TID Test Results for 4th Generation iPad™

S. M. Guertin, *Member, IEEE*, G. R. Allen, *Member, IEEE*, S. S. McClure, *Member, IEEE*, K. A. LaBel, *Member, IEEE*

Abstract**-- TID testing of 4th generation iPads is reported. Of iPad subsystems, results indicate that the charging circuitry and display drivers fail at lowest TID levels. Details of construction are investigated for additional testing of components.**

I. Introduction

Modern smart phones and tablets carry significant computing power and an impressive collection of sensors, networking ports, and IO devices. In fact the iPhone 4 has been used by NASA during an ISS mission [1]. There is significant interest in determining the viability of using these units as-is for possible space use.

In general, commercial devices are enticing for satellite or astronaut usage. Significant processing increase can be achieved. For example, an iPhone 4S has about 10 times the processing power of a rover compute element on the MSL Curiosity rover [2]. However, these devices carry inherent risk due to being designed to perform well in a terrestrial environment. While they may perform well for very limited and relatively low reliability space missions, it is unclear what types of missions they may be appropriate for without testing.

This data workshop develops TID data on 4th generation Apple iPads to help establish the limiting features of possible use for space. It is unknown if users would be interested in flying them as assembled units, or if they would be selected component-by-component, or subsystem-by-subsystem for use in a space mission. Hence our approach is to develop relevant data concerning how the entire unit performs under whole-device total ionizing dose (TID) exposure using Co-60 and to provide an examination of the structure of the iPad and connect that information to how the device performs under TID exposure using protons where targeting can be setup to hit specific regions on the iPad – so that any failures may be linked to the components in the area of exposure.

Figure 1. The 4th Generation iPad™ from Apple Computer Inc.

II. Test Devices

This work concerns a very complex commercial system with essentially no radiation consideration included in the design or construction of the unit. Because of this we know we need to explore the types of components in the iPad and their physical positions in order to have a solid expectation of radiation-related failures and how to ensure we are testing for them appropriately.

Paralleling some other studies available [3-4], we opened and disassembled a functional unit in order to locate all the pieces and examine the components. The resulting collection of items is presented in Fig. 3 – Fig. 5. This analysis gives information concerning the types of devices present. Because of lack of knowledge about how components are selected for use in these tablets, we provide information about components but use that information only from a functional standpoint. For example, although our disassembled device uses Hynix flash memory, it is conceivable that another manufacturer could be used (and certainly different sizes – since the iPad is available with several flash memory options).

Using our teardown and those in other studies we identified the following active components of potential study

Manuscript received 7/8/2013. The research in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference herein to any specific commercial product, process, or service by trade name, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology. This work was supported in part by the NASA Electronic Parts and Packaging Program (NEPP)..

Steven M. Guertin is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 (USA), phone: 818-393-6895, e-mail: steven.m.guertin@jpl.nasa.gov.

Gregory R. Allen is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 (USA), phone: 818-393-7558, e-mail: gregory.r.allen@jpl.nasa.gov.

Steven S. McClure is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 (USA), phone: 818-354-0482, e-mail: steven.s.mcclure@jpl.nasa.gov.

Kenneth A. LaBel is with the National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, MD, 20771 (USA), 301-286-9936 ken.label@nasa.gov.

(many of which are highlighted in Fig. 3 – Fig. 5). These sources provided a fairly exhaustive list of components in the iPad. They are: Broadcom four-in-one combo wireless chip (BCM4334), Broadcom touchscreen controllers (BCM5974 and BCM5973), Cirrus Logic amplifier (CLI1583B0), Omnivision cameras (OV297AA, and OV290B), Dialog Semiconductor power management unit (D2018), Hynix NAND flash (2-die package) H2DTDG8UD1MBR, Hynix DDR2 DRAM (H9TCNNN4KDBMUR), Texas Instruments display port driver, NXP Semiconductor display port multiplexer (CBTL1608A1), Paradise LCD timing controller (DP635), Integrated Memory Logic programmable gamma buffer (iML7990), and RichTek touchscreen power management (RT9910). And the iPad is powered by the A6X system on a chip processing unit.

