: Aeroflex POL, 3D plus POL, and Texas Instrument POL.

The task should also leverage a research and development initiative led by the power system section at JPL. They are also slated to evaluate some commercial POLs.

We will also continue performing two-stage evaluations by comparing implementation and performance (efficiency, dynamic loading, transient response, etc.) using different combination of manufacturers.

Appendix A. ESR Stabilities Measurements for the MSK5920

The following figures (Figures 24–43) provide examples of transient step load change or turn-on tests for different values of ESR. Table 5 summarizes the results.

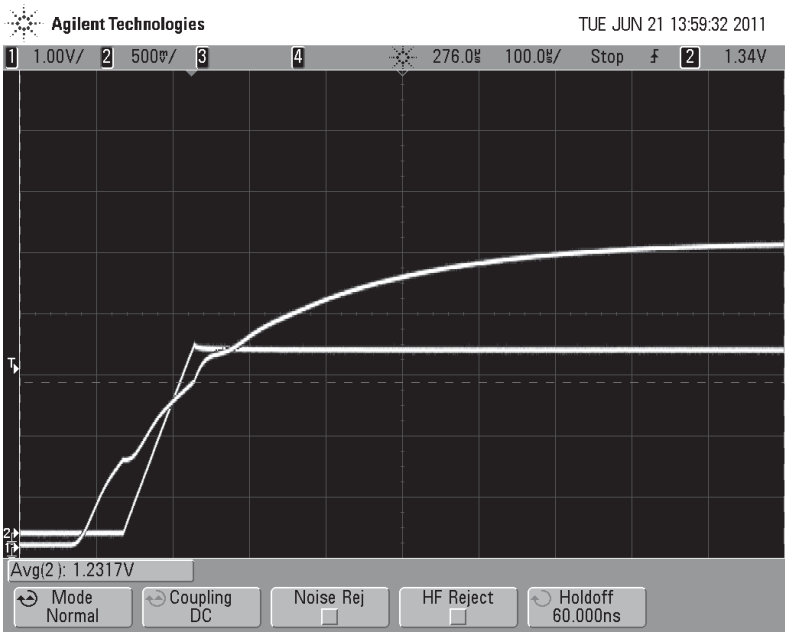

Figure 24. The 1.5 V MSK5920 turn-on curve with minimum load. Channel 1 is the input power supply, and channel 2 is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0244) with a measured ESR of 40 mOhm.

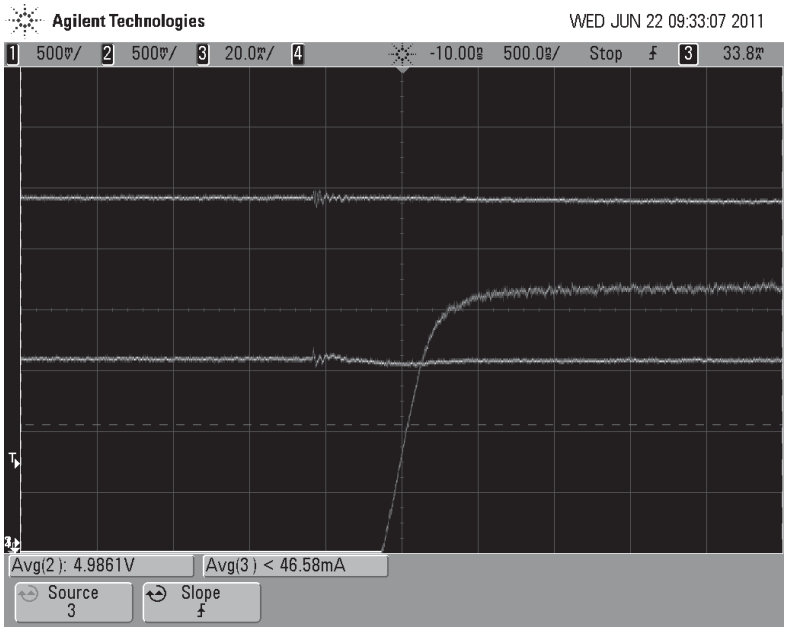

Figure 25. The 1.5 V MSK5920 low to high switching load characterization is shown here. The top trace is the input power supply, and the middle trace is the regulator's output. The capture was triggered on the rising edge of the output supply current. The output capacitor was a CWR29 220uF 10V device (SN R0244) with a measured ESR of 40 mOhm.

