PL-TR--95-1149

THIN ONBOARD POWER STORAGE FOR PHOTOVOLTAICS (TOPS-PV)

Joseph H. Armstrong, Ph.D

ITN Energy Systems
Wheat Ridge, CO

October 1995

Final Report

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This final report was prepared by ITN Energy Systems, Inc, Contract F29601-95-C-0075 Job Order, 3005C0JV, with Phillips Laboratory, Kirtland Air Force Base, New Mexico. The Laboratory Project Officer-in-Charge was Lt Keener (VTP)

This report has been reviewed and is approved for publication.

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1. Report Date (dd-mm-yy) October 1995	2. Report Type Final	3. Dates covered (from... to) 03/95 to 12/95
4. Title & subtitle Thin Onboard Power Storage for Photovoltaics (TOPS-PV)		5a. Contract or Grant # F29601-95-C-0075
		5b. Program Element # 62601F
6. Author(s) Joseph H. Armstrong, Ph.D.		5c. Project # 9991
		5d. Task # SB
		5e. Work Unit # IR
7. Performing Organization Name & Address ITN Energy Systems Wheat Ridge, CO		8. Performing Organization Report #
9. Sponsoring/Monitoring Agency Name & Address Phillips Laboratory 3550 Aberdeen Ave SE Kirtland AFB, NM 87117-5776		10. Monitor Acronym
		11. Monitor Report # PL-TR-95-1149

12. Distribution/Availability Statement
Distribution authorized to DoD components only; Proprietary Information; October 1995. Other requests for this document shall be referred to AFMC/STI.

13. Supplementary Notes

14. Abstract Thin Onboard Power Storage for Photovoltaics (TOPS-PV) is a concept where a thin, flexible battery is placed onto a thin, flexible photovoltaics device, thereby consolidating both electrical power generation and power storage. Flexible PV has been demonstrated in both amorphous silicon (a-Si) and copper-indium-diselenide (CIS), as well as laboratory-scale flexible solid-state lithium ceramic batteries. However, no attempt has been reported at combining the two technologies. This concept would reduce the cost, weight, and storage volume of both the PV array and the battery storage required in the spacecraft bus. The TOPS-PV program investigated the combination of the solid-state battery and a-Si to determine the compatibility of the two technologies with regard to roll-to-roll manufacture. Phase I investigated the PV/battery stack using existing PV devices and sputtering, chemical vapor deposition, and evaporation battery processing techniques.

15. Subject Terms Thin film, photovoltaics, flexible, batteries, integrated, power system.

Security Classification of			19. Limitation of Abstract	20. # of Pages	21. Responsible Person (Name and Telephone #)
16. Report unclassified	17. Abstract unclassified	18. This Page unclassified	Limited	64	Lt Dave Keener (505) 846-5393

GOVERNMENT PURPOSE LICENSE RIGHTS (SBIR PROGRAM)

Contract Number: F29601-95-C-0075
Contractor: ITN Energy Systems
Wheat Ridge, CO

FOREWORD

This document represents the Final Report for the Air Force Phillips Laboratory (AF/PL) Small Business Innovative Research (SBIR) project entitled "Thin Onboard Power Storage for Photovoltaics (TOPS-PV)," Contract Number F29601-95-C-0075. Period of performance of this program was from 13 March through 13 October 1995. The program was performed by Dr. Joseph H. Armstrong of ITN Energy Systems, Inc. (ITN/ES), Wheat Ridge, Colorado. Lt David Keener, PL/VTPP, served as Project Manager.

The author would like to acknowledge valuable discussions with the following ITN/ES personnel: Dr. Mohan S. Misra, President of ITN/ES; Mr. Robert Wendt, Program Manager, ARPA Vapor Phase Manufacturing Program; Mr. Robert Hanson, Marketing; and Mr. Tim Havens, Technical Staff. These discussions were very useful in determining the proper scope and direction of this and subsequent efforts. The author would also like to express his gratitude to Dr. David Olson of the Colorado School of Mines for his timely discussions regarding processing and analyzing lithium-bearing materials.

This work was conducted in collaboration with Dr. Steve Jones, Eveready Battery Company, Westlake, Ohio where the thin-film batteries were deposited. EBC performed these tasks at no cost to the program.

We at ITN/ES would also like to thank Lt Keener, Lt Marc Rainbow PL/VTPP and Mr. Drew Sommerville, Aerospace Corporation for their help and guidance in this effort.

CONTENTS

FIGURES

FIGURES (continued)

TABLES

EXECUTIVE SUMMARY

There is a continuous drive in the development of satellite power systems to produce cost effective, lightweight, stowable, and efficient power systems. One approach to accomplishing this overall goal has been the development of thin film photovoltaics and batteries. Thin film amorphous silicon (a-Si) and copper-indium-diselenide (CIS) are two types thin film photovoltaics and several types of thin batteries have been developed including lithium ceramic technology. The concept investigated during this project was a combination of photovoltaic and battery technologies into an integrated, modular, flexible power system. Such a system could have significant positive impact on the specific power of space power systems especially for small satellites. This report describes the efforts of ITN Energy System to develop Thin Onboard Power Storage for Photovoltaics (TOPS-PV) under the Phase I SBIR Contract No. F29601-95-C-0075. The period of performance of this project was 17 Mar - 13 Oct 95.

The objectives of this program were to demonstrate a thin film PV/battery stack in terms of material interactions. The demonstration was to produce several devices and demonstrate each device individually while showing no degradation over several cycles. Deposition of the batteries on the PV devices was the most significant technical problem of the project.

ITN's approach to this project was to team with Eveready Battery Company for the deposition of the batteries because they had developed the battery technology and had the equipment to deposit them. Two sets of samples were accomplished during the

program and each showed significant degradation after only a few cycles. Reasons for the degradation were generally attributed to a reaction of the Kapton substrate with moisture. Unfortunately, because of management and equipment problems encountered with Eveready during the remainder of the project, no other meaningful samples were produced. The initial results collected during the initial samples were encouraging and informative, but overall, the project fell short of meeting its stated objectives.

The benefits of this type of modular power system are definitely still on the horizon, and this project has taken the first steps to developing such a system. Because of the technical problems encountered, however, the program was truncated after Phase I.

1.0 INTRODUCTION

For many years, reliable, clean, compact electric power generation has been a goal for both space and terrestrial applications. Due to the great expense associated with on-orbit maintenance of spacecraft, and the difficulty of reaching remote sites housing critical terrestrial applications, reliability throughout the serviceable life of the power source is essential (Fig. 1). Cleanliness of the power system is also essential. Exhaust emissions for space applications are generally considered undesirable due to sensitivity of electronic components and onboard sensors; likewise, emissions are being curtailed in terrestrial applications as well. Size of a given power source is driven by several factors: its efficiency at converting electricity from its energy source, the ability of its components to operate effectively throughout the designed lifetime of the system without significant oversizing and/or redundancy. Neither the space nor the terrestrial community are complacent regarding the present state of power generation in their respective products.

Several configurations of electric power generation systems exist, but all have significant tradeoffs regarding their use. A common source for electric power generation, burning fossil fuels and converting the subsequent release of energy into electricity, is impractical for both space and remote terrestrial applications due to the requirement of transporting and storing fuel for combustion and the associated exhaust emissions. Nuclear energy has been used for space and terrestrial applications. However, increasing concern over nuclear waste handling, reliability and safety of the nuclear process, and associated political sensitivity to the proliferation of nuclear materials have limited its use in space to deep space probes and have all but excluded nuclear power from consideration in future terrestrial applications. Other sources of electrical energy generation, such as wind energy, obviously is limited to terrestrial applications.

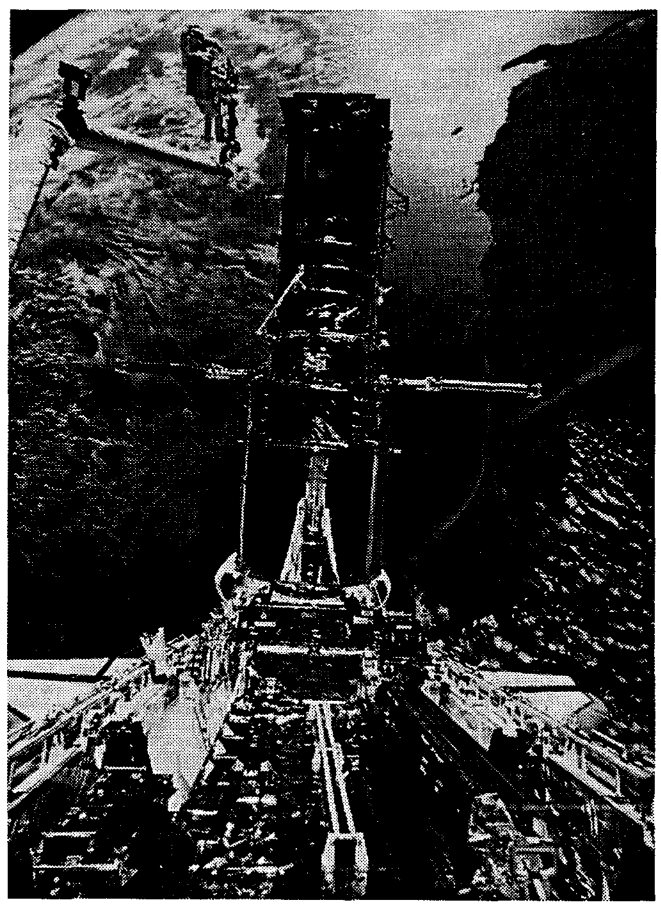

Figure 1. ***Photograph of Hubble Telescope Repair Mission Which Replaced Several Systems, Including Photovoltaic Power Components.***

The most widely-used electric power generation solution in space applications, and a solution gaining ground for remote electric power generation on earth, is photovoltaic energy. Photovoltaics (PV) is a technology in which photons (generally in the visible spectrum) are converted to electrical current in an elegant, solid-state manner which does not have moving parts to reduce reliability. Most common PV devices are rigid, semiconductor wafer-based solid-state devices. However, companies such as ITN Energy Systems Inc. (ITN/ES) are developing low-cost, lightweight, flexible polycrystalline thin-film PV devices. Arrays made with this technology are easier to store and represent a much higher power density technology than conventional rigid solid-state devices.

Unfortunately, neither spacecraft nor terrestrial applications have uninterrupted access to the sun for energy conversion. In fact, the demand for power is often the greatest when the sun is inaccessible. In applications where continuous power is required, rechargeable (secondary) batteries are used to store electricity for use when the sun is shaded from the array. Secondary batteries used in photovoltaic power systems have been an Achilles' heel, primarily due to excessive weight, limited service life, substantial form factor, and cost associated with them. Weight is especially an issue with common battery technology such as lead-acid. Nickel-Cadmium (NiCd) suffers from a memory effect where precise charge-discharge protocol must be followed to ensure continued performance. NiCd, along with other technologies under investigation, such as nickel-metal-hydride (NiMH), have limited charge-discharge cycle life at useable depth-of-discharge (DOD), thus requiring PV system designs to over-size battery systems. Packaging for these power storage components can account for significant volume in spacecraft, and can often require entire buildings in terrestrial applications.

As a result, ITN/ES is developing a lightweight, flexible thin-film battery technology based on a patented Eveready Battery Company (EBC) concept to complement ITN/ES' flexible thin-film PV products. Both ITN/ES and the Air Force Phillips Laboratory (AF/PL) Space Power Branch are interested in the actual integration of the PV and battery technologies into a single device which would allow for a stowable, lightweight, self-contained power generation and storage unit. This document represents the final report of an Air Force Phillips Laboratory Phase 1 Small Business Innovative Research (SBIR) program awarded to ITN/ES to investigate the feasibility of combining flexible photovoltaic and battery technologies.

1.1 PHOTOVOLTAIC POWER GENERATION

Nearly all spacecraft launched to date, and a growing number of terrestrial applications, utilize PV as a source of electrical power. In terms of history, PV was selected as an afterthought for a backup power supply on the US' first satellite, Explorer. Designers assumed that a primary battery would provide sufficient power for the intended life of the satellite. Due to a lack of knowledge concerning battery performance in the space environment, however, the selected battery failed and the backup power supply, namely the PV, remained to power the satellite. PV was used for subsequent flights because of its ability to provide clean, reliable renewable energy without costly weight for additional fuel. These features are also becoming attractive for terrestrial applications as PV system costs decrease.

Photovoltaics is the science of converting electromagnetic radiation, usually visible or near-visible light, into electricity. Basically, the foundation of the photovoltaic effect is that semiconductor materials, which normally behave like an insulator, become electrically conductive when subjected to an external source of energy. In this case, photons enter the semiconducting material and generate electrons and holes. If left unaltered, no current would flow because there is no electric field. However, if this semiconductor material is a junction by virtue of a p-type (excess holes) and n-type (excess electrons), a potential barrier is formed. This potential barrier separates free holes and electrons from the p-type material and forces electrons in opposite directions as shown schematically in Figure 2. Thus, the electric field generated makes the solar cell act as a battery and generates a current with a relatively fixed output voltage. By collecting the photocurrent generated by this effect, an operating solar cell is formed.

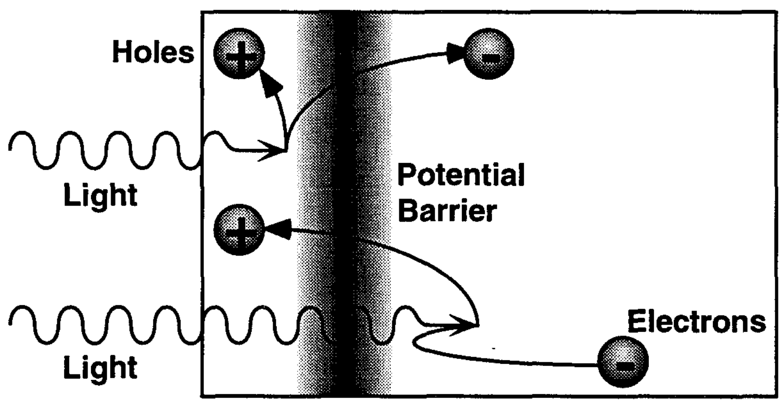

Figure 2. Schematic of the Photovoltaic Effect in the Presence of a Potential Barrier.

Many types of solar cells exist. Most common is crystalline silicon (z-Si) which utilizes a homojunction structure; namely, a single Si wafer provides the basis for the solar cell and dopants are introduced to the material to form p-type and n-type parts within the silicon.

Crystalline solar cells are limited in size to the largest high-quality monocrystalline or polycrystalline boule available (presently 8 cm x 8 cm is the practical limit). Thin-film technologies are emerging as a potential replacement of z-Si if production and reduced cost can be realized. Thin-film devices involve stacking of semiconductor materials with appropriate electrical properties to produce the junction. Amorphous silicon (a-Si) can employ a p-i-n structure with an intrinsic material placed between the metallurgical junction, while other devices such as copper-indium-diselenide (CIS) can have a simple p-n stack to form the junction. Thin film devices are only limited in size by the deposition equipment used to lay down the individual films; 30 cm x 120 cm devices are commonplace.