This list above does not explicitly indicate many of the sensors, which may be the most sensitive to TID. From a functional point of view we have broken the iPad down into the following subsystems: Processing unit – Apple A6X processor, Flash memory, DRAM memory, Battery power delivery, Battery charging circuit, Power input power delivery, Touchscreen, LCD output (retina™ display), Microphone, Speaker output and output jack, Wi-Fi antenna and adapter, GPS receiver, Three-axis accelerometer, Three-axis magnetometer, Cameras (2), and High speed IO port.

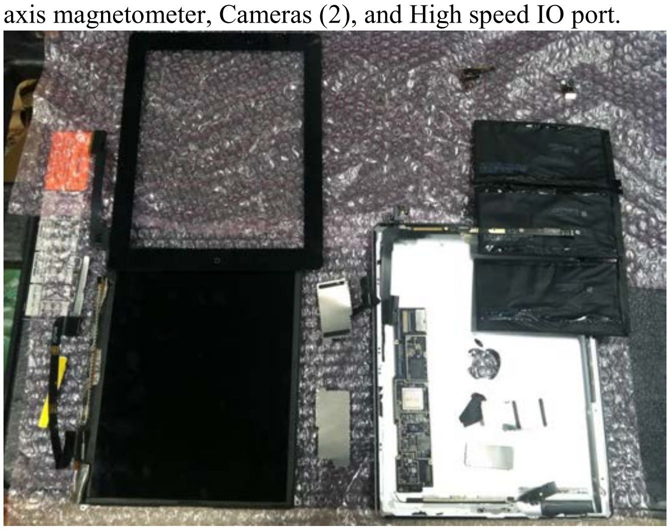

Figure 2. Results of tearing down a 4th generation iPad. The active components are primarily on the logic board in the middle of the case and along the side of the LCD. There are also two cameras and another device between the cameras.

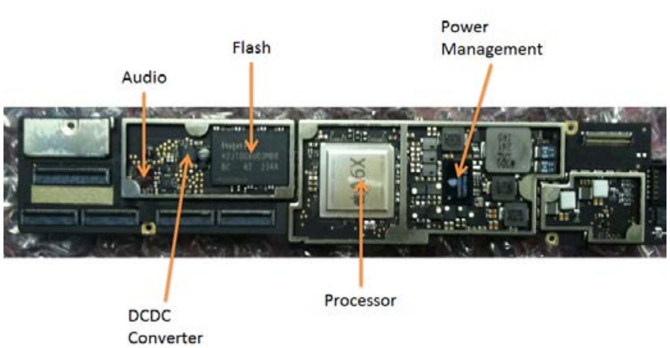

Figure 3. The front side of the main processing board for the 4th Generation iPad.

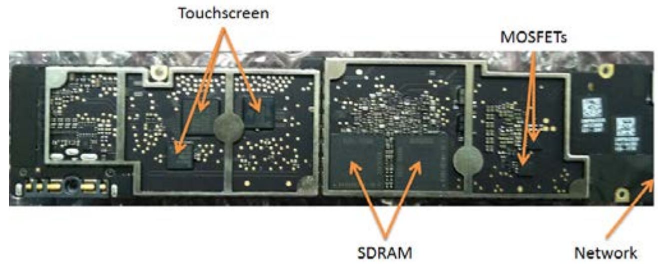

Figure 4. The back side of the main processing board.

Figure 5. The front side of the LCD board.

For Co-60 exposure we were able to use JPL's high dose rate room irradiator to provide flat-field TID exposure for all test points. For the proton exposures we utilized the teardown information and our own measurements of the positioning of circuit boards within the iPad, we determined a 2-inch-by-2-inch collimator would provide a controlled beam and that the collimated beam would expose all active components with only seven test points. This beam structure and positioning also ensured that no area of an active component would be overlapped by multiple beam exposures. The layout of the target locations is shown in Fig. 6.