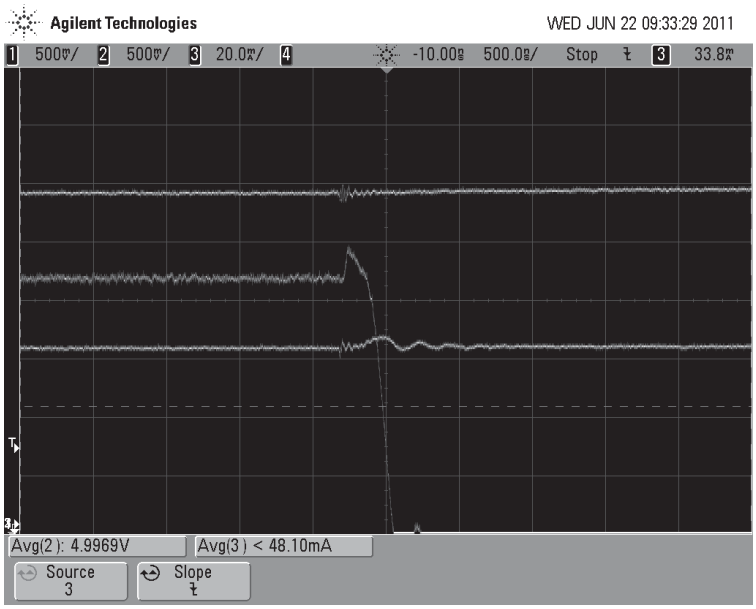

Figure 26. The 1.5 V MSK5920 high to low switching load characterization is shown here. The top trace is the input power supply, and the middle trace is the regulator's output. The capture was triggered on the falling edge of the output supply current. The output capacitor was a CWR29 220uF 10V device (SN R0244) with a measured ESR of 40 mOhm.

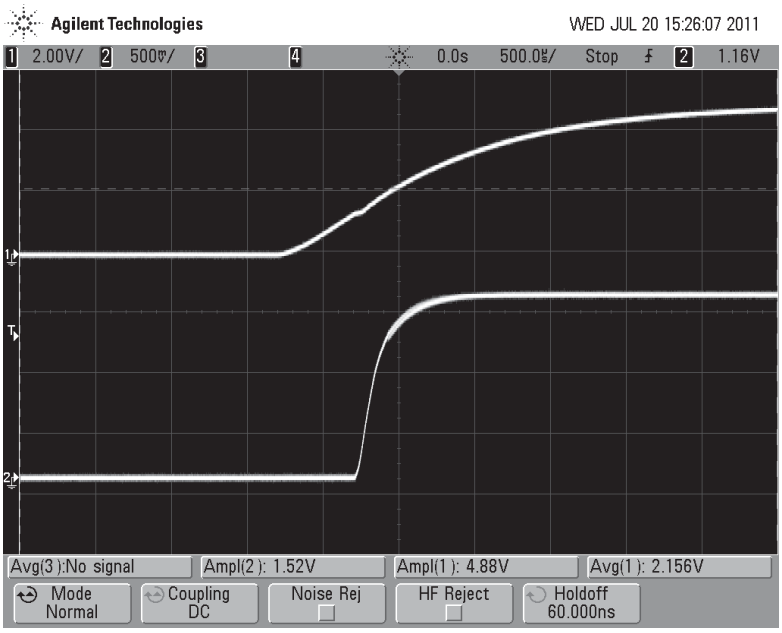

Figure 27. The 1.5 V MSK5920 turn-on curve with minimum load is shown here. Channel 1 is the input power supply, and channel 2 is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0244) with a measured ESR of 40 mOhm. A 0.5 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor.

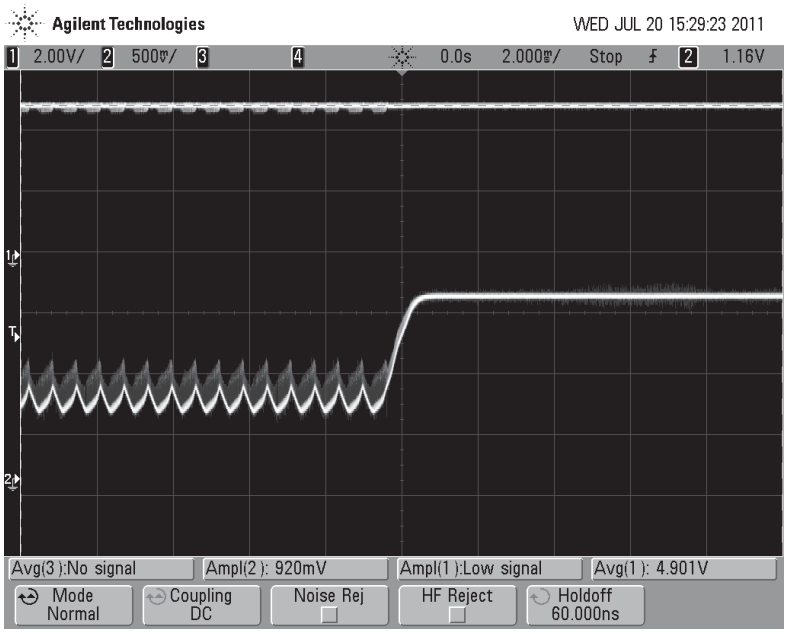

Figure 28. The 1.5 V MSK5920 high to low switching load characterization is shown here. The top trace is the input power supply, and the bottom trace is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0244) with a measured ESR of 40 mOhm. A 0.5 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor. Note that the device is not regulating when at full load.