The basic design of a photovoltaic system which is a primary source of power for an application is the same for either space or terrestrial applications. A schematic of components contained in a photovoltaic power system is shown in Figure 3. First, the electrical energy is converted from solar energy by the PV solar cells assembled into an ***array***. In applications where uninterrupted electrical power is required, some sort of electric ***battery storage*** is required. The state of charge of these batteries is maintained by ***charge control circuitry*** which monitors the state of charge of the batteries and disconnects them from the PV array when charging is complete. The main difference between space and terrestrial is how the arrays are disconnected from the batteries; spacecraft often shunt this power to keep the arrays cool and to prevent surges through electrical harnesses that can harm sensitive instruments, while terrestrial controllers merely disconnect the array when the charge has been reached. Charging circuitry can also vary the rate of charge and two-stage charging systems are common.

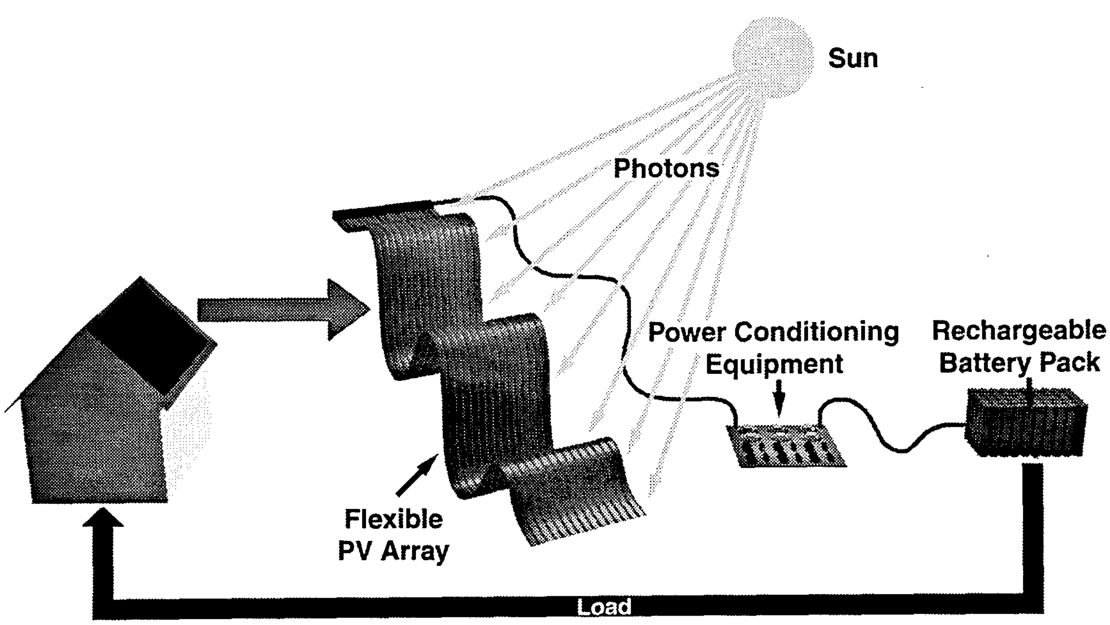

Figure 3. Schematic of Components in a Photovoltaic-Based Electrical Power Generation System.

1.1.1 Environment and its Effect on PV System Design.

Unique requirements for space and terrestrial applications initially resulted in a divergence of goals. Traditionally, primary emphasis within the relatively-small volume (100-150 kW/year U.S.) space market has been end-of-life (EOL) system efficiency due to its implications on array size and weight. Terrestrial emphasis has been on EOL cost per watt due to its implications on system cost and project feasibility. With severe budget constraints on space programs, however, even the space community can benefit from much of the terrestrial low-cost technology developments. Both are discussed below.

1.1.1.1 Space Application Design Issues. Space applications are extremely sensitive to weight, stowage volume and, recently, cost. These three constraints upon spacecraft are interwoven; none of them are independent. For example, weight can limit a spacecraft to a larger launch vehicle, thereby increasing launch costs. Even for a given launch vehicle, launch cost savings range from $10K/lb to $50K/lb. Likewise, spacecraft stowage volume constraints can drive a spacecraft to a larger launch vehicle, or limit the number of simultaneous launches of a given launch vehicle.

While space may appear to be the ideal environment in which to operate a solar electric power system, many complications exist which tax many systems selected to generate power, including duty cycle and environment. Duty cycle, while predictable for a given mission, varies dramatically from mission to mission. This variability has led to PV power system designs to be rather unique for a given application or mission. Space environmental issues include temperature extremes and radiation environments. The actual temperature experienced by a PV power system in space varies dramatically at a given time. While space components are often tested between -100°C to +150°C, the solar array, which is subjected to sunlight, can exceed 100°C while the battery, which is in the shade within the spacecraft body, must rely on its own heating to remain in operation. Because a spacecraft in orbit can pass through the Van Allen radiation belts, the PV power system (as well as onboard electronics) must be designed to survive charged particle and X-ray environments. Also, the degree of radiation bombardment varies with orbit and mission length. Thus, EOL efficiency of the entire system affects weight, volume, and ultimately, cost. Component cost itself can be a major driver as well, especially with the new class of low-cost, small, lightweight spacecraft under consideration.

1.1.1.2 Terrestrial Application Design Issues. While terrestrial applications do not subject PV systems to extremes noted in previous discussions of space applications, an entirely different set of requirements for terrestrial applications are equally as challenging and affects EOL cost per watt. First, terrestrial PV systems must survive erosive and corrosive environments, including moisture, salt spray, wind-blown particles, and oxidation. While temperature swings are not as extreme, they are nonetheless critical because methods for protecting the PV system from the above environments can be far more sensitive to temperature than the PV system itself. Terrestrial applications also must cope with a variable duty cycle due to weather-related potential sources of sun blockage not encountered in space. Clouds and inclement weather can obscure sunlight, thus requiring more power generation and subsequent storage than a space-based system. For example, a terrestrial-based system may be required to operate solely from battery storage for several days or even weeks due to inclement weather, thus dramatically increasing the battery storage system requirements. Correspondingly, the solar arrays must be oversized in such a way as to charge the batteries sufficiently.

1.1.2 Critical PV Power System Components

In both space and terrestrial applications, however, power generation and storage components are under scrutiny as areas requiring vast improvement. Below, the two major components of the PV system, namely the (1) PV array and (2) storage battery, are discussed in reference to both space and terrestrial application requirements.

1.1.2.1 Photovoltaic Array. Common to all of the common photovoltaic (PV) arrays is a component called a submodule. A rigid submodule consists of PV cells interconnected in a pre-determined pattern of series and parallel connections to achieve desired output voltage and current. Solar cells, such as crystalline silicon (z-Si), produce a set voltage (≈ 0.5 V) and as such, must be connected in series called a "string" to achieve a usable voltage (nominally 24 volts). These strings are then interconnected in parallel to achieve desired current density, thereby increasing the power capability of the submodule. These submodules are then encapsulated to form the PV module. Figure 4 is a schematic comparison between (a) a rigid crystalline solar cell module, (b) a rigid thin-film module, and (c) flexible thin-film module for terrestrial applications. In a conventional rigid crystalline PV array (Fig. 4(a)), solar cells are interconnected by soldering and bonded in a string onto a rigid substrate. This subassembly is known as a submodule. EVA, an encapsulant, is placed between the submodule and a protective tempered glass and heated to seal and protect cells from hail and rock impact, as well as moisture and corrosion. Conventional space arrays are constructed in a similar fashion to Figure 4(a) except that the EVA, glass and frame are replaced by a thin "microsheet" of glass designed to shield the solar cell from radiation. A rigid thin-film array uses the basic encapsulation scheme as

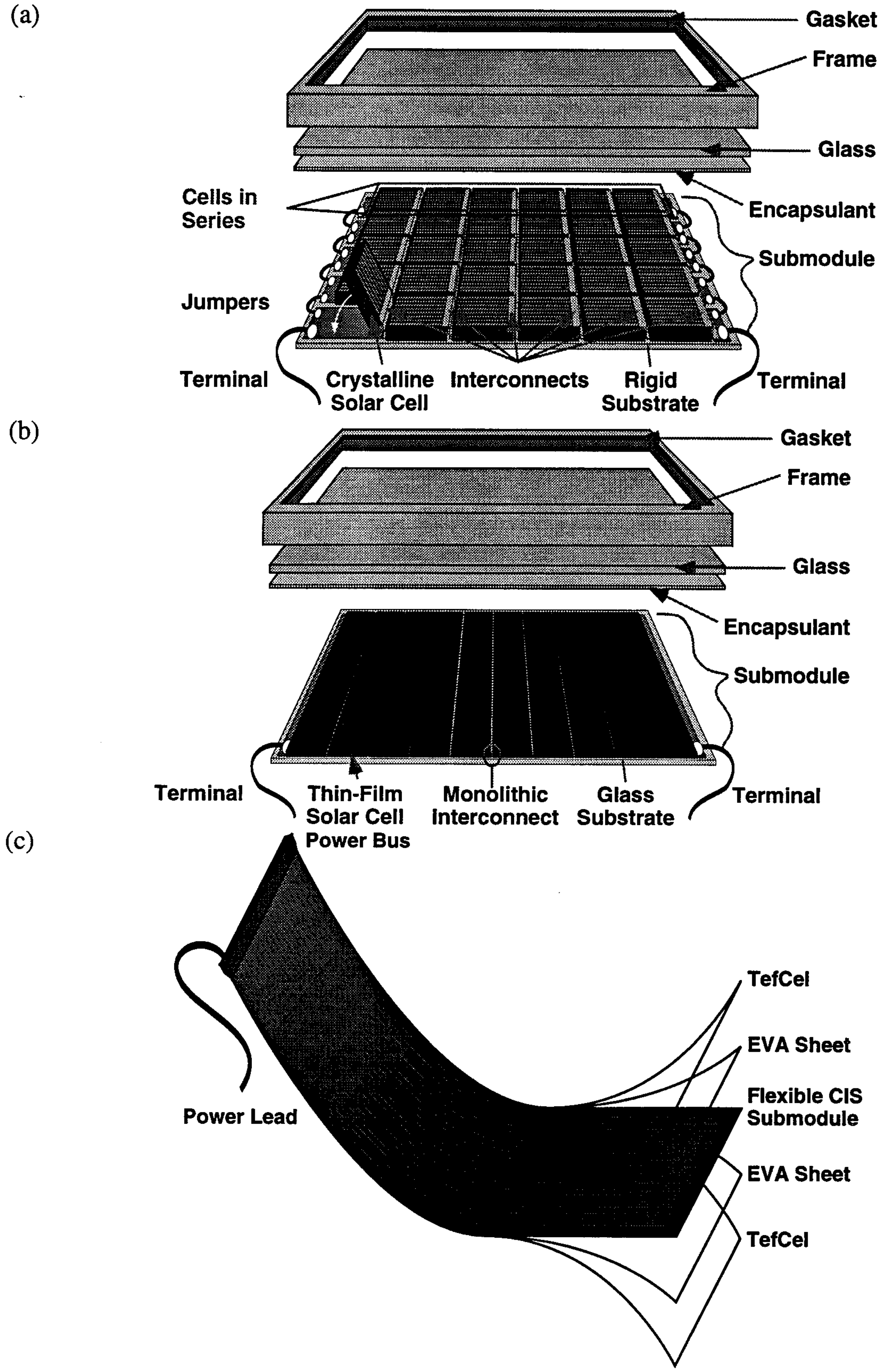

Figure 4. Comparison Between (a) Rigid Crystalline PV Module, (b) Rigid Thin-Film PV Module and (c) Flexible Thin-Film PV Module.

shown in Figure 4(a), but thin-film cells in the submodule are interconnected during manufacture by a process known as "monolithic integration". Thus, much of the "touch labor" is eliminated and module cost can be reduced. By utilizing flexible thin-film PV, such as amorphous silicon (a-Si) and copper-indium-diselenide (CIS), a significant portion of the array weight can be eliminated. As shown in Figure 4(c), a flexible PV array can include encapsulation for moisture and corrosion protection while accommodating roll up for compact stowage.

CIS and a-Si modules can eliminate manual interconnecting of cells through the use of monolithic integration as shown schematically in Figure 5. Monolithic integration of the module provides two distinct advantages over conventional interconnect schemes, namely (1) lower cost through reduced touch labor and automated processing, and (2) enhanced reliability of solid-state interconnects compared to manually soldered joints. Patterning of the submodule during monolithic integration is dictated by the desired voltage and current output. Each cell generates a voltage based on the physics of the semiconductor materials used.

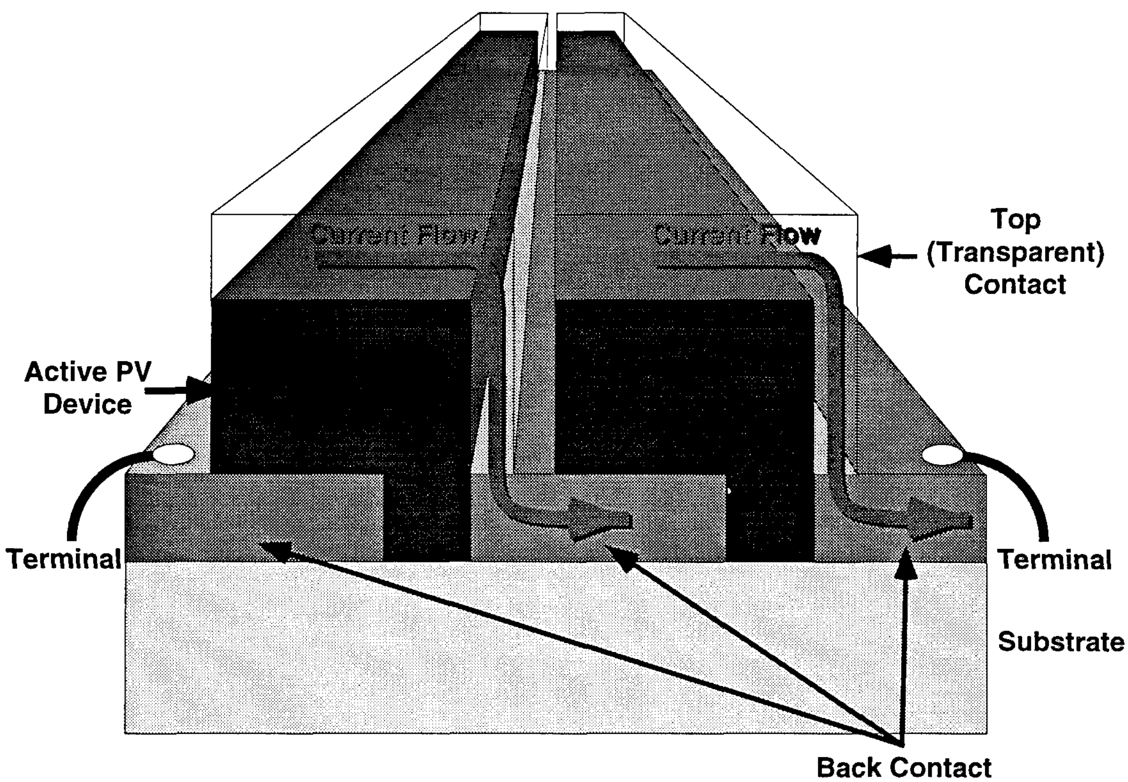

Figure 5. Schematic Representation of Monolithic Integration of Thin-Film Devices.