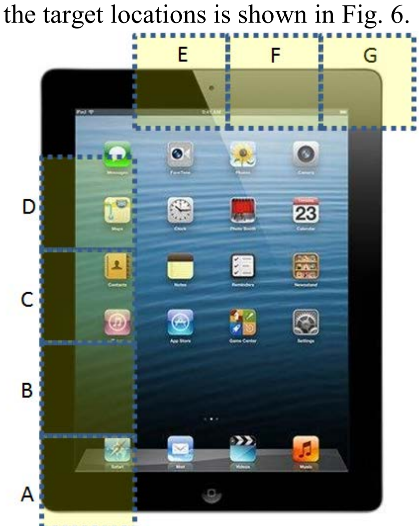

Figure 6. The beam positions used in proton exposure of the iPad.

In addition to the positions A-G, we also used a smaller collimator (2"x1") to avoid exposing the display board. This was done because it was known (and observed in proton exposure) that an early TID failure mode of the iPad is failure of the display. The alternate positions, (A'-D') were developed to expose only the microprocessor board.

During proton exposures the DUT was recorded with a high definition video camera. For biased exposures a facetime connection was recorded between the DUT and an external computer. This setup provided real-time information about the state of the DUT as well as providing a video record of anomalous behavior.

III. Test Approach

A key goal of this research is to establish an approach for overall evaluation, and then perform TID testing using the developed approach. It is desired that this approach include both the overall functionality of the iPad, but also be able to isolate and characterize individual components and subsystems in the iPad. The iPad is a collection of many subsystems, each of which has its own TID response, and each component in each subsystem would traditionally have a detailed TID test approach. However, it is not viable to perform all of the TID characterizations for every component or subsystem, because the characterization effort between TID steps would be overwhelming. Also, the data may be of limited value do to the lack of control over how the devices are constructed.

For this TID evaluation we have focused the approach into global testing of full units. And then after identification of the weakest elements, we identify those cases where it is possible to limit exposure to the weak element in order to find the next failing subsystem or element. We expected the majority of failures to be from linear bipolar devices and expect very little TID degradation of deep submicron logic devices due to improvements that are expected to apply to the memory and processor of the iPad [5].

For the data reported here, two test units have been evaluated for Co-60 TID and five have been evaluated for proton exposure (TID and effectively some SEE). Iit is unclear if additional devices would significantly improve statistics, due to lack of lot-to-lot and even manufacturer-level control on the components used from one iPad to another. The qualitative and quantitative results here provide a solid examination of the weakest subsystems in the 4th generation iPad with regards to TID and proton exposure.

Testing is performed by first characterizing the performance of each test unit using a set of characterization tests. Then testing proceeds by performing the two-step test operation of exposing the device and then characterizing it again. Testing was performed at ambient room temperature using JPL's Co-60 room irradiator. Devices were exposed to dose rates of 1 rad(si)/s. The basic characterization was performed using a positioning jig to ensure each unit is tested in the same orientation relative to gravity and local magnetic field. Power was provided with a standard iPad power adapter with the power line run through an ammeter to observe current. Two items of note: first the ammeter had to be tapped into the iPad's lightning adapter cable, otherwise the unit would detect a problem and would not charge correctly (i.e. we were not able to modify a USB extender cable and use that to monitor current); second, the location of any additional iPads (such as a control unit) is important because they have an internal magnet which can disrupt the magnetometer of nearby units.

Characterization was designed to test as many of the subsystems mentioned in Section II as possible. However it must be understood that some items, such as the battery charging system, would take prohibitively long to test at each characterization point. The majority of characterization testing was performed using either applications (apps) for the iPad (or iPhone), or by observing nominal operation of the device. Apps used are the following: xSensor [6] (for accelerometers, magnetometers, and GPS) – we did not use the special NASA SpaceLab app [1],[7] because it is not designed for terrestrial use and would not support the measurements needed; a standard video player was used to exercise biased samples during irradiation and provide a means to evaluate graphics and sound performance during characterization; a test pattern image was used; MP3 audio playback was used; and Passmark's iPad benchmark software [8] provided general benchmark results on DUTs (processor, memory, flash, and 2D and 3D graphics performance). We also observed the following behavior from the DUTs at each characterization point: verification of power up and down; observation of battery charging by way of current draw through the power adapter; photographs taken with fixed output brightness; and nominal behavior of the touchscreen as observed by the test engineer.

The xSensor used a basic positioning rig in order to guarantee the same placement (within our uncertainty limits) for each characterization and between units. Positioning was locked in by masking tape on a lab bench, as in Fig. 7.

