Printing the Future of Spaceflight: Simplified, massively redundant, solid state electronic and electrical systems for the future of spaceflight. W. Ray[1,4], M. Lownthal[1], B. Oraw[1], T. Youngbull[1], V. Lockette[1], L. Fabisinski/ISSI/ED04[2], D. Frazier/ZP30[2], C. Johnson/ED04[2], J. Rogers/EM50[2], K. Fuller[3], [1]NthDegree Technologies, Tempe AZ, [2]Marshal Space Flight Center, [3]Kafuller, Inc, Huntsville AL, [4]wjr@nthdegreetech.com.

Introduction: In response to elements of key challenge areas 2 and 3 for the Martian reformulation workshop, we present a new form of inorganic printed electronics (PE) that may help to solve some of the problems of long duration space exploration, particularly in terms of power generation and use. The technique demonstrated allows for very high speed, inexpensive production of such PE products.

A critical issue facing human Mars exploration is power. Previous studies have not been favorable to electrical power derived from photovoltaic (PV) cells on the Martian surface because PV array power generation suffers distance efficiency losses due to the inverse square law combined with the fact that any human Mars surface base will suffer atmospheric losses. We present here a relatively inexpensive, low-mass and easily packaged approach to PV arrays that can be rolled out to cover hundreds of square meters. Furthermore, their inherent radiation insensitivity will increase their usable lifetime, thus reducing mission risk and overall mission cost due to our novel implementation of the philosophy of statistical electronics.

We will also address some of the unique problems of long duration missions such as; 1) extreme environment (Single Event Effects, the need for radiation hard systems) and 2) critical system persistence in an environment that is unforgiving in terms of replacement or repair of malfunctioning systems.

To this end, we will briefly describe three printed technologies that are relevant to spaceflight and we will propose what we believe to be a new, highly persistent approach to spacecraft and Mars based electrical systems.

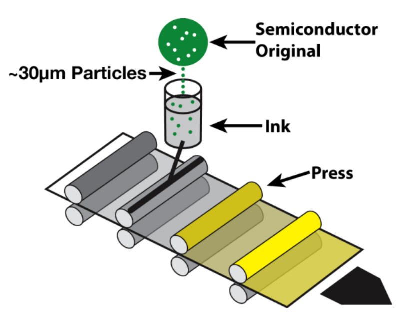

Figure 1: The PE manufacturing process.

Figure 1 illustraes the general ink and printing process used in this approach to printed electronics manufacturing.

Printed Photovoltaic Panels:.As illustrated in Figure 2, we have designed and are building thin, very lightweight micro structured monocrystalline photovoltaic (PV) modules using printing and slot die coating techniques. The PV device is a low cost monocrystalline silicon sphere with a printed concentrator. The P-N junction is installed inline. The resulting materials build has an estimated cost below $22/m2 and a currently estimated AM 1.5 efficiency of 15% that may approach 20% over the next few years. Panels derived from this material are flexible and have an extremely low mass of 0.2kg/m2.

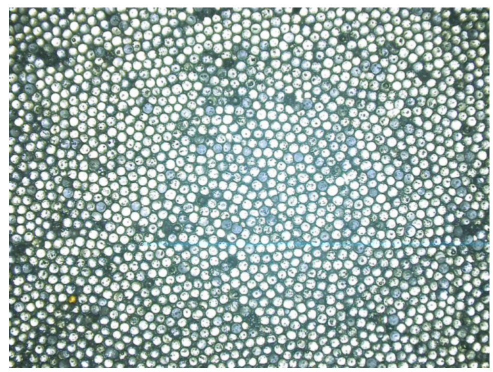

Figure 2: Photovoltaic monolayer.

The design of the device allows capture of both diffuse and direct light, and eliminates the need for tracking devices through spherical optics while improving light capture efficiency by up to 60%. The PV device will incorporate a UV downshifting layer that is expected to dramatically improve efficiency in the space environment.

Elsewhere, we have proposed printing PV arrays onto a fluted balloon for micro satellites. If we were to print a balloon very much like ECHO 2 (41m diameter, 256 kg balloon) then, at 15% conversion efficiency, this would yield about 250 kW of power output continuously regardless of orientation.

Because the device is extremely light it could be carried up in a small package and simply inflated with a few pounds of gas. Indeed, because of the low mass, multiple backup systems could be carried for manned systems.

Printed Power Storage: Electronic Double Layer Capacitors (EDLC) store electricity by physical charge separation. EDLC charge is stored through reversible ion adsorption on high surface area electrodes. The purpose of this research is to build lightweight, printable supercapacitor "plates" from carbon nanotubes and ionic liquids that can be stacked and wired in parallel (or series – parallel depending upon requirements) in order to act as either a portable battery replacement or as a fixed electrical "buffer" storage for distributed power systems.