Thin-film PV is the subject of extensive investigation due to its potential for low-cost manufacturing (Refs 1-5), excellent resistance to both space (Refs 6-8) and terrestrial environments

(Ref 5). In particular, interest in flexible devices for space and terrestrial have the potential of combining high power-to-weight ratio, low stowage volume, and low manufacturing cost (Refs 9-11). CIS cells have been demonstrated on flexible substrates which allow submodules to be rolled up for reduced shipping cost and weight. Fabrication of amorphous silicon (a-Si), another thin-film PV technology, has been demonstrated on roll-to-roll processing equipment with polyimide substrates. Roll-to-roll, or web processing, can result in further reduced manufacturing cost, as well as easier transport of final product as continuous roll of PV material. CIS roll-to-roll development is being pursued by ITN/ES in conjunction with Iowa Thin-Film Technologies, Inc. (ITFT), and ITN/ES is the sole distributor of ITFT technology for space applications. Figure 6 is a photograph of the ITN/ES web coater to be used for a variety of thin-film projects, including thin-film batteries. As a result, ITN/ES, other PV manufacturers, and universities have initiated programs to develop a highly-reliable scalable manufacturing process to provide significant quantities of thin-film PV (Refs 12-14).

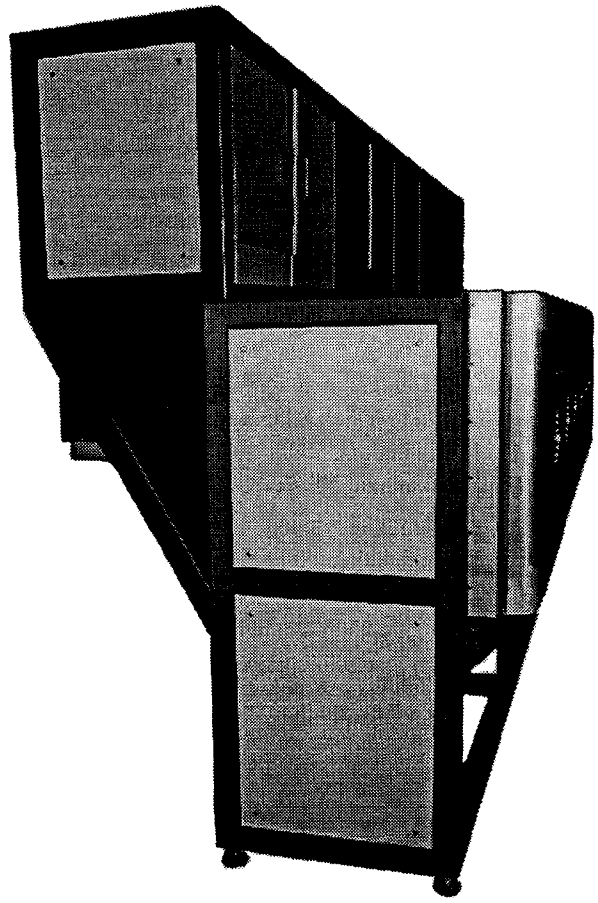

Figure 6. Photograph of ITN/ES' Web Coating Deposition System.

A PV array must be sized such that sufficient power is collected during solar exposure to provide power for an entire solar cycle (sunlight and eclipse). For terrestrial applications, this period is nominally 24 hours, although weather can increase the eclipse period. Space application solar cycles are determined by the spacecraft orbit. Regardless of the application, the array power requirement (P_{sa}) can be determined by the following relationship (Ref 15):

$$P_{sa} = (P_e T_e / X_e + P_d T_d / X_d) / T_d \qquad (1)$$

where P_e and X_e represent the load's requirements in power and transmission efficiency during the eclipse period of duration T_e, and P_d and X_d represent the load's requirements in power and transmission efficiency during the solar exposure period of duration, T_d. X_e and X_d can vary between 0.65 and 0.85 for direct energy transfer and 0.60 and 0.80 for peak-power tracking. Once the power requirement is determined, the efficiency of the solar array to convert sunlight into electricity, the solar insolation on the array, and the stability of that array during the designed life of the power system determines the array size. Typical efficiencies for crystalline silicon can range from 11% to 18%; recent laboratory results for CIS with low-cost potential were 17.1% at the National Renewable Energy Laboratory.

1.1.2.2 **Electrical Energy Storage.** As was the case with PV, not much significant change has occurred with battery technology since its inception. Most terrestrial systems worldwide utilize crystalline silicon (Si) with liquid electrolyte lead-acid batteries. Small electronics applications primarily use nickel-cadmium (NiCd) and are now starting to design with nickel-metal-hydride (NiMH) and lithium ion (LiI) batteries which allow for rapid charging and higher power density. Typically, crystalline Si and gallium-arsenide (GaAs) are used in space applications to generate electrical power for charging onboard NiCd batteries, with some use of NiMH and research into common pressure vessel (CPV) Nickel Hydride. Regardless of application, however, batteries account for significant weight, storage volume and cost of a PV power system.

Space Applications. While each component of a power system can affect the final performance, we will consider the most prominent, namely power generation and storage. Aspects that can affect these constraints include 1) battery power density, 2) production volume, 3) cycle life and depth of discharge, and 4) battery form factor.

Unlike past space markets, near-term and future space applications have imposing requirements upon power systems which coincide significantly with terrestrial applications. Several new space and terrestrial applications have emerged which require high-volume production, low-cost, lightweight power systems with low stowage volume. Some of these applications, such as Teledesic global satellite constellations, will require significantly higher production at greatly-reduced cost than currently available for space. In fact, because the satellite constellation (both operational and spares) can be as high as 950 with up to 10 kW of power required beginning of life (BOL), existing annual space PV manufacturing capacity can be exceeded by over an order of magnitude! Furthermore, since batteries for space applications are also produced on limited production scale, batteries for these spacecraft will also not be available in sufficient quantity.

One of the major drivers in battery system weight and volume is the cycle life and depth of discharge of the battery. For example, most batteries do not exhibit long cycle life (< 1000 cycles) unless the system is designed to only require 30-40% depth of discharge (DOD). Figure 7 shows expected cycle life as a function of preferred depth of discharge for NiCd and NiH batteries (Ref 15). For deep depth of discharge (>60-70%), cycle life can be limited to below 100 cycles.

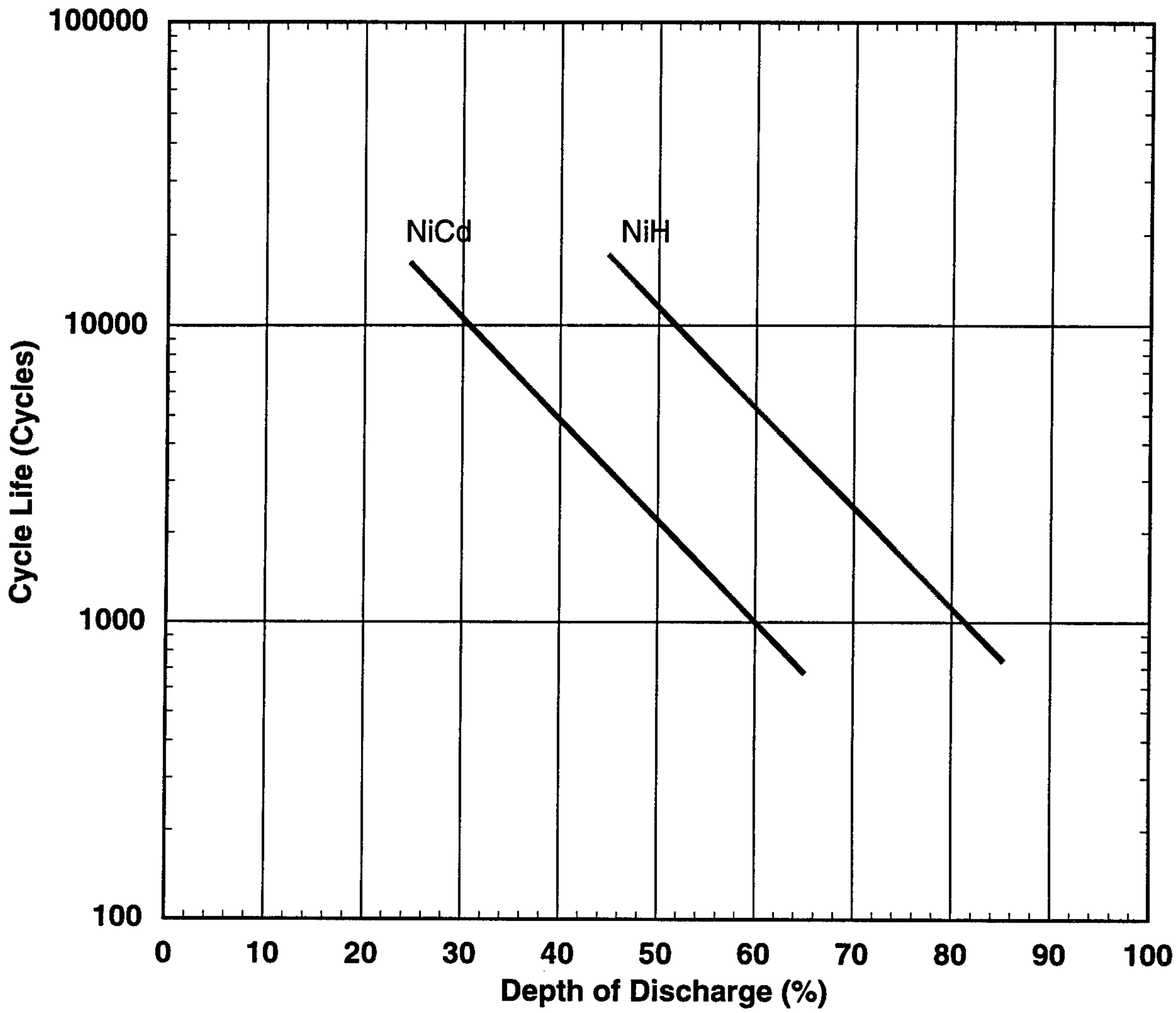

Figure 7. Battery Cycle Life as a Function of Depth of Discharge (DOD) for Nickel-Cadmium and Nickel Hydride (NiH) Technologies (Ref. 15).

To provide power for long-duration spacecraft, battery systems are often oversized to allow for sufficient power at only 30% DOD. An estimate of the required capacity (C_r) of secondary batteries in terms of amp-hours can be described in the following manner:

$$C_r = (P_e T_e)/(C_d N V_d n) \quad (2)$$

where C_d is the limit on DOD, N is the number of batteries, V_d is the average discharge (bus) voltage, and n is the transmission efficiency between the battery and the load. As a result, battery mass is increased by 200% over a battery capable of the same cycle life at 60% DOD.

Finally, with the advent of the Small Spacecraft Technology Initiative at NASA, and other programs at the Air Force Phillips Laboratory, spacecraft size is being reduced to reduce launch cost. Present battery systems are voluminous, and even high-power density batteries still are quite large. CPV batteries are often referred to as a "pig in a blanket" due to its size. As these satellites decrease in size, the power system becomes a major part of the spacecraft. Flexible, lightweight PV has a significant chance of reducing the weight of the array and of reducing the stowage volume during launch. A similar technology for batteries would also prove advantageous.

Terrestrial Applications. Power storage for terrestrial applications is decidedly not sophisticated. In stationary applications (remote power, telecommunications, etc.) lead-acid battery technology is used almost exclusively. In portable power applications, NiCd batteries are almost always used. Charge control circuitry is rather simple in response to reduced cost and improved reliability of the balance of systems (BOS). Four areas of concern include 1) limited life of rechargeable batteries, particularly at high depth of discharge (DOD), 2) need for reduced maintenance, 3) PV system weight and volume, and 4) production volume. This list of issues is almost identical to that of space applications; however, implications of these concerns are slightly different.

As stated above, life cycle costs for battery replacement must be incorporated into the overall system cost. Because conventional batteries must be constantly replaced due to the low cycle life of lead-acid batteries at high depth of discharge, the overall system cost over the life of that system can drive the cost of PV systems above that of competing technologies, such as generators. Even if battery replacement can be kept to an 8-year cycle (for a 25 year facility), the additional batteries can account for an additional 30% to the system cost.

Maintenance is one of the major stumbling blocks when installing stationary PV in remote facilities with untrained inhabitants. Several experiences in India have shown that remote PV facilities have failed due to lack of maintenance. In these cases, batteries were not maintained and allowed to run dry, thereby ruining the batteries. Some automated watering systems have been developed that can maintain this water level, but these systems themselves also require periodic maintenance. Thus, a truly maintenance-free battery would be very useful in spreading PV technology worldwide.

Weight is a critical issue with terrestrial applications as well. While weight and stowage volume of PV systems have not been seriously considered in the past for terrestrial applications, many new markets for reliable, maintenance-free power exist in extremely remote locations. Unlike most of the developed world, emerging countries have little or no transportation infrastructure upon which to rely. Many locations are only accessible by beast of burden (donkey, oxen) which severely limits the size and weight of packages that can be carried in a single trip. Even within developed countries, shipping cost and weight can have significant impact upon system cost. Thus, weight and storage volume can impact the terrestrial market as well. Also, citing the example above for portable power on reconnaissance missions, a radio requires one hundred pounds of batteries to operate remotely for one week which must be carried by troops both into and out of an area.

Terrestrial applications that ITN/ES is investigating can require very high volume production capability for PV and battery alike. Low-cost housing along can be in excess of 125,000 homes per year for China alone. In many cases, there are no suitable sources for batteries in these areas. Thus, a method for transporting large-volume, lightweight battery technology for terrestrial applications is essential.

1.2 RECHARGEABLE BATTERY TECHNOLOGIES

Nearly all PV electric power generation systems utilize rechargeable, or secondary batteries to store electric power during solar exposure for use later during eclipse. Because nearly all terrestrial applications use either lead-acid (large stationary applications) or NiCd (small, portable applications), most discussions in this section shall be limited to battery technologies for space applications, although a brief description of lead-acid battery technology will also be included.

1.2.1 Existing Rechargeable Battery Technology

Table 1 compares battery technologies for space in terms of specific power and power density. Lithium-based batteries have tremendous potential, both in terms of specific power (80 W•hr/kg) and power density (210 W•hr/l) over the nearest competition. It is important to note, however, that these designs are in development and must be evaluated thoroughly for space applications. A brief description of rechargeable, or secondary, battery technology is presented below.

1.2.1.1 Lead-Acid. Probably the most common and oldest secondary battery technology, lead-acid batteries are commonplace in automotive applications, as well as security and other applications which require low-cost power storage with the potential of high current draw. Unfortunately, excessive weight and the fluid electrolyte of these batteries all but eliminates them from space usage. Lead-acid is still the battery of choice for stationary terrestrial PV applications, but maintenance of these batteries continues to be an issue.

Table 1. Comparison of Secondary Battery Technologies for Space Applications.

Performance		NiH_2	Super NiCd	NiH_2 2-Cell CPV	NiH_2 Planar	NiH_2 CPV	NiMH	Lithium Ion
Specific Energy	(W•hr/kg)	33	30	36	49	55	43	80
Energy Density	(W•hr/liter)	35	80	50	27	87	117	210
Depth of Discharge Comments		Long Life at High DOD	Short Life at High DOD	Long Life	Long Life at High DOD	Long Life at High DOD	Medium Life at High DOD	Unknown

1.2.1.2 <u>Nickel-Cadmium</u>. Nickel-Cadmium batteries are commonplace in both spacecraft and small, portable PV power systems. However, NiCd batteries suffer from a memory effect which requires tightly-controlled charge-discharge cycling of the battery to ensure long life. Also, NiCd cannot be used in high depth-of-discharge applications. Terrestrial applications using NiCd are numerous on small-scale applications, but cost and environmental restrictions on Cd-bearing compounds are proving to be a limitation on their use.