Figure 7. Positioning of the iPad during characterization was ensured by matching to a masking tape jig.

In order to monitor the power delivered to the test units we modified a charging cable to enable the delivered current to go through an ammeter. We used this setup to monitor the charging current.

IV. Co-60 Test Results

Unbiased tests were performed at room temperature with the iPad in the "off" mode (power button held, then the slider dragged to turn the device off – though it still maintains some standby circuits). Devices were alternately characterized for performance and placed in front of the TID source for exposure to Co-60 gamma rays. TID levels at which characterization was performed were 200 rad(Si), 400, 600, 800, 1k, 1.3k, 1.6k 2k, 2.4k, 2.8k, 3.2k, 3.7k, 4.2k, 4.7k, 5.2k, 5.8k, 6.4k, 7k, 7.7k, 8.4k, 9.2k, 10k, 11k, and 12k. Functional failure was observed after 12 krad(si).

The three-axis accelerometer showed essentially no change over the TID exposure range. Fig. 8 shows the measurements taken in the 1st characterization position versus TID, for the biased testing. The magnetometer response was also taken and showed essentially no change over the exposure range. Fig. 9 shows the magnetometer measurements for the biased testing.

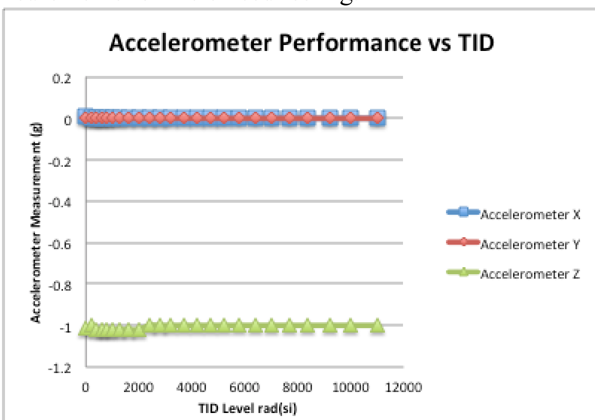

Fig. 8. The accelerometer performance for the biased iPad versus TID.

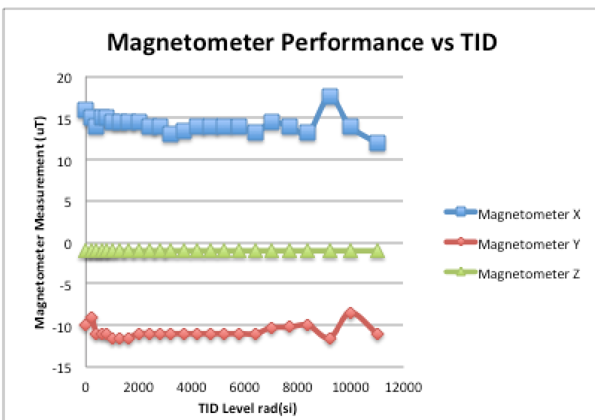

Fig. 9. The magnetometer performance for the biased iPad versus TID.

No apparent degradation of performance of any of the characterization operations was observed except for two that will be discussed shortly. That is, video playback, audio playback, photographs using both cameras, GPS measurement, and performance benchmarking (including processor, memory, flash, and GPU) had no significant change over the TID range used for biased testing.

Biased tests were performed at room temperature under nominal power delivered by the battery circuits. The devices were also powered via the iPad power adapter and charging cord. Devices were alternately characterized for performance and placed in front of the TID source for exposure to Co-60 gamma rays. TID levels at which characterization was performed were 500 rad(Si), 1k, 1.5k, 2k, 2.5k, 3k, 3.5k, 4k, 4.5k, 5k, 6k, 7k, 8k, 9k, and 10k. Functional failure was observed after 10 krad(Si). The biased testing showed the same leading performance degradation mechanisms. The accelerometer and magnetometer performance is essentially the same as in Figs. 8 and 9.