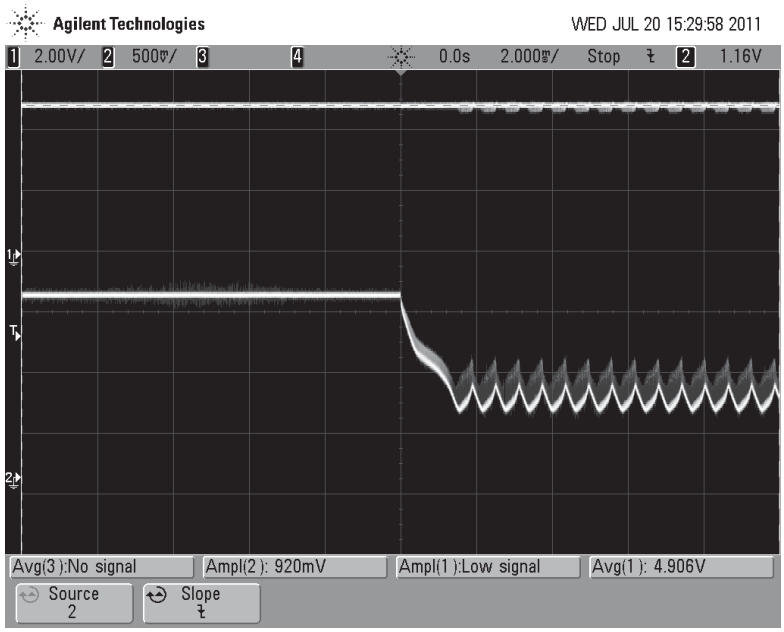

Figure 29. The 1.5 V MSK5920 low to high switching load characterization is shown here. The top trace is the input power supply, and the bottom trace is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0244) with a measured ESR of 40 mOhm. A 0.5 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor. Note that the device is not regulating when at full load.

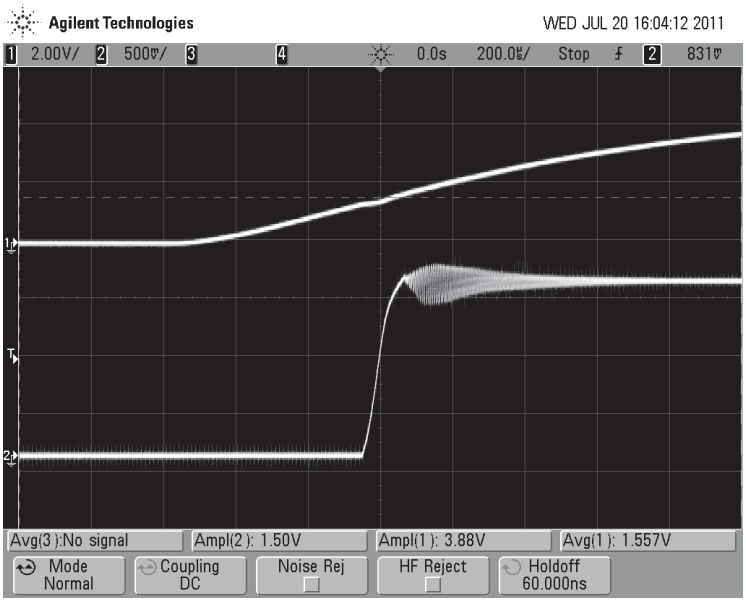

Figure 30. The 1.5 V MSK5920 turn-on curve with minimum load. Channel 1 is the input power supply and channel 2 is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0244) with a measured ESR of 40 mOhm. A 0.1 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor. Note the damped ringing on the output.