1.2.1.3 <u>Nickel-Metal-Hydride</u>. A promising technology, particularly for terrestrial use, are nickel-metal hydride batteries (NiMH). These batteries have a higher capacity than NiCd and can charge at high rates, thus charging a battery in a fraction of the time needed to discharge it. However, rapid charging can result in possible explosions if recharging is mishandled.

1.2.1.4 <u>Nickel-Hydrogen</u>. Nickel-Hydrogen (NiH_2) batteries are generally of two forms for space, namely (a) individual pressure vessel and (b) common pressure vessel (CPV). By eliminating redundancy in packaging, NiH_2 CPV batteries can exhibit higher specific power and long life at high DOD. However, the form factor associated with this type of battery is creating concern in smaller spacecraft designs.

1.2.1.5 <u>Sodium-Sulfur</u>. Sodium-Sulfur battery technologies are very promising, providing up to 140-210 W-hr/kg. However, sodium-sulfur batteries must operate at high temperatures which can inhibit their acceptance in spacecraft design.

1.2.1.6 Lithium-Ion. The latest of the battery technologies to become commercially available, particularly for the microelectronic and microcomputer markets is lithium ion (LiI). At present, DOD for these technologies is unknown for space applications.

1.2.1.7 Lithium-Polymer. Finally, one technology under investigation by the DoD (Air Force Phillips Laboratory, Advanced Research Projects Agency) is lithium polymer. In this technology, the electrolyte is embedded into a polymeric film. Thin-film deposition and mechanical lamination can be used to apply the cathode and anode onto the electrolyte, but low cycle life due to reactions at the electrolyte interface are limiting its progress.

1.2.2 Solid-State Thin-Film Microbattery Technology

To complement the flexible PV arrays, thin-film solid-state batteries can provide power storage while retaining all of the afore mentioned benefits of low weight and low stowage volume. Thin, solid-state lithium ceramic batteries is one such technology which has promise of many charging cycles while remaining flexible when deposited onto a thin substrate. Tests conducted at Eveready Battery Company (EBC) indicate that these batteries can generate up to 140 W•h/l and up to 270 W/l. Furthermore, this solid-state technology is compatible with large-area, large-volume roll-to-roll deposition techniques such as sputtering, evaporation, and chemical vapor deposition (CVD) which are being investigated by ITN Energy Systems (ITN/ES) for their photovoltaics. This battery design is based on EBC's technology for their other chemical-based batteries and are covered under three U.S. patents (Refs 16-18).

Figure 8 shows the simplicity of the design of the microbattery. All of the layers are deposited by vapor phase manufacturing techniques through masks to pattern the film appropriately. After deposition of a chromium (Cr) contact through a mask onto a glass substrate to yield two pads, a TiS_2 thin film approximately 3 μm thick is deposited by DC magnetron sputtering to serve as the cathode. Next, a $6LiI\text{-}4Li_3PO_4\text{-}P_2S_5$ film is RF magnetron sputtered to a thickness of approximately 2 μm which serves as the electrolyte. A thin LiI barrier layer is evaporated onto the stack to protect the electrolyte from passivation during deposition of the anode. The anode consists of a lithium (Li) thin film evaporated onto the stack in such a way that it makes contact with the second Cr pad, thus providing two Cr contacts for the battery. Total thickness of this device is approximately 10 μm (without substrate).

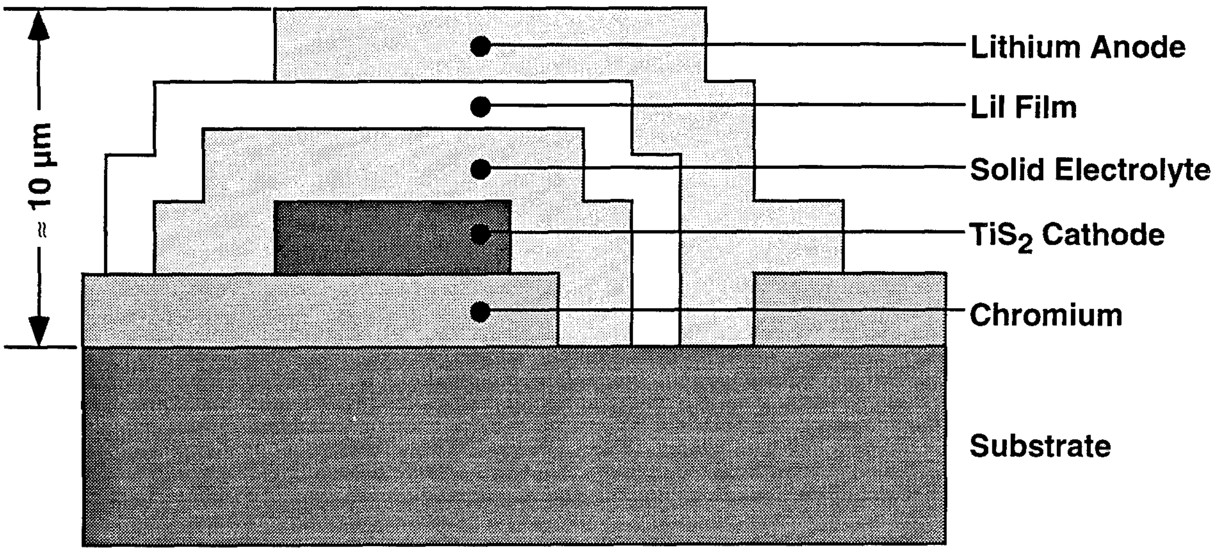

Figure 8. Eveready Battery Company's Microbattery Structure.

Performance of these Microbatteries is outstanding (Ref 19). Devices were tested over 12,500 cycles with little degradation observed (Fig. 9). Temperature performance is shown in Figure 10. Battery capacity is tailorable by adjusting the thickness of the TiS_2 film; normally these batteries exhibit a capacity of 35 μA•hr/cm²/thickness of cathode in microns. Hence, in our example shown in Figure 8, the device would have 105 μA•hr/cm² capacity.

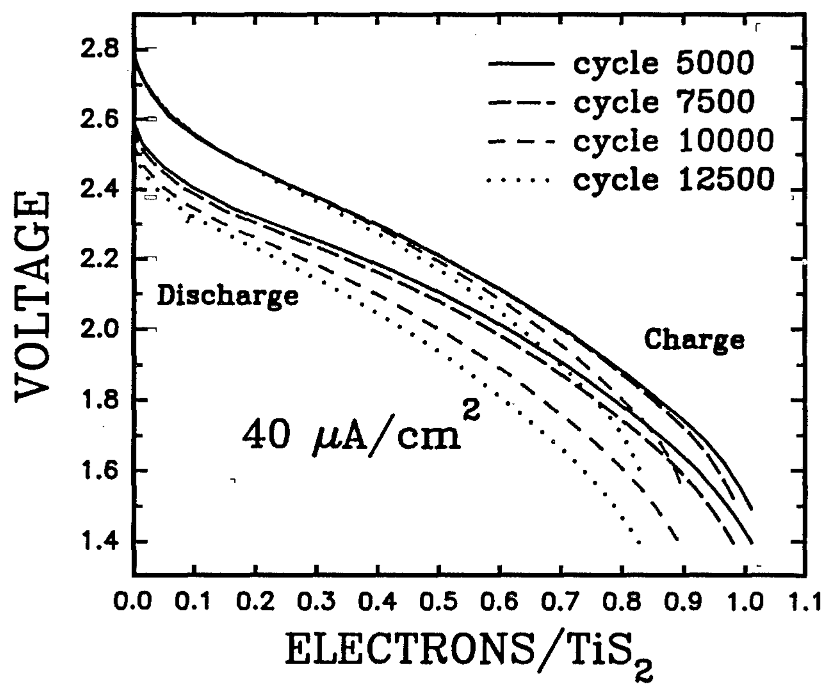

Figure 9. Performance of Microbattery Over 12,500 Cycles Indicating Outstanding Secondary Battery Performance (Ref 19).

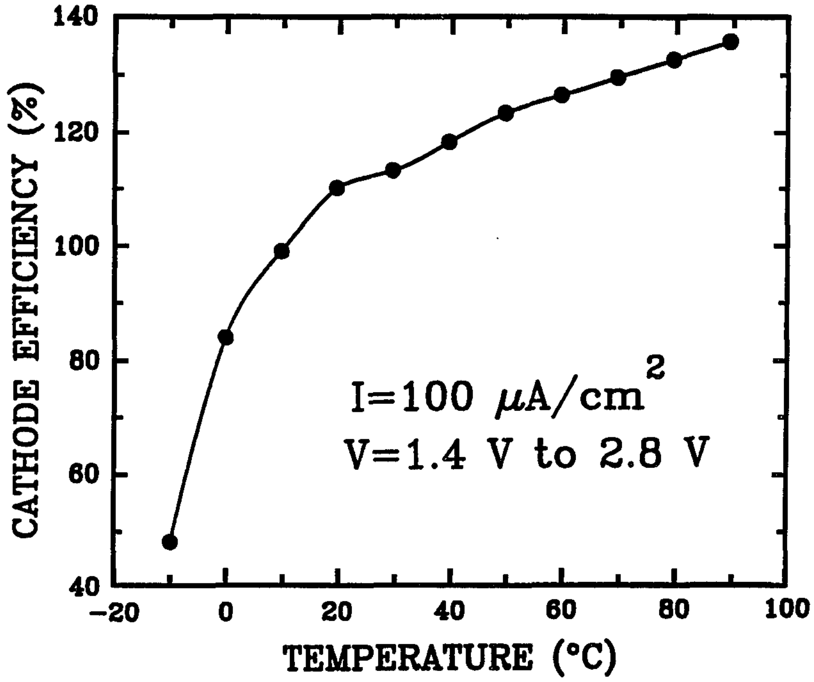

Figure 10. Temperature Dependence of Cathode Efficiency for the EBC Microbattery (Ref 19).

2.0 THIN ONBOARD POWER STORAGE FOR PHOTOVOLTAICS (TOPS-PV)

Thin Onboard Power Storage for Photovoltaics (TOPS-PV) represents an innovative approach to space power storage with phenomenal dual-use applications. Utilizing a thin-film solid-state battery approach demonstrated by Eveready Battery Company in Westlake, OH, coupled with flexible thin-film photovoltaics, ITN Energy Systems is developing an on-board power alternative for space and terrestrial applications. In this approach, a thin-film ceramic battery with phenomenal secondary battery characteristics (Fig. 11a) will be deposited directly onto a flexible photovoltaic device, either amorphous silicon (a-Si) or copper-indium-diselenide (CIS) (Fig 11b) to achieve a self-contained power generation and storage system (Fig. 11c). This approach will provide a flexible single source for battery generation and storage, thus allowing for a rollup solar array/battery system with minimal stowage volume. Reduced volume of the battery storage alone will result in spacecraft size reduction, and the accompanying weight reduction will have an impact on launch costs.

Phase 1 of this SBIR effort was designed to assess the compatibility of the EBC battery with flexible substrate PV devices and to determine the market and configuration of products with this combination (Fig. 12). Work during Phase 1 was conducted at EBC's laboratory in Westlake, Ohio. During the development of Phase 1, a Phase 2 effort was developed to scaleup the EBC technology to large-area deposition commensurate with a-Si and CIS photovoltaic production. Scaleup of the technology in a Phase 2 program would be conducted at ITN/ES's facility in Wheat Ridge, Colorado. Finally, Phase 3 will demonstrate production of the TOPS-PV project.

Significant issues were found during the performance of Phase 1, the most critical of which wasthe commitment of labor at EBC to perform the work. All of the schedule slippage was due to the fact that key EBC personnel were assigned to other higher-priority tasks within the company and were not available to TOPS-PV as promised. However, despite the lack of cooperation, we did determine that the prospect of putting a flexible Microbattery onto a flexible PV device is feasible. Below is a summary of the results.

2.1 SUBSTRATE SELECTION

It was the goal of this project to investigate the marriage of the Microbattery and flexible PV technologies. Physical bonding of the two components was not considered due to the amount of touch labor and additional weight of the adhesive. Because a common substrate would be used, a suitable material which could survive both PV and Microbattery processing had to be

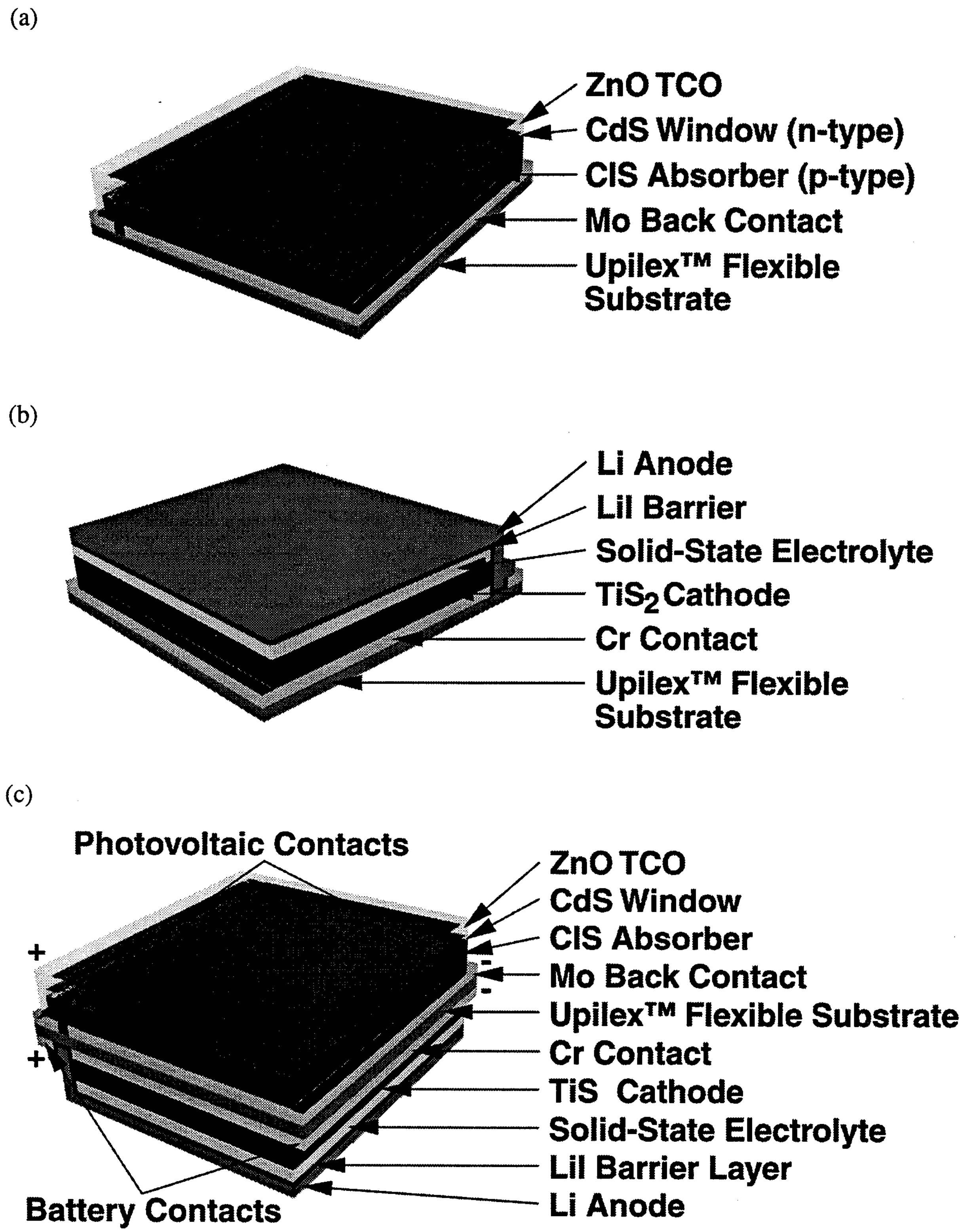

Figure 11. Schematic Representing the Basic Components of the TOPS-PV concept, namely (a) Microbattery on a Flexible Substrate, (b) Thin-Film PV on a Flexible Substrate, and (c) Fully Integrated Power Generation and Storage.

found. Processing temperatures in the CIS process can reach as high as 450°C to 525°C; microbattery deposition temperatures, although not accurately known by EBC, would ideally not exceed 180.54°C (the melting point of Li). Thus, the only processing path for a common substrate was to deposit the PV first, followed by surface preparation on the reverse side of the PV device and subsequent deposition of the microbattery.