In unbiased testing, the first circuit to have degraded performance was the battery charging circuit. We observed this performance change by monitoring the current draw by the unit during characterization between exposures. The current draw of the lightning port on the iPad is shown versus TID exposure in Fig. 10. The current holds steady at just over 2A until something happens that makes the device essentially stop charging the battery. When this happens the current draw drops down to about 700mA. Because of observations when developing the charging current measurement setup, it is possible this is due to an inability of the iPad to determine the quality of the charging source. In the lower current mode the iPad appears to not use any battery power to operate, but also does not appear to be charging the battery. It is important to note that the current consumption of the iPad charging circuit is dependent upon both the state of the battery (fully charged or not) and the state of the iPad (active, asleep, or off). The unbiased sample had degraded battery performance by 3 krad(Si) while the biased device's battery charging survived longer, to about 9 krad(Si). This may indicate that low dose rate performance may be worse. 168 hour room temperature anneal of both the biased and unbiased samples have not shown any recovery in the current draw of the battery charging system.

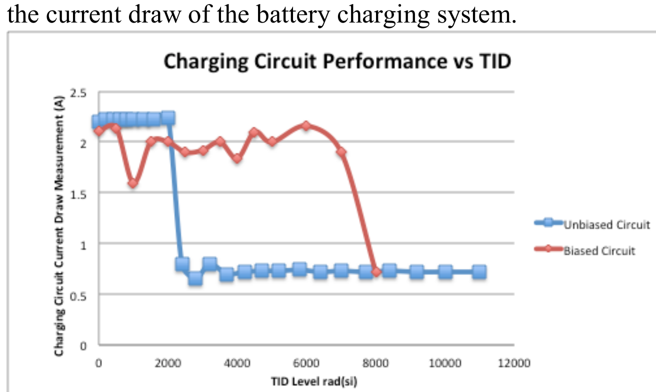

Fig. 10. The current drawn by the lightning port as a function of TID for unbiased and biased iPad exposures in active, charging mode.

The battery charging circuit failure behavior fit well into the test approach and we were able to continue irradiation of the iPads to the next failure. The next failure was the screen driver. The failure mechanism is that the screen is washed out to varying degrees relatively quickly close to the level at which it is completely washed out (gray). The degradation of the display is shown in 11. The screen is essentially useless by 11 kRads of exposure.

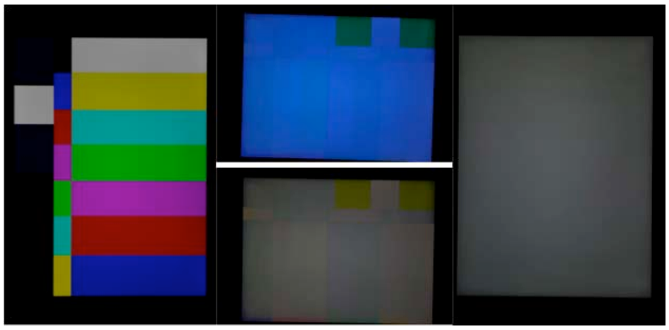

Figure 11. Degradation of the iPad display with increasing TID near the failure level of the screen.

A 168 hr room temperature anneal of iPads with unusable screens showed no improvement. However connecting the iPad to a VGA display through the lightning port showed that the iPad is still displaying useful information. Also we were able to verify that the touch screen still works properly and there is no indication of decay in calibration, though the test engineer has to fumble around to select the right icon to launch apps. The finding with the VGA port is new and the iPad testing will continue till the next failure of a subsystem on the devices.

V. Proton Test Results

Proton test results were varied. Most of the devices that survived to the Co-60 TID levels showed the same failure mechanisms as observed during Co-60 testing. That is, one of the test devices irradiated to 4kRad(Si) on positions A, B, and C showed failure of the charging circuit when unbiased. After this it was irradiated to about 8kRad at which point the screen stopped working.

Proton exposure also caused permanent failure with no Co-60 analog. This happened during exposure of the processor board in various positions. Failures occurred during exposures of about $2x10^{10}p/cm^2$, however because of the irradiation method (hitting multiple target locations with the same amount of beam) it is not obvious how to identify the failing position.

No permanent iPad failures were observed as a result of exposure at position A.