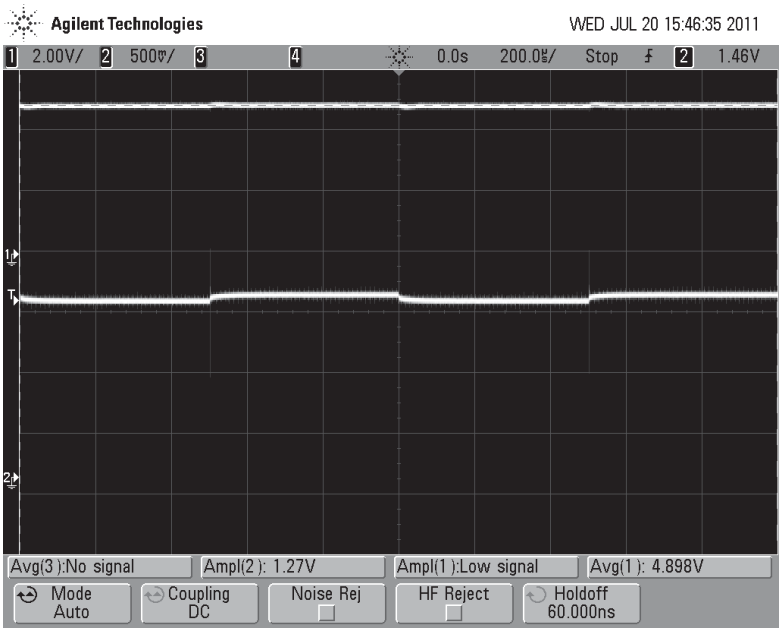

Figure 31. The 1.5 V MSK5920 low to high, high to low switching load characterization is shown here. The top trace is the input power supply, and the bottom trace is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0244) with a measured ESR of 40 mOhm. A 0.1 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor. Note the short output spike at each load change.

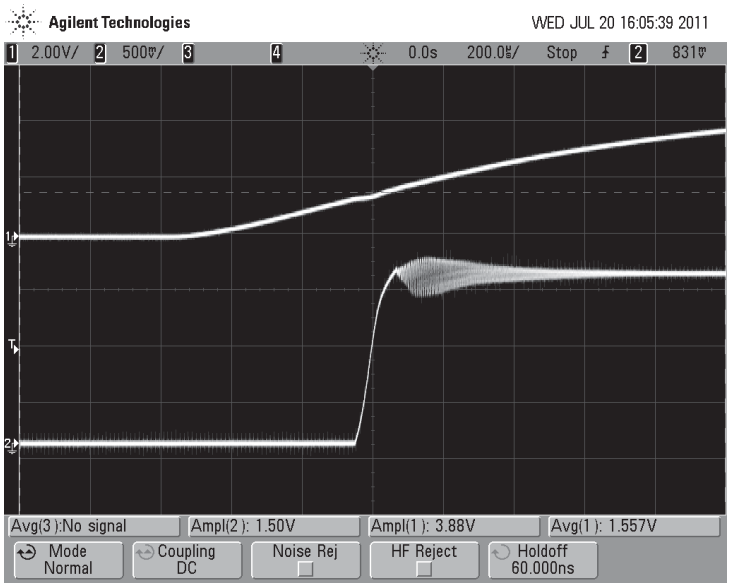

Figure 32. The 1.5 V MSK5920 turn-on curve with minimum load is shown here. Channel 1 is the input power supply, and channel 2 is the regulator's output. The output capacitor was a CWR19 220uF 10V device (SN R0240) with a measured ESR of 338 mOhm. Note the damped ringing on the output.

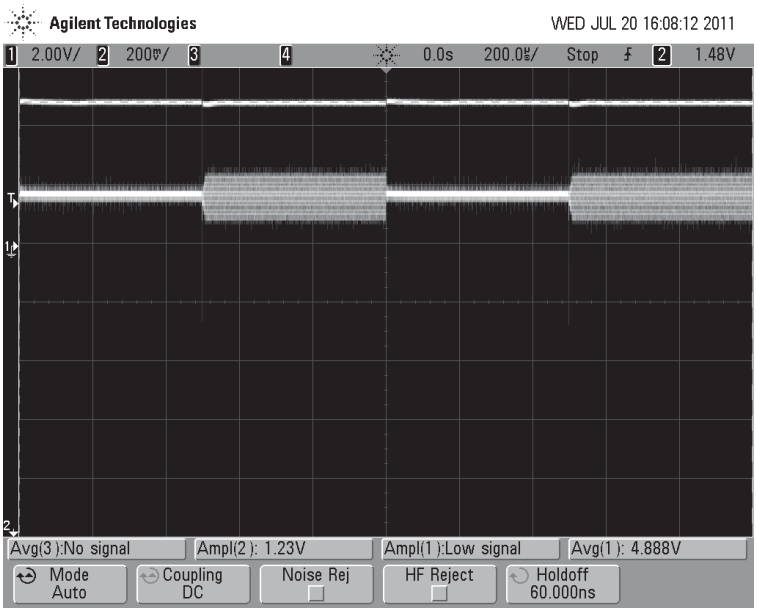

Figure 33. The 1.5 V MSK5920 low to high, high to low switching load characterization is shown here. The top trace is the input power supply, and the bottom trace is the regulator's output. The output capacitor was a CWR19 220uF 10V device (SN R0240) with a measured ESR of 338 mOhm. While the output still regulates at high load, there is observable sustained ringing.