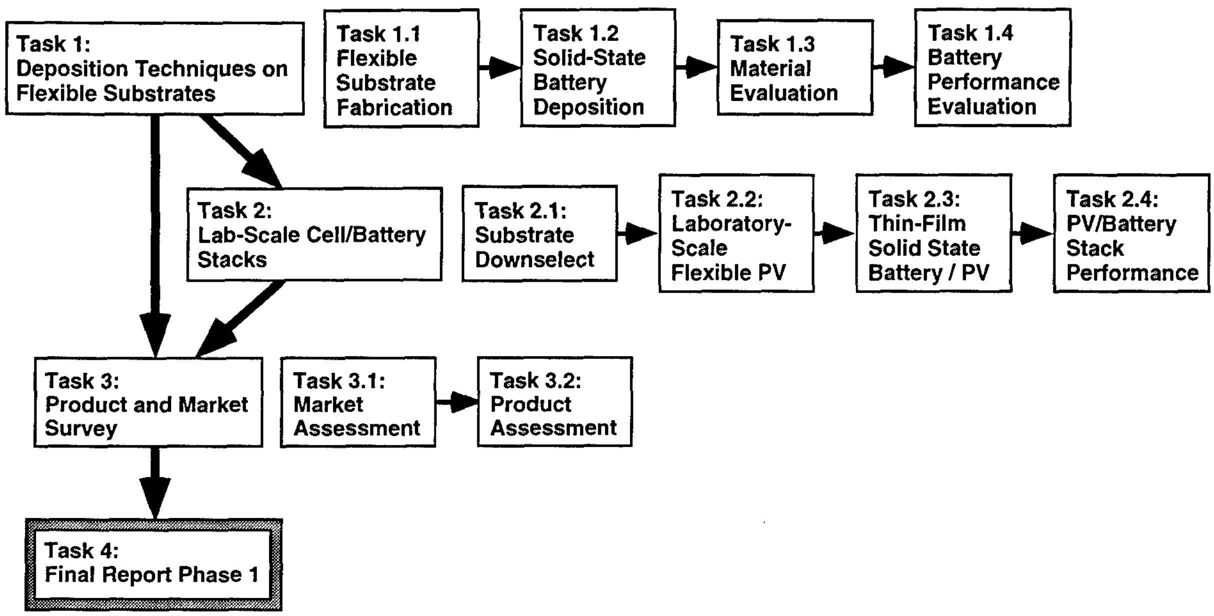

Figure 12. TOPS-PV SBIR Phase 1 Flowchart.

Metal foils and polymers are two viable classes of materials that can withstand all a-Si, CIS and microbattery processing steps and maintain both structural and chemical stability. A metal foil substrate requires a pinhole-free insulating or dielectric coating to isolate the substrate electrically from the back contact. Initial attempts at depositing a pinhole-free ceramic coating onto a titanium foil was successful; however, obvious surface roughness of the ceramic coating excluded it from further consideration in the program.

Under the guidance of ITN/ES, several flexible, nonmetallic, insulative substrates were studied as to not only their use in microbatteries, but also in a-Si and CIS as well. It was determined that only substrates capable of use in the photovoltaics industry would be considered. Because high process temperature was less critical for a-Si, one candidate substrate was Kapton™, a polyimide. Another polyimide tested was Upilex™, a higher-temperature variation that is being used in some a-Si processing and in a new ARPA program at ITN/ES for vapor phase manufacturing technology for CIS devices. Other, more exotic R&D polyimides were not included due to limited temperature survivability (Refs 20 and 21).

The biggest issue with substrates of this type is moisture retention. Significant contamination of the Li anode can occur as a result of using Kapton. As shown in Figure 13, Li darkening can be observed within 24 hours, even in a vacuum, due to the moisture in the substrate. Similar tests with Upilex™ showed reduced sensitivity of the Li; hence, all subsequent work is being done on Upilex™. However, Upilex™ still can retain up to 0.8% moisture, so care was taken to drive the moisture away.

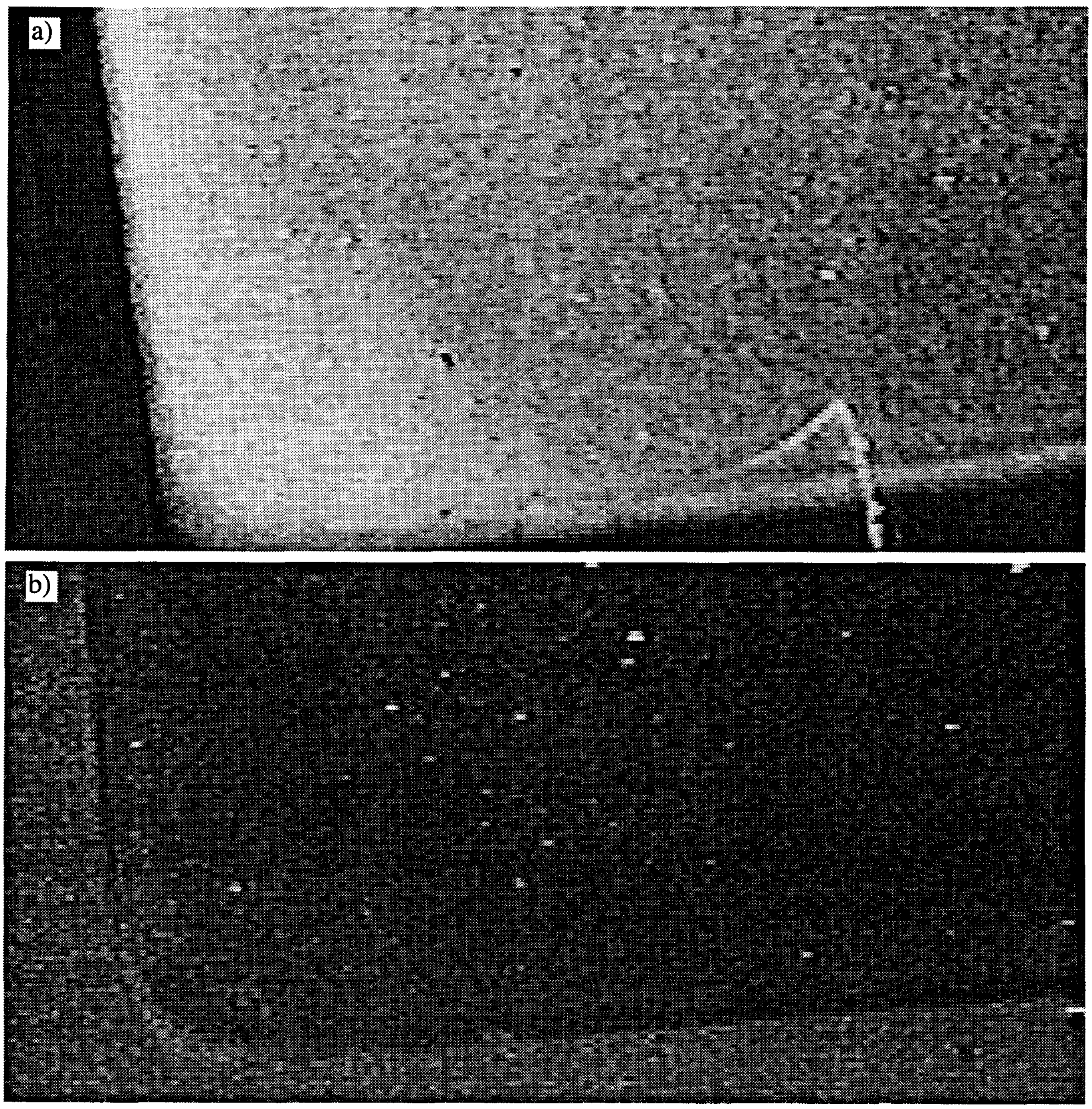

Figure 13. Indications of Contamination of Lithium Thin Films from Kapton™ Foils After 24 Hours in Vacuum.

2.2 FLEXIBLE MICROBATTERY DEVICES

Microbatteries were deposited onto flexible polyimide substrates in a systematic manner. After deposition, devices were tested at EBC to determine the quality of the device. Some photographs were taken at EBC using video from their CCD camera system which was required due to the environmental concerns with Li reactions to air. Additional photographs were taken at ITN/ES in air of faulty devices. Devices which exhibited proper electrical behavior were subjected to charge-discharge cycling. Details are given below.

2.2.1 Device Deposition

Devices were deposited by EBC onto Kapton™ and Upilex™ supplied by ITN/ES which were identical to those used in a-Si and CIS devices. In addition, a-Si solar cell strips were supplied by ITN/ES for subsequent TOPS-PV device fabrication. The following process was followed for device deposition.

2.2.1.1 Substrate. Upilex™ and Kapton™ flexible substrates were prepared by washing them in deionized water and dried in an inert Ar environment.

2.2.1.2 Back Contact. The first layer deposited onto the prepared substrate was the chromium (Cr) back contact. This contact is patterned via a mask in such a way that the anode (Li) can be deposited onto an adjacent pad and to facilitate easier connection.

2.2.1.3 TiS_2 Cathode. The TiS_2 cathode is critical to the performance of the Microbattery device. For example, the capacity of this type of battery is measured at 35 μA•hr/cm2/cathode thickness (in microns). Thus, a successful, rapid deposition of this film was critical to battery operation. Deposition of this film occurs through a mask to prevent the cathode from bridging the gap in the back contact, as well as provide room on the other side of the pad for connection to the cathode. EBC used an RF sputtering facility to deposit the TiS_2 film.

2.2.1.4 $6LiI\text{-}4Li_3PO_4\text{-}P_2S_5$ Electrolyte. Another film critical to the performance of these devices is the electrolyte. This film was deposited through the same mask used in the cathode deposition by RF sputtering.

2.2.1.5 LiI Protective Barrier Layer. Because depositing lithium (Li) directly onto the electrolyte causes a passivation of that interface, EBC developed a lithium iodide (LiI) barrier layer to be placed between these two films. LiI has high electrical resistance and may also serve as an insulating layer for the substrate. Evaporation in a small belljar was used to deposit the LiI film.

2.2.1.6 Li Anode. The final layer used to complete the battery is the Li anode. This film was deposited through a mask which provides similar coverage to that of the LiI layer, but not in such a way as to short out the cathode pad. In this case, however, the Li was allowed to touch (and thus connect) to the adjacent pad over the LiI layer. Again, evaporation was used to deposit the Li anode.

2.2.2 Results

Two specimens on Kapton™ were obtained for inspection whose performance was reported in the previous issue. Each specimen contained five (5) 1.0 cm^2 cells. Four of the five cells on Specimen #1 performed well initially. A photograph of Specimen #1 Cell #1 taken by ITN/ES is given in Figure 14. Note that the white discoloration is due to reaction between the Li top contact and air/moisture. Open circuit voltage ranged from 2.50 V to 2.55 V and closed-circuit voltages ranged from 2.30 V to 2.33 V when pulsed at 50 μA. However, cells degraded with time dropping from 1.65-1.84 V after two days and 1.28-1.40 V after 16 days despite specimens being kept under vacuum. Figure 15 illustrates the difficulties of working with unpackaged batteries by recording Cell #1 5 minutes after Figure 14 was taken. As a result, ITN/ES is acquiring three (3) inert environment chambers for future Microbattery development.

Because Dr. Jones assumed that lithium may have evolved from electrolyte with time, Specimen #2 was deposited with additional Li (Fig. 16). Figure 17 shows Cell #1 from Specimen #2 indicating smooth deposition of the device. However, indications of high-temperatures seen by the substrate is shown in Figure 18 where the lithium top contact appears to have been melted. Thus, preparations for a third specimen were begun.

Due to the possible contamination from the polyimide foil shown earlier in Figure 13 and the degradation of Specimen #1, all subsequent tests were designed to ensure that no contact directly between the Li and substrate would be made. Lithium Iodide (LiI), which serves as a barrier layer to protect against passivation, was used as a protective layer. Hence, a slight variation was made to the EBC device structure as noted in Figure 19. In this case, the LiI layer was extended across the gap in the Cr pads to isolate the underlying polyimide (Kapton™, Upilex™) from the Li anode.

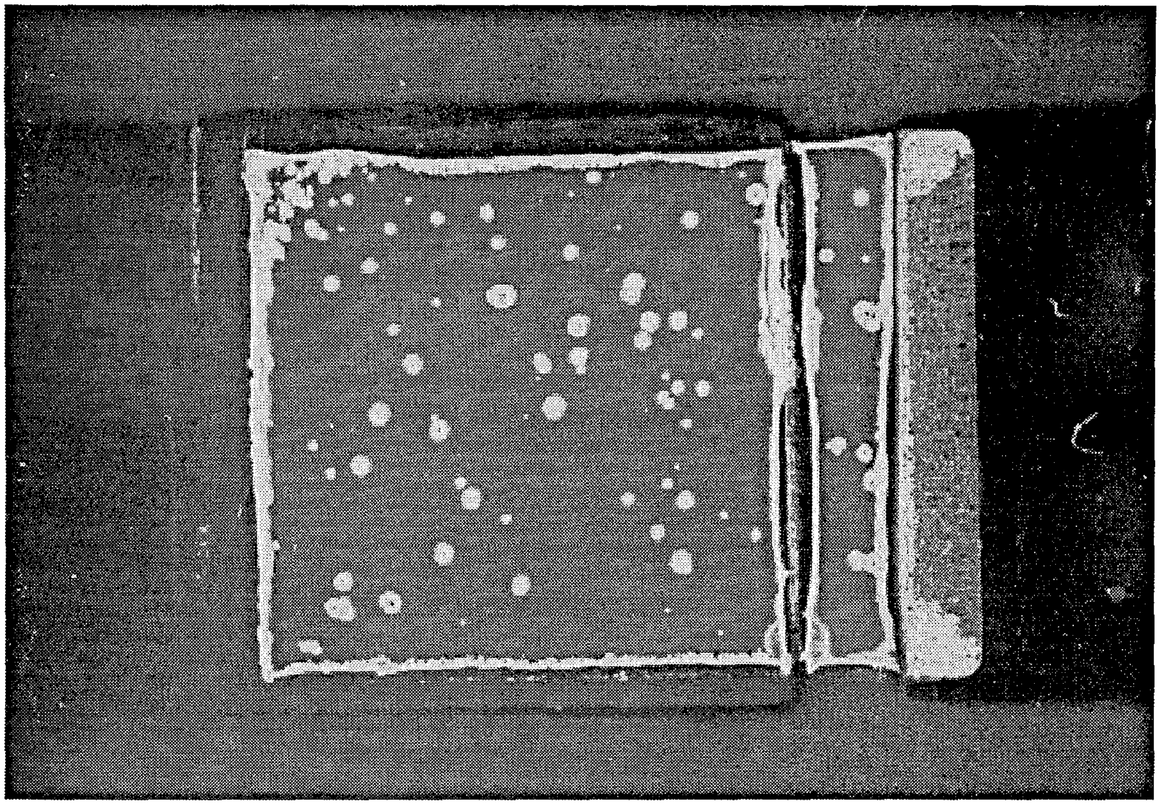

Figure 14. Photograph of a 1 cm x 1 cm Cell #1 from Specimen #1.