Permanent failures were seen after exposures of 4 kRad (approximately $2x10^{10}p/cm^2$) delivered to positions C and D. The former resulted in a device that no longer even tries to turn on, while the latter now exhibits infinite reboot behavior where the power switch brings up the screen with the Apple™ logo, but then after a delay it shuts off and starts up again. A third failure was observed with a similar infinite reboot behavior however the immediate exposure before observing the failure included 8kRad delivered to all positions A-D.

One device was singled out for exposure to positions A and C. This device received biased irradiation to more than $5x10^{10}p/cm^2$ at position A and more than $3x10^{10}p/cm^2$ at position C. No failures were observed in this device.

VI. Discussion

The primary finding of this work was that the 4th generation iPad™ shows many different and complex failure modes as a result of general TID and proton exposure. We observed charging circuit failures, degraded screen performance, failure to boot, and other failure modes where the device does not respond at all to being turned on. This is not surprising, however it is a difficult result to get a grasp of. That is, given the complex nature of the device one would likely expect many different possible failure mechanisms. However it is possible that given the high-end commercial nature of the device, cursory inspection may suggest that the system would work very well for TID and proton exposure since modern devices tend to behave well for both of these. However the reality is that the iPad is a combination of different systems and each has its own vulnerabilities to TID and SEE.

The key failures observed are listed below for the seven tested devices, observed across Co-60 and proton exposures.

1. Screen no longer usable: 1 – 8 kRad biased Co-60,
2. Charging circuit not working: 2 – 4 kRad unbiased Co-60 (next failure is screen at 11kRad); and 4kRad unbiased protons in positions A-C (next failure is screen between 8 and 12kRad)
3. Failed with no sign: 1 – 4 kRad biased protons in position C
4. Failed with infinite reboot behavior: 2 – one with 4 kRad delivered only to position D with protons; the other after 12 kRad delivered to A-D (device already passed with 20 kRad delivered to E and 8 kRads to A-D)

VII. Conclusion

Commercial computing devices such as Apple's 4th Generation iPad™ are enticing for solving many satellite computing problems simultaneously, but they cannot be blindly used from a radiation standpoint. We observed several different failure mechanisms – some of which are clearly related to accumulated TID while others may be related to SEE. Out test approach focused on general behaviors and we did not collect a statistically relevant sample size for all failure types observed. However our testing was destructive on all units tested (at various exposure levels).

This workshop presented TID test results on unbiased and biased test samples, showing the unbiased device has an initial drop in the charging circuit at about 4kRads. Both devices showed screen failures once TID reaches levels of 11 kRads. TID results from protons also mix in a limited amount of SEE information. Due to permanent failures and lack of configuration control the results are all statistically limited, however we found that a few locations on the processor and display driver boards were more likely to result in failures which were of a different sort than the TID testing and likely due to proton SEE. However, once the dose level reached the Co-60 failure levels the proton-tested devices also showed the Co-60 type failure modes.

VIII. Acknowledgment

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. This work was partially supported by the NASA Electronic Parts and Packaging Program (NEPP), and the Juno, SMAP, and MSL projects.

IX. References

[1] Paul, I.; "Apple's iPhone 4 Hired as Tricorder for Space Station", PCWorld article, (www.pcworld.com), (7/2011)

[2] Mack, E.; "iPhone processor way outguns Mars Curiosity rover's", CNET website (news.cnet.com), (8/2012)

[3] Yogasignam, A.; "Teardown: Apple iPad 4", EE Times, Nov, 2012 (http://www.eetimes.com/electronics-news/4400917/teardown-Apple-iPad-4?pageNumber=1)

[4] Slashgear, "iPad 4 teardown: More of the same (and a missed opportunity)", http://news.grouperly.com/news/ipad-4-teardown-more-of-the-same-and-a-missed-opportunity

[5] Fabula, J. J.; DeJong, J. L.; Lesea, A.; Hsieh, W.-L.; "The Total Ionizing Dose Performance of Deep Submicron CMOS Processes", MAPLD (2008)

[6] Xsensor software for iPad, https://itunes.apple.com/us/app/xsensor/id345145166?mt=8 (01/2013)

[7] SpaceLab for iOS, https://itunes.apple.com/us/app/id441829040?mt=8 (01/2013)

[8] Passmark benchmark software for iPad, http://www.iphonebenchmark.net/ (01/2013)