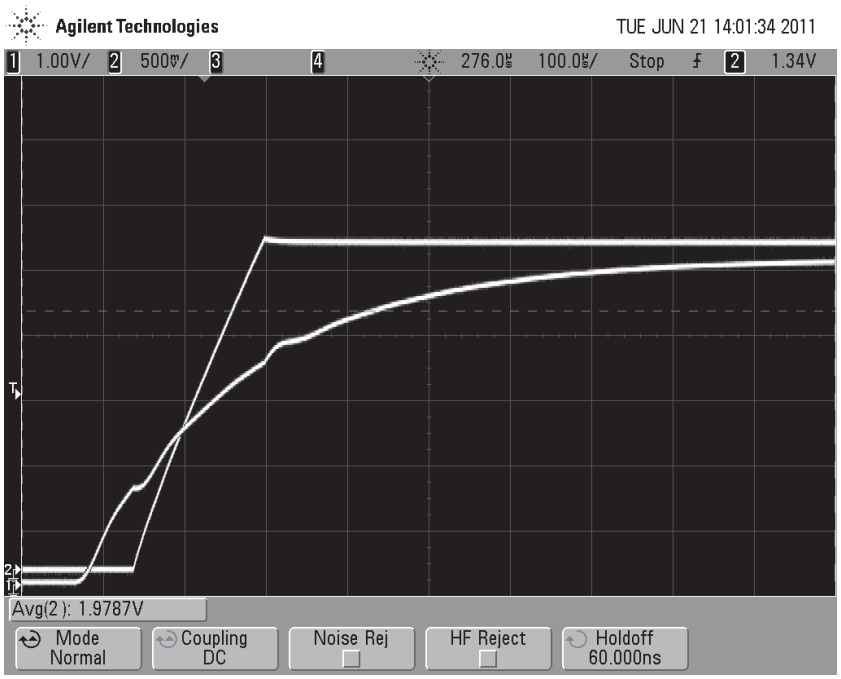

Figure 34. The 2.5 V MSK5920 turn-on curve with minimum load is shown here. Channel 1 is the input power supply, and channel 2 is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0231) with a measured ESR of 51 mOhm.

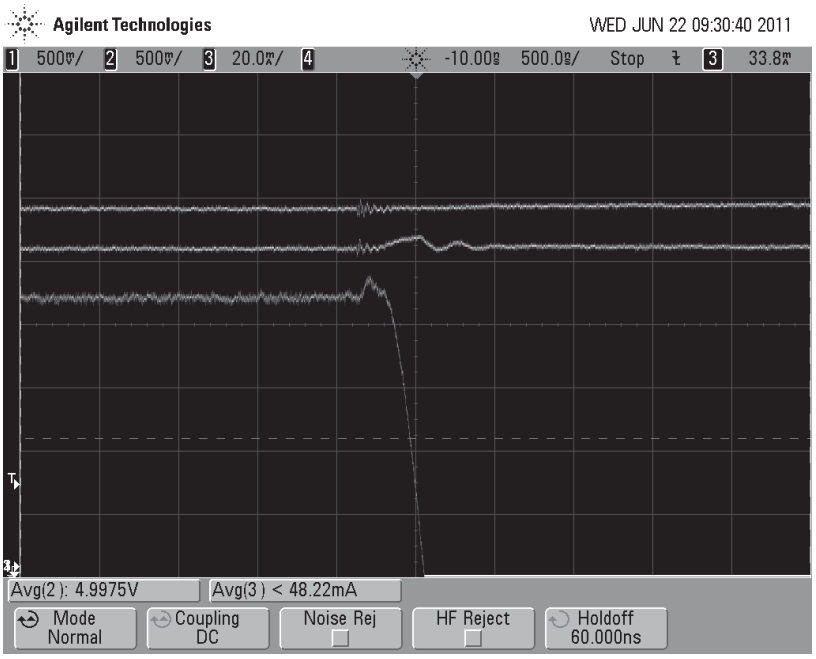

Figure 35. The 2.5 V MSK5920 high to low switching load characterization is shown here. The top trace is the input power supply, and the middle trace is the regulator's output. The capture was triggered on the falling edge of the output supply current. The output capacitor was a CWR29 220uF 10V device (SN R0231) with a measured ESR of 51 mOhm.