Figure 3 illustrates where EDLC devices stand in the existing energy storage hierarchy. To date, we have

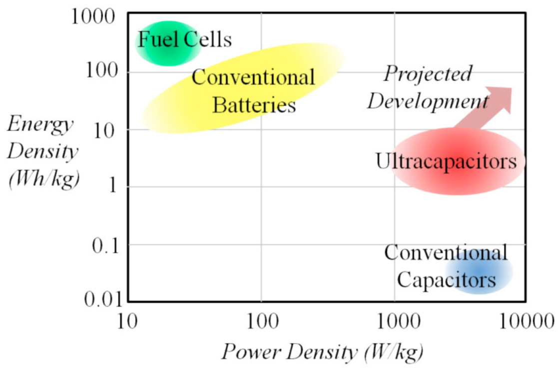

Figure 3: Plot of power versus energy by source. Note the upper right shift in performance.

achieved significant improvements in the energy density of our laboratory devices versus traditional EDLC builds. Figure 4 is an image of a current test device. The theoretical potential for this device greatly exceeds 200 F/gm.

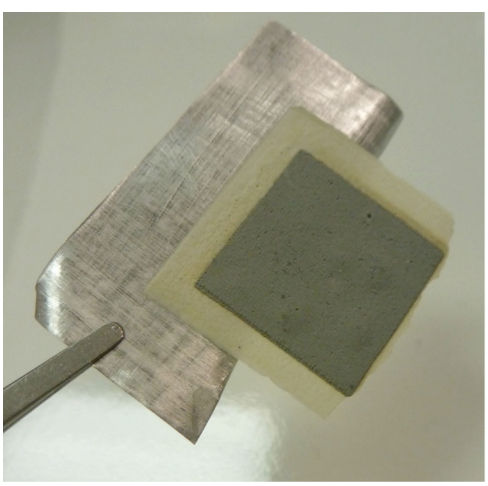

Figure 4: EDLC device separated for inspection.

Printed LED Lighting: Micro LED die structures emitting 450 nm were fabricated using a mask set developed for this purpose. As illustrated in Figure 5, the 27µm die were released into a proprietary ink binder developed for this purpose.

Figure 5 photographically illustrates two sections of a printed light panel. This panel section is less than 150 m thick, is 7cm X 14 cm and weighs about 3.75 grams, not including the electrical leads. The panel section operates in the mid 40°C range without a heat sink.

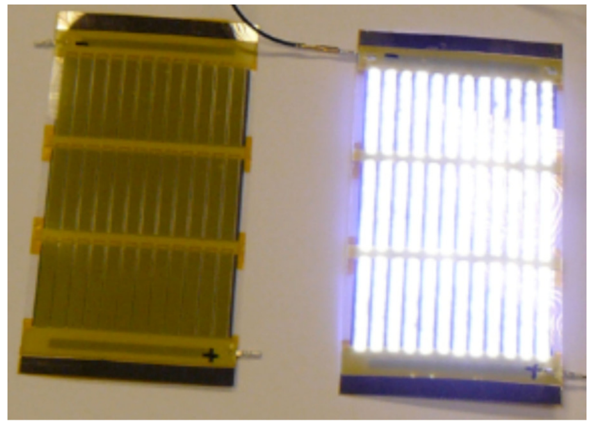

Figure 5: Unpowered and powered lighting panel.

The Philosophy of Statistical Electronics: The nature of printing is statistical and our inks will demonstrate a random dispersion using the printing techniques that we have currently. For instance, an orthogonal array of N discrete devices will be difficult to produce at this juncture, however, an orthogonal array of N cells of M devices per cell is nearly certain of success. Thus, the concept of *statistical electronics* where M self-similar devices are functionally equivalent to the individual discrete device N.

Simple transistors present the same statistical problem certain LED designs do in the sense that up / down orientation is somewhat random. The statistical electronics model assumes that printed devices fall into two groups – functional orientation or non-functional orientation ("yes" or "no") and that there can be no other orientation. Statistical builds presuppose that devices are printed in functional areas and that, within a given area, the devices are wired in parallel. Therefore, all that is required for, say, logic or a switch, is that at least one "yes" device be printed in a given functional area.

Two critical things are gained by statistical electronics. These are 1) massive parallelism where an individual device failure does not yield a function failure and 2) the ability to manufacture electronics in a similar fashion to "post it" notes that can both easily be carried and easily replaced via "peal and stick" techniques and conductive wiring pens. Persistence and massive redundancy are a necessary part of the route to Mars.