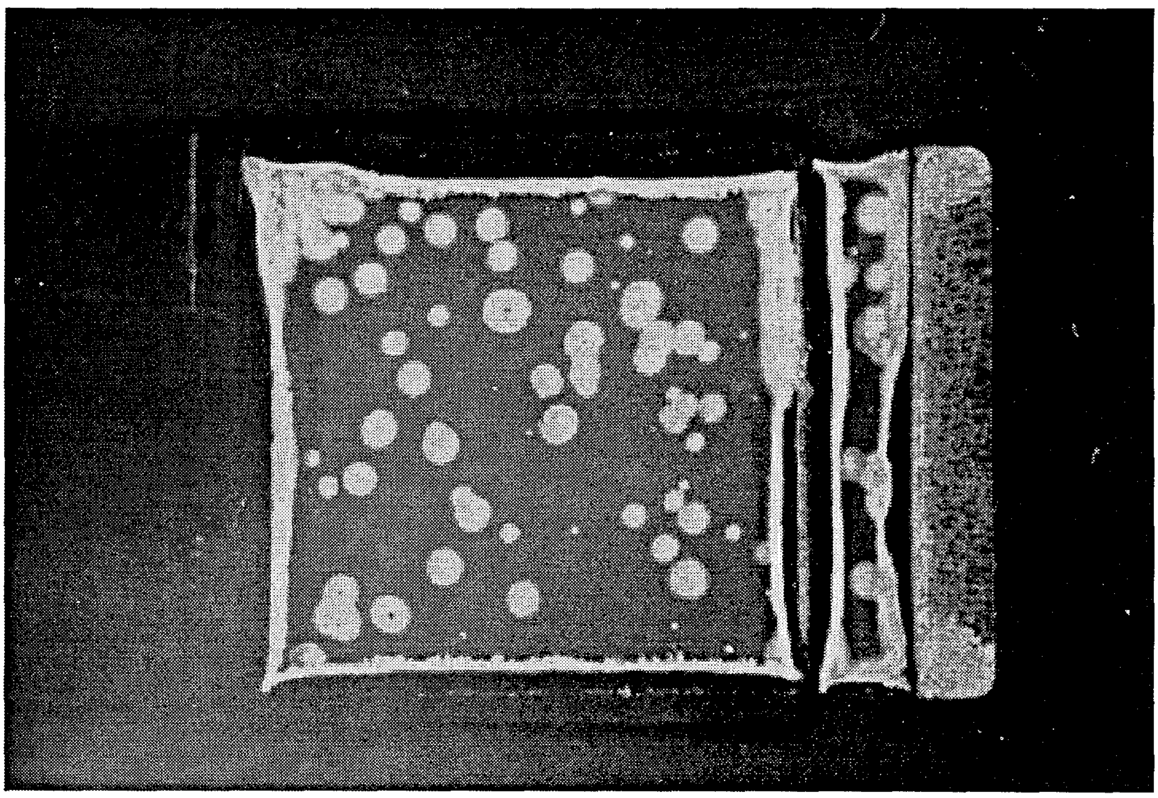

Figure 15. Photographs of Cell #1 After a 5 Minute Time Period Indicating Rapid Degradation of the Li Anode Due to Exposure to Air.

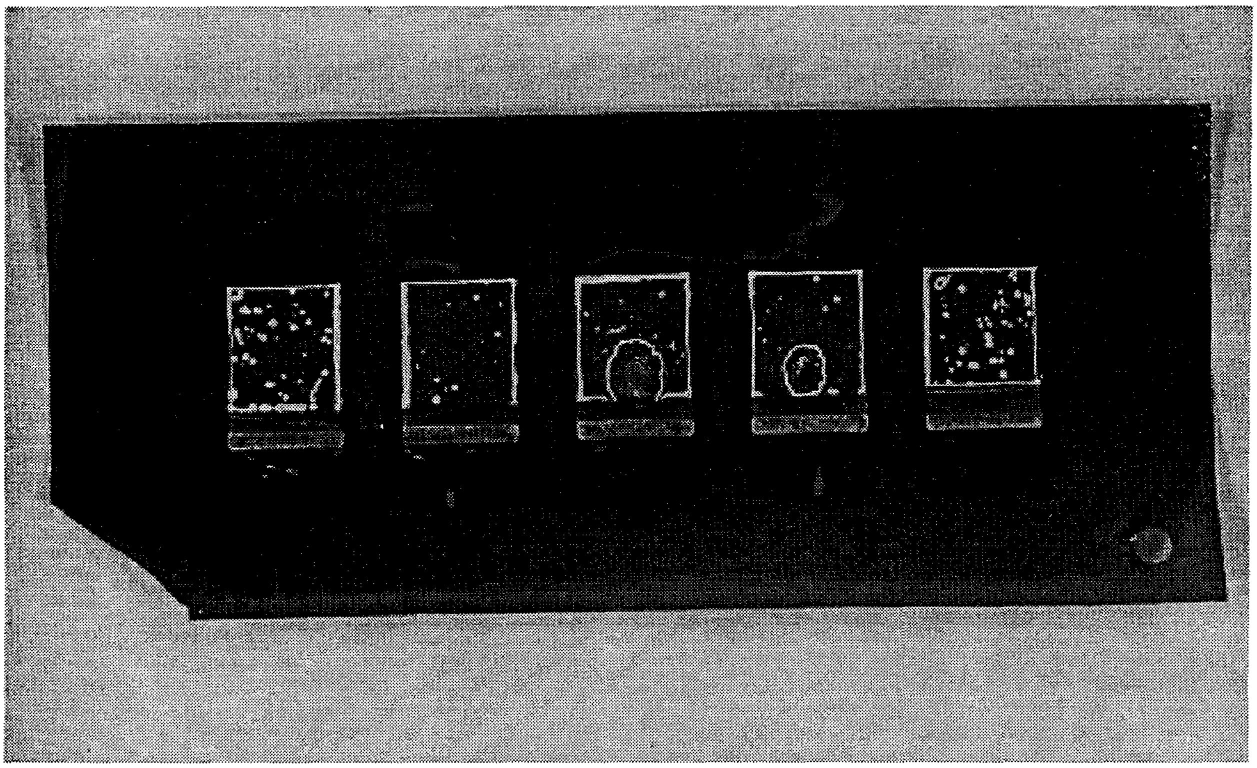

Figure 16. Photograph of Specimen #2 with Additional Li Deposition.

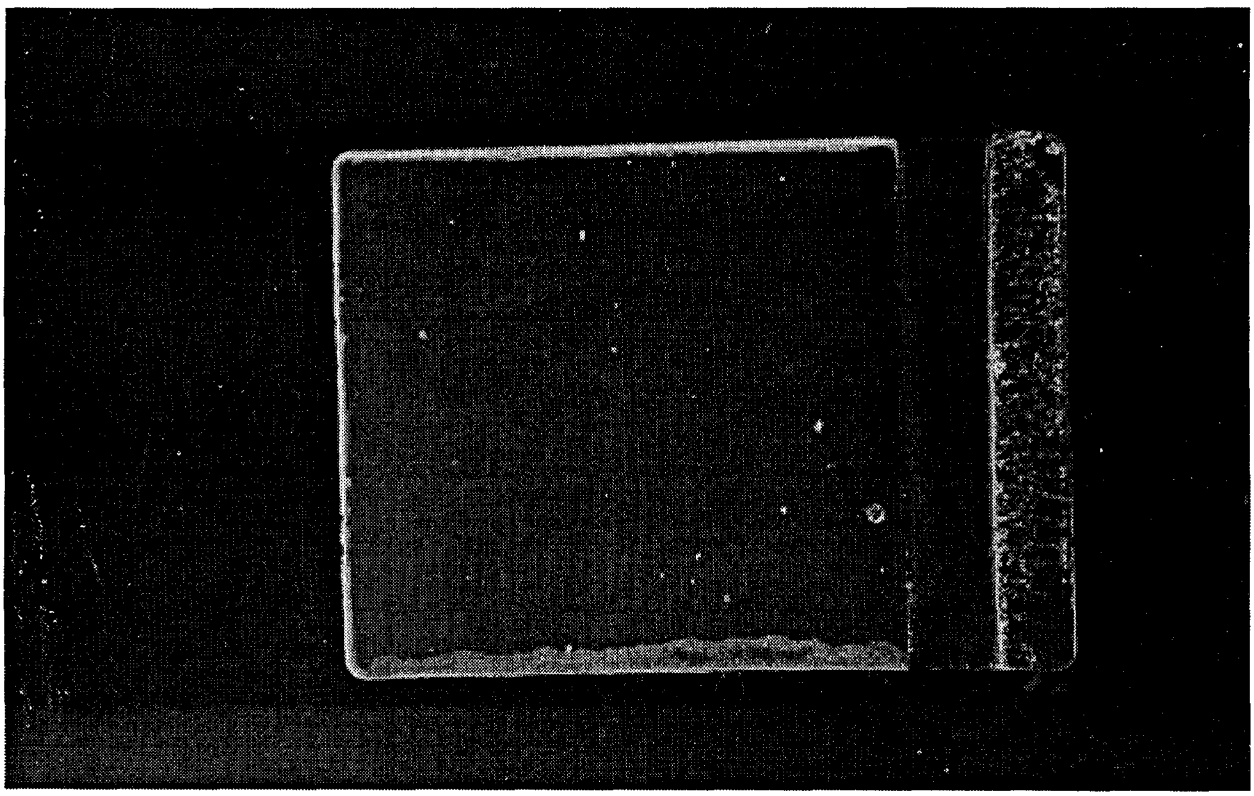

Figure 17. Photograph of Cell #2 from Specimen #2 Indicating a Smooth, High-Quality Li Deposition.

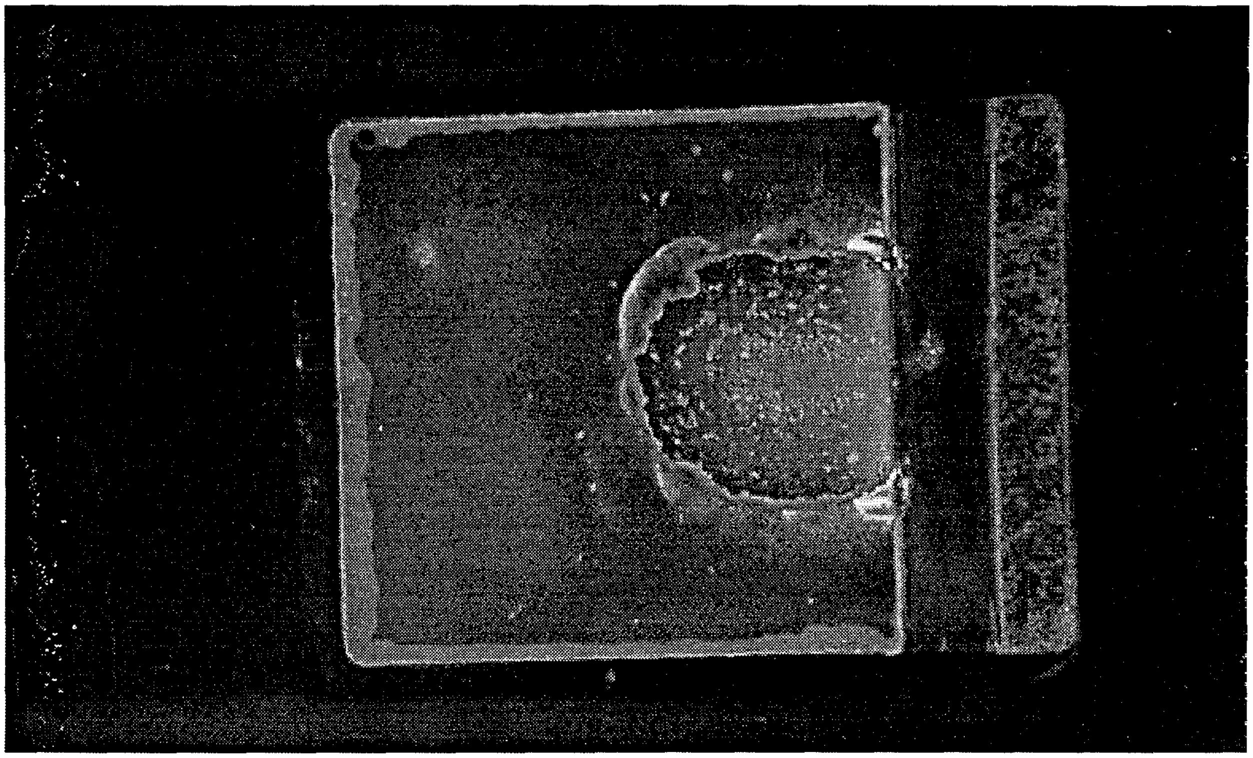

Figure 18. Photograph of Cell #3 of Specimen #2 of Melting of the Li Anode, Indicating Higher Temperatures Present at the Center of the Specimen During Deposition in the Evaporation Chamber.

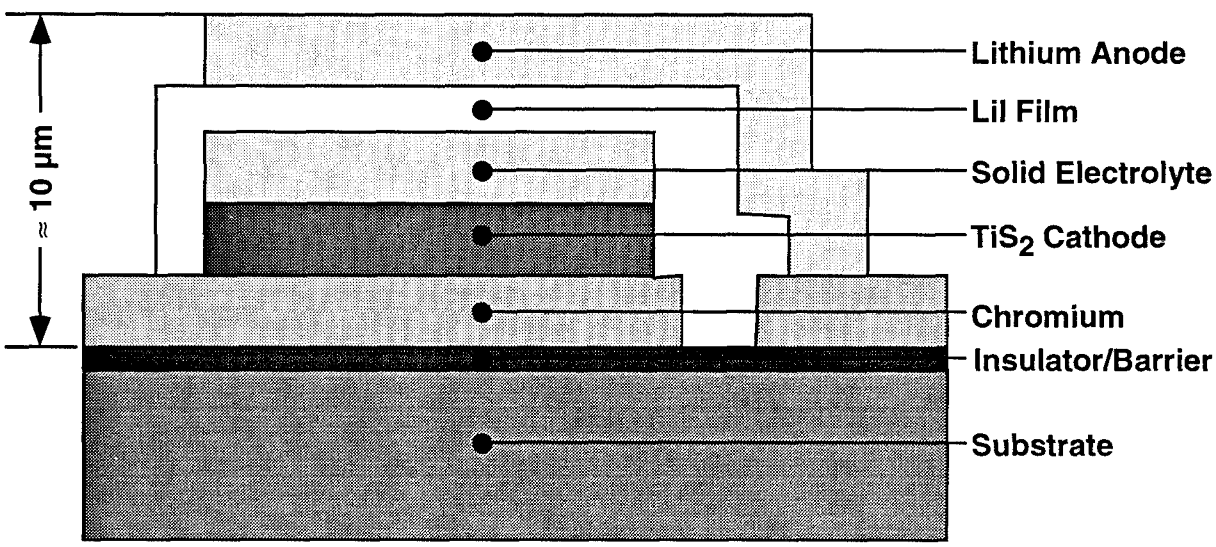

Figure 19. Revised Microbattery Design to Help Isolate Flexible Polyimide Substrates from the Lithium Anode.