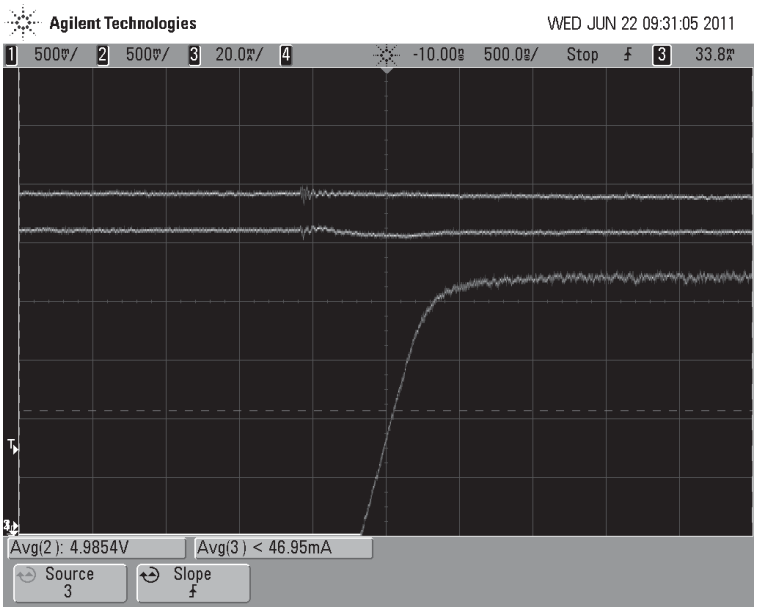

Figure 36. The 2.5 V MSK5920 low to high switching load characterization is shown here. The top trace is the input power supply, and the middle trace is the regulator's output. The capture was triggered on the rising edge of the output supply current. The output capacitor was a CWR29 220uF 10V device (SN R0231) with a measured ESR of 51 mOhm.

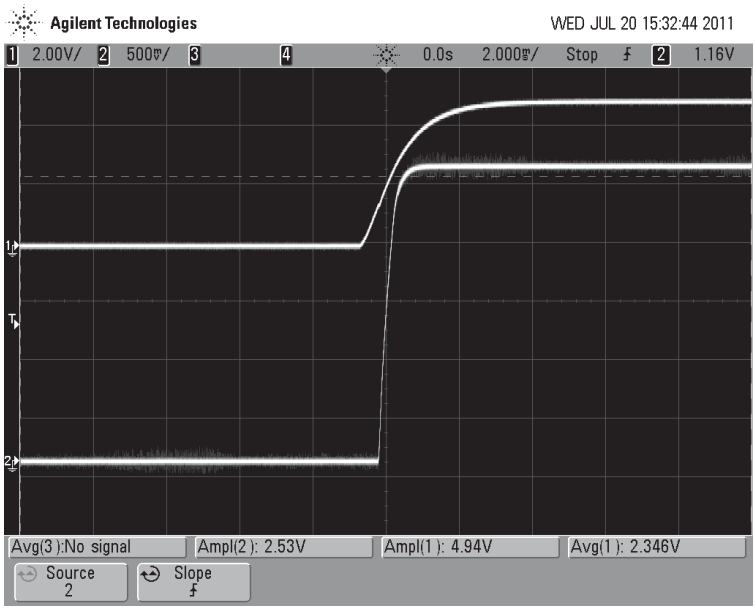

Figure 37. The 2.5 V MSK5920 turn-on curve with minimum load is shown here. Channel 1 is the input power supply and channel 2 is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0231) with a measured ESR of 51 mOhm. A 0.5 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor.

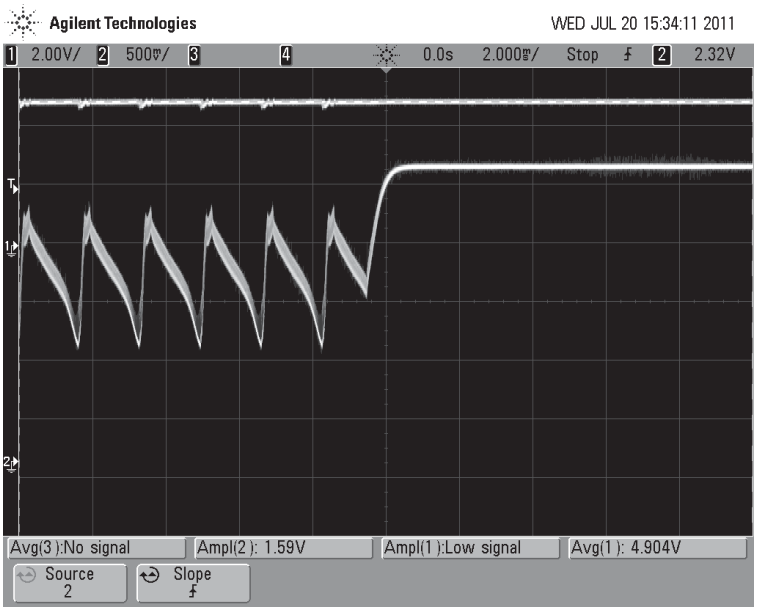

Figure 38. The 2.5 V MSK5920 high to low switching load characterization is shown here. The top trace is the input power supply, and the bottom trace is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0231) with a measured ESR of 51 mOhm. A 0.5 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor. Note that the device is not regulating when at full load.

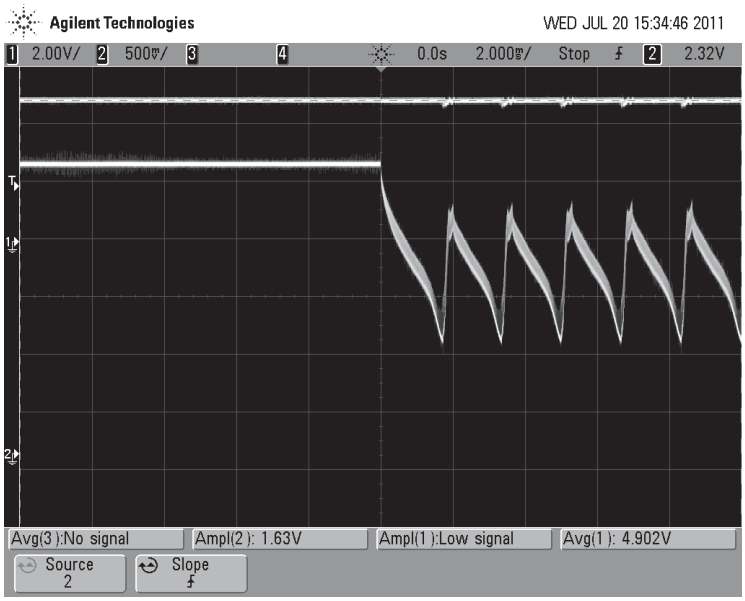

Figure 39. The 2.5 V MSK5920 high to low switching load characterization is shown here. The top trace is the input power supply, and the bottom trace is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0231) with a measured ESR of 51 mOhm. A 0.5 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor. Note that the device is not regulating when at full load.

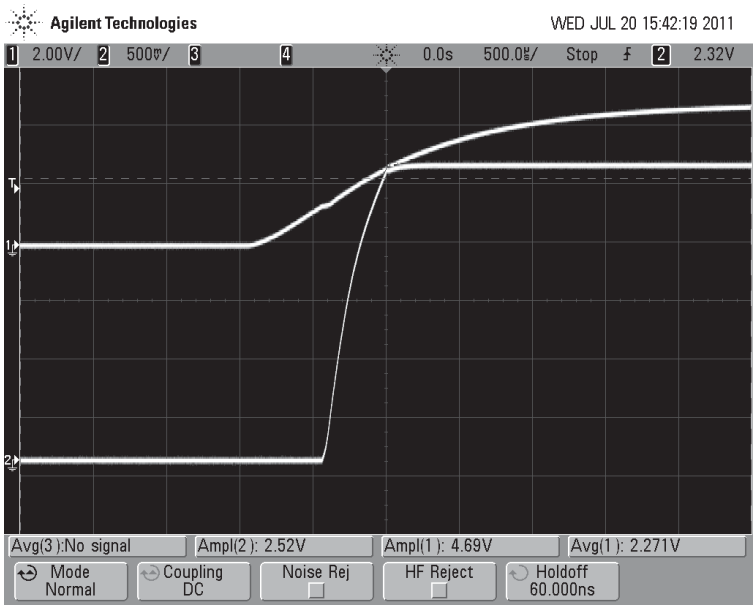

Figure 40. The 2.5 V MSK5920 turn-on curve with minimum load is shown here. Channel 1 is the input power supply, and channel 2 is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0231) with a measured ESR of 51 mOhm. A 0.1 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor.