As stated earlier, significant work time was lost during the project at EBC due to the low priority they placed on this project. For this reason, we had little time to deposit devices onto flexible substrates. However, we did have success during this period. The charge-discharge performance of a cell from the third specimen was good, albeit short-lived. Figures 20 and 21 show the cycling of this battery from 1-12 cycles and from 20-27 cycles. Noise observed in early cycles disappeared in later cycles. Note, however the sudden open circuit behavior on the 27th cycle. As shown in Figure 22, a breakage in the Li anode as it bridges the gap in the Cr contact caused the test to be terminated. In fact, upon request from ITN/ES, Dr. Jones reconnected the microbattery, this time with the anode connection directly onto the top of the Li anode and the battery still worked. However, due to the dramatic difference in contacting Li and Cr with the alligator clip, we were unable to continue the test. After discussions with EBC's Dr. Steve Jones, coinventor of the Microbattery technology, we determined that stresses in the Li film and reaction with the Li caused the break. However, this phenomenon was observed also in the standard, rigid cells that EBC as well.

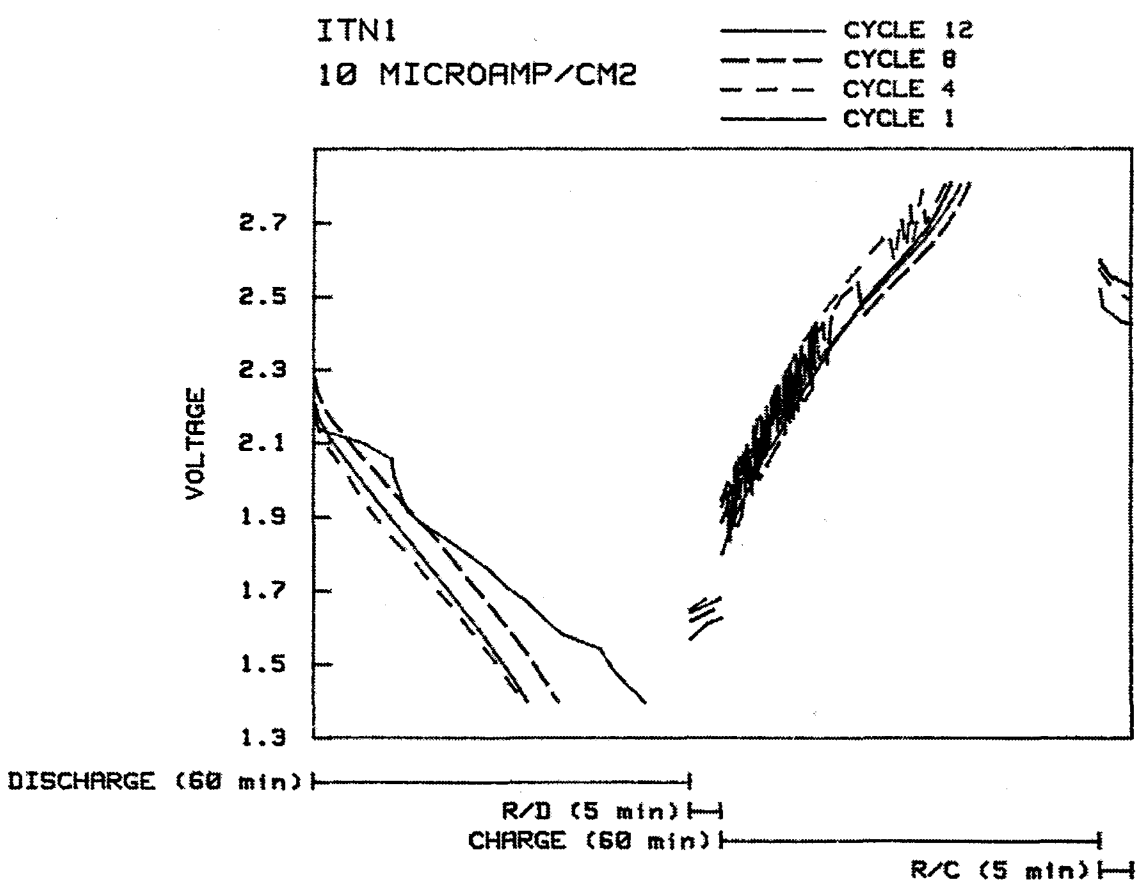

Figure 20. Charge-Discharge Characteristics for a Microbattery Indicating Some Instability During Initial Cycling.

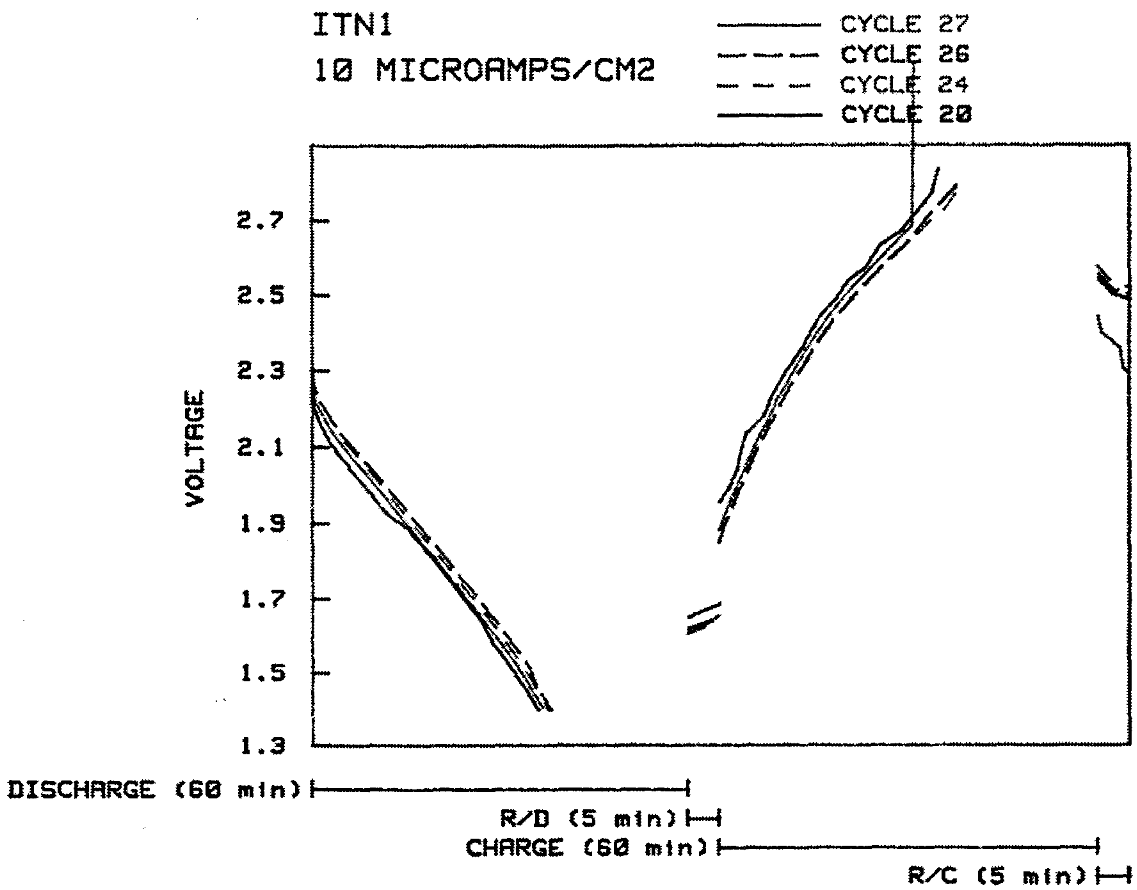

Figure 21. Charge-Discharge Characteristics for a Microbattery Indicating Stable Behavior Until Cycle 27.

Figure 22. Photograph of Microbattery in Figure 15 After 27th Cycle Indicating Breakage in the Lithium Anode Over the Gap in the Underlying Chromium.

2.2.3 Analysis of Flexible Microbattery Performance

As is evident from the breakage observed in Figure 22 and from similar occurrences at EBC, some mechanism must be in effect to fatigue the film selectively in this area. A photograph of the back of one of the devices (Fig. 23) indicated significant deformation around the Cr gap. This deformation was not observed until after the Li deposition and appeared to be worse with higher Li deposition rates. This phenomenon during Li anode deposition was commensurate with high stresses due to the high temperature of the Li vapor. While Li melts at 180.54°C, it boils at 1347°C. EBC personnel have indicated that the tantalum boat used for evaporation is red-hot during deposition which was also supported by the melting observed in Figure 18.

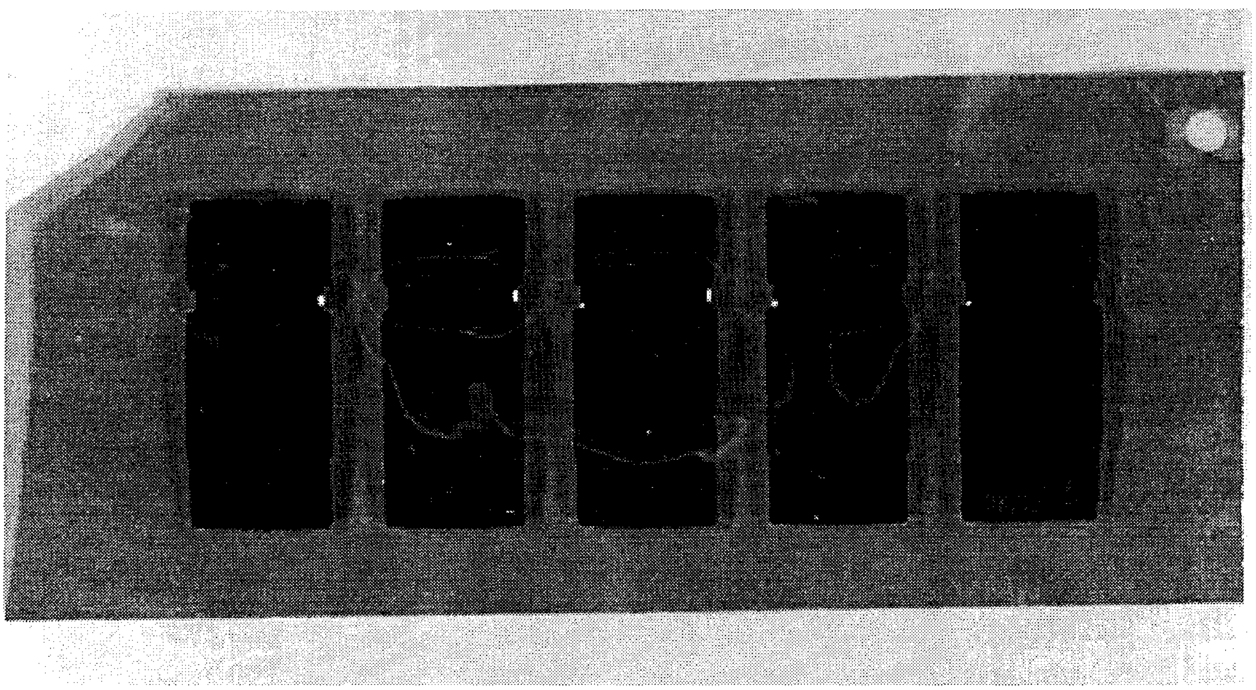

Figure 23. Photograph of the Back of Specimen #2 Indicating High Stresses In the Gaps of the Cr Contacts.

Stresses and their effects on thin film devices has been studied extensively (Refs 22-26). In addition to the high temperatures observed in evaporation, high compressive stresses have been observed in sputtered Cr which serves as the back contact of the Microbattery (Ref 24). This high stress was attributed to "peening" of the depositing film during deposition by accelerated ions or neutral atoms. This effect could be more pronounced with a flexible substrate compared to a "conventional" rigid glass substrate, and could combine with the Li deposition stresses to create this high-stress breakage. Further tests to prove this was beyond the capability of EBC's equipment. Metallographic capabilities for Li-bearing films will be developed at the Colorado School of Mines to study these phenomena. In addition, ITN/ES has extensive experience in modifying processes to reduce stresses and, in some cases, applying unique deposition equipment capable of low-temperature deposition. These approaches are under consideration for future work in this area.

2.2.4 TOPS-PV Demonstration

After the success of a 27-cycle flexible Microbattery on Upilex™, several characterized strips of a-Si solar cells were sent to EBC for Microbattery deposition. However, the only source of flexible a-Si (Iowa Thin Film Technologies) utilizes a metallized backing to mitigate charging of the insulative substrate; charging of the substrate in the web coater at ITFT causes the web to stick to a stationary platen. Due to the rubbing of the back of the devices on this platen, however, deep scratches were made into the stainless steel backing which short out the Microbattery. We are presently removing the stainless steel to lessen the depth of these scratches and are also investigating insulative films to microlevel them. However, EBC cannot support Microbattery deposition at this time due to severe workload in their R&D facility.

2.3 MICROBATTERY SCALEUP ISSUES

Part of the Phase 1 effort was to assess the issues involved with future Microbattery products, including (1) possible product configurations for space and terrestrial applications, (2) sizing the TOPS-PV array, and (3) first-order cost modeling of the Microbattery. These three issues are discussed below.

2.3.1 Flexible TOPS-PV Product Configuration

Because TOPS-PV components (Microbattery and PV) are substrate compatible, several flexible TOPS-PV array options are possible. The most promising design includes an on-array charging circuit as shown in Figure 24. In this case, the back surface of a monolithically-integrated flexible PV module (CIS or a-Si) is used as a substrate. The charging circuit connects to the array and battery leads on either side of the array; thus, all connections are made at one end of the array in the form of a bus. This configuration can be used for the basic TOPS-PV array for either space or terrestrial applications. While terrestrial applications do not require any further structure, a deployable array is assumed for space, using either a telescoping, inflating, or shape-memory deploying mechanism.