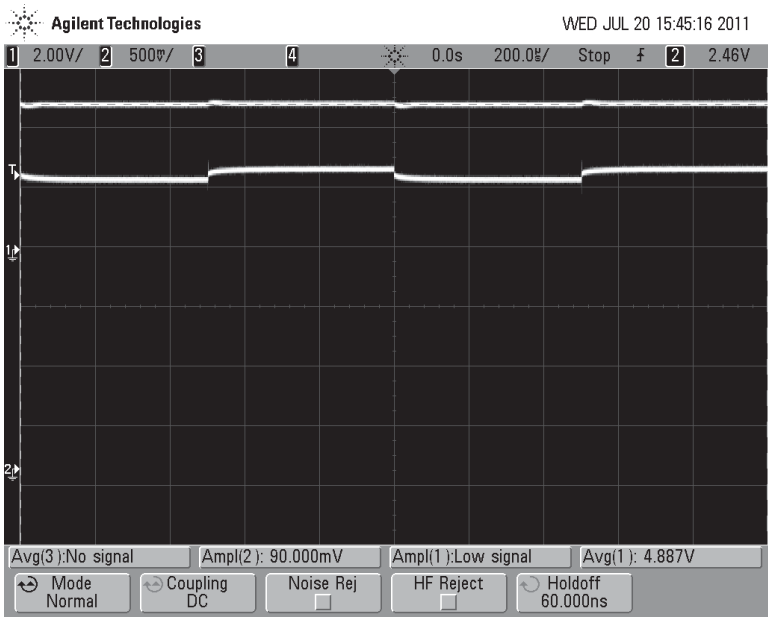

Figure 41. The 2.5 V MSK5920 low to high, high to low switching load characterization is shown here. The top trace is the input power supply, and the bottom trace is the regulator's output. The output capacitor was a CWR29 220uF 10V device (SN R0231) with a measured ESR of 40 mOhm. A 0.1 ohm series resister was inserted in line with the regulator's output and the tantalum output capacitor. Note the short, small output spike at each load change.

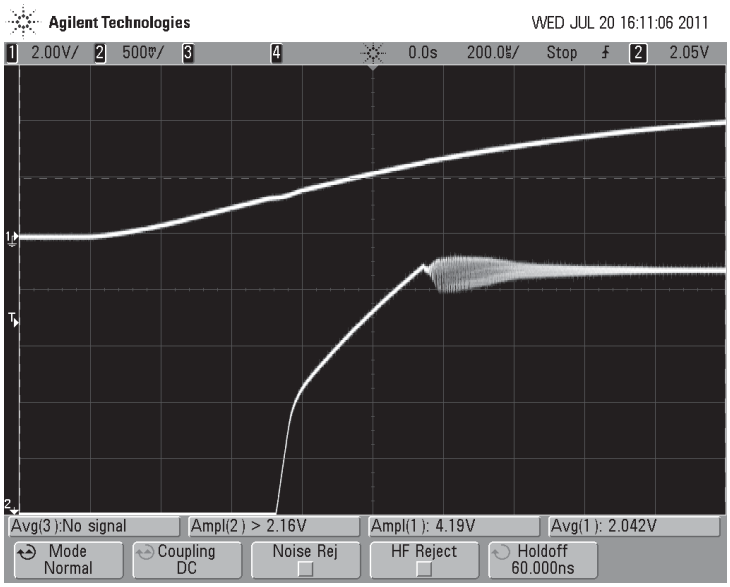

Figure 42. The 2.5 V MSK5920 turn-on curve with minimum load is shown here. Channel 1 is the input power supply, and channel 2 is the regulator's output. The output capacitor was a CWR19 220uF 10V device (SN R0235) with a measured ESR of 413 mOhm. Note the damped ringing on the output.

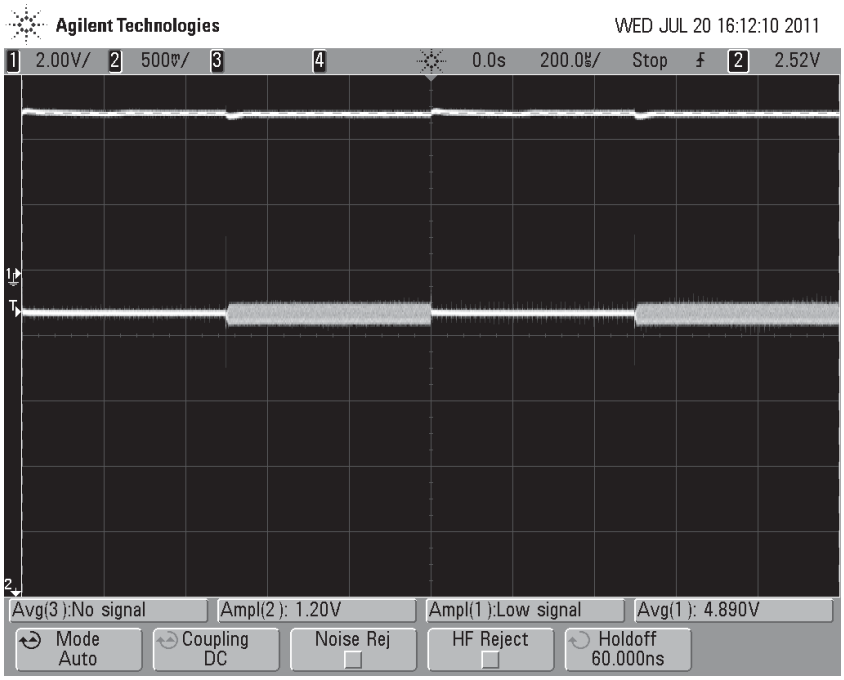

Figure 43. The 2.5 V MSK5920 low to high, high to low switching load characterization is shown here. The top trace is the input power supply, and the bottom trace is the regulator's output. The output capacitor was a CWR19 220uF 10V device (SN R0235) with a measured ESR of 413 mOhm. Note the ringing while at the maximum test load.