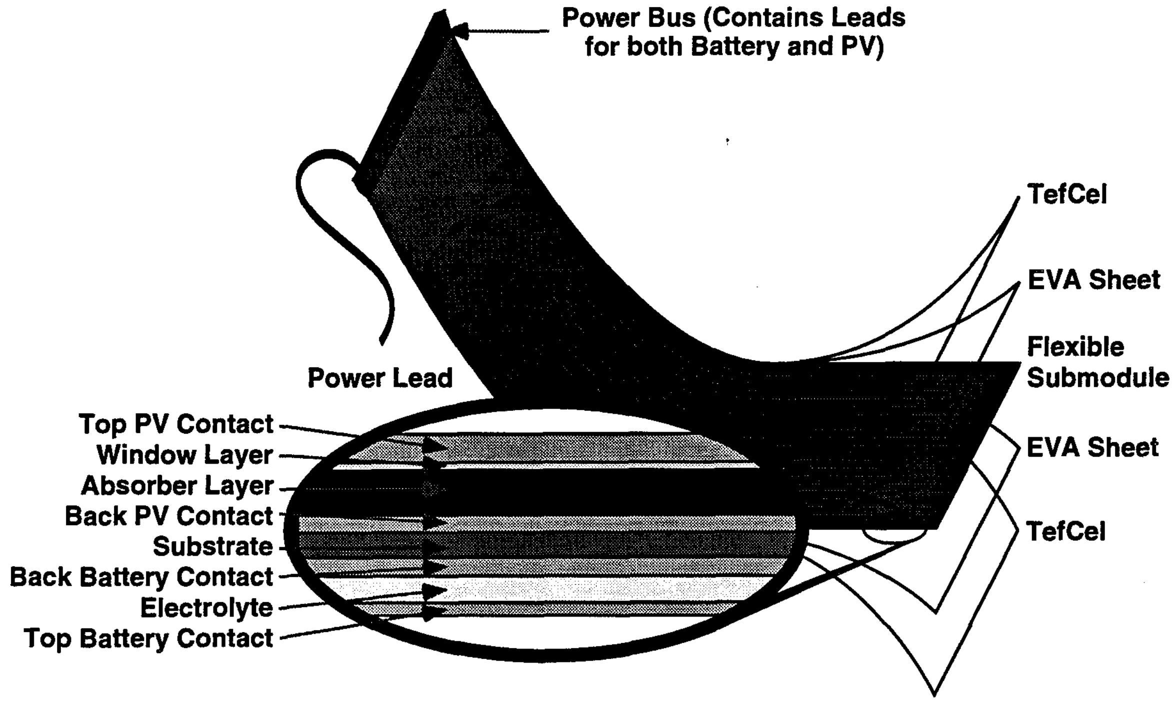

Figure 24. Schematic of a TOPS-PV integrated array for Either Space or Terrestrial Applications.

It is assumed that a technology to monolithically-integrate the Microbattery exists; a proposed method for doing so is shown in Figure 25. Thus, no rigid metallic interconnects are used in the array and the entire component can be rolled and stowed conveniently.

2.3.2 Sizing the TOPS-PV Array

Because the TOPS-PV technology is intended for both space and terrestrial applications, one example each is discussed below, indicating the feasibility of using TOPS-PV for such an application.

2.3.2.1 Space Applications. For this exercise, a flexible TOPS-PV array was assumed where the array area was dictated by the PV alone; it is assumed that the microbattery would have to be stacked or made thicker to achieve the desired battery capacity. For a typical small satellite with a 500 Watt system, batteries are in the 20 - 40 A•h range and can range as much as several thousand amp-hours for communication satellites. Based on 230 W•h/l for the EBC battery, a low-earth orbit (LEO) satellite array of 10% efficient CIS generates 140 W/m^2 of power. This array would generate 140 W•h/m^2 in each orbit (60 minutes in sun, 30 minutes in shadow). Thus, the battery would only have to store 47 W•h/m^2 each orbit. Assuming that the battery area is limited to that of the array, the thickness of the battery should be approximately:

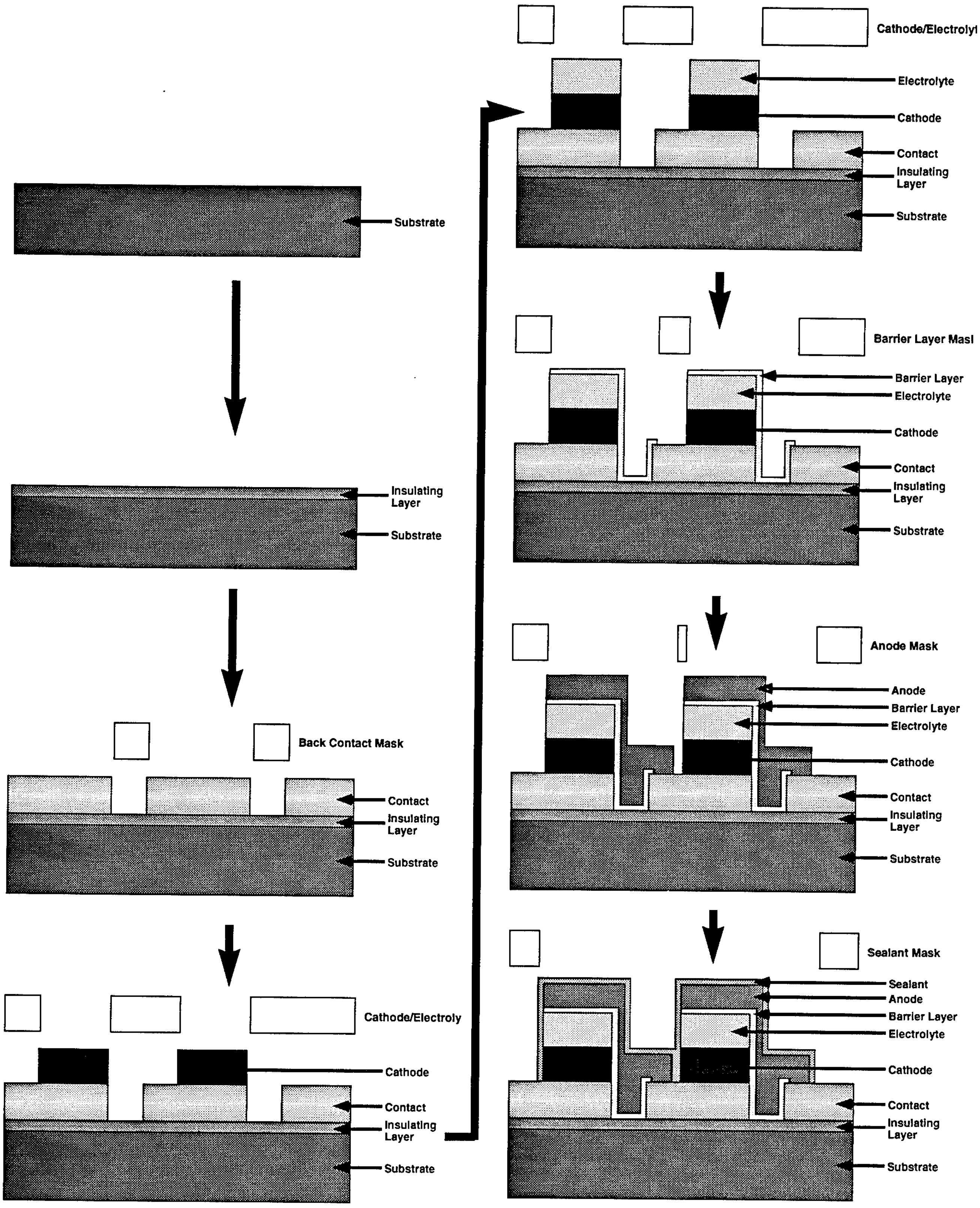

Figure 25. Method for Monolithically-Integrating a Microbattery.

$$T = (47\ W \bullet h/m^2) / (230\ W \bullet h/l) = (47\ W \bullet h/m^2) / (230{,}000\ W \bullet h/m^3) = 0.20\ mm \quad (3)$$

which indicates that the TOPS-PV array would still be flexible. Space applications that can utilize the TOPS-PV product include Teledesic™, New Millennium, and small classified spacecraft. Virtually any spacecraft can utilize this technology, although high-efficiency arrays may not present enough surface area to provide enough battery capacity.

2.3.2.2 Terrestrial Applications. As stated at the beginning of this program, ITN/ES sees the TOPS/PV as a true dual-use technology in that a very similar product can be used for both space and terrestrial applications. Based on previous models for a typical four-room home, an array of 507.7 Watts would be required. With amorphous silicon (a-Si) at 5% efficiency, a total PV area of 9.43 m^2 would be required. This PV area would take up only three (3) 1.2 m x 3.1 m roof sections out of five total on a four-room 37.2 m^2 house (6.1 m x 6.1 m) home. For battery requirements based on a 7 day capacity, a battery capacity of 1,104.5 A•h would be needed. Because this is significantly more than the power required for a satellite, we must make two conclusions. First, if the power storage is limited to the rooftop, device flexibility would be nonexistent. This is, however, not as critical in that the rooftop itself is rigid; the only limitation would be in the ability to store/ship the PV prior to lamination to the roof. The second option is that the battery does not have to be limited to the rooftop; other walls could serve as substrates for the battery apart from the PV. In fact, a wall with a thick application of the battery could serve as the power center.

2.3.3 First-Order Cost Model

Another aspect to Phase 1 was to determine the approximate cost of producing the microbattery on a flexible substrate (utility cost not included). The following assumptions were made:

- Nominal thin-film deposition rates,
- 100,000 m^2 annual production (corresponds to 10 MW CIS production volume),
- 30 cm wide web,
- Five year equipment depreciation, and
- *In Situ* Patterning and Deposition.

The last assumption is not trivial; as discussed earlier, patterning the Microbattery cannot be the same as the PV itself. For a monolithically-integrated solid-state battery using EBC's basic structure, the device is deposited charged; hence, the final layers (LiI, Li) would complete the device and short it out. ITN/ES has been developing proprietary equipment designs such as the Rotomask design shown in Figure 26 which would allow for simultaneous deposition and patterning. By using a rotating mask which also serves as the substrate drive, a thin film can be deposited in a pattern while ensuring the previously-deposited thin films are not scratched by contact with a stationary mask. Another advantage with this design is that since web speed is accurately controlled by the rotating mask, web tensioning (usually a critical aspect with web coaters) is not as critical. Since the spacing of all the patterning does not change, only the rotary blade width and rotomask shift need be changed during processing. The system shown in Figure 26 will allow for a prototype system to be mounted in a glove box with a 15 cm web capacity. All subsequent discussion assumes the basic Rotomask design duplicated in a linear fashion to allow in-line production-level processing.

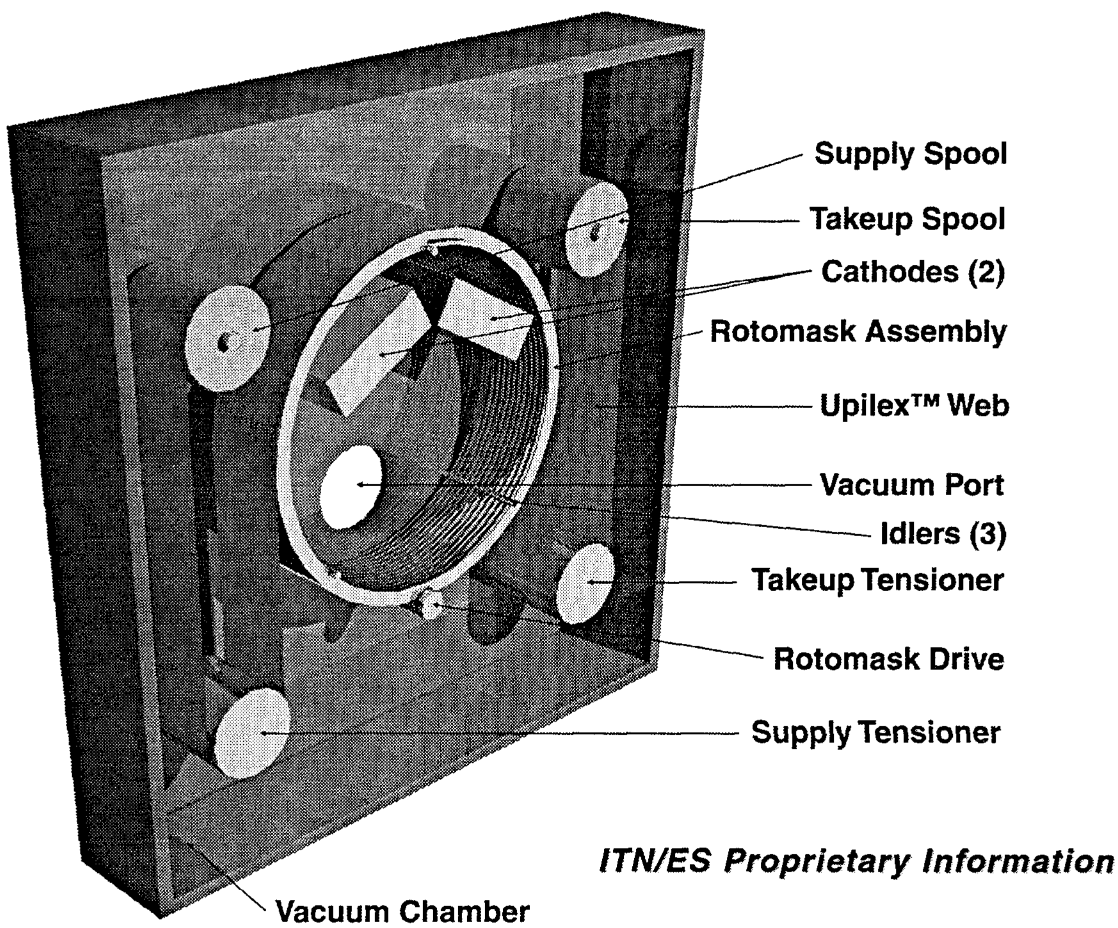

Figure 26. Schematic of a Rotomask Prototype Deposition System Based on an ITN/ES Proprietary Design.

Table 2 provides an estimate of the equipment needed, based on the assumptions at the beginning of this chapter. Based on three shifts and 25% downtime for the equipment, 333,333 m web length must be processed, which corresponds to 74.07 m/hr (1.23 m/min) processing speed. To provide the necessary deposition thickness based on this rate, five (5) systems will be required to reduce this requirement to 24.69 cm/min which is still high for a normal vacuum system, but it is assumed that the simplicity of the drive mechanism of the Rotomask would allow it to reach this rate. Based on this rate, each system must have 30 cathodes to deposit all the films, including an insulating/barrier film on the Upilex™ to prevent moisture from contaminating the Li. The entire deposition system will be placed in a large, custom glovebox to minimize exposure to air of all internal components and target materials. A separate vacuum pump system would be placed in each of the deposition areas to ensure high vacuum quality. Based on these assumptions, the approximate cost of such a system is \$825 K per system, or \$4.23 M for five systems. In the final cost table, this would correspond to \$589 K per year over five years.

*Table 2. **Equipment Cost for Estimating Production Cost of the Thin-Film Microbattery.***

Production Requirements			
Area/Year		100,000 m^2/yr	
Hours/Year/Shift		2,000 hr/yr/shift	
# Shifts		3 shifts	
% Downtime		25% downtime	
Total Prod Hrs		4,500 hours/year	
Web Width		30 cm	
Annual Web Length		333,333 m	
Web Process Speed		74.07 m/hr 1.23 m/min	
Required Web Speed Calculations			
1 System		123.46 cm/min	
2 Systems		61.73 cm/min	
3 Systems		41.15 cm/min	
4 Systems		30.86 cm/min	
5 Systems		24.69 cm/min	
Vacuum System	**Quan**	**Unit Cost ($K)**	**Total Cost ($K)**
Load Locks	2	50	100.00
Vacuum System	6	100	600.00
Cathodes	30	0.85	25.50
Glovebox	1	100	100.00
System Total ($K)			825.50
Total for 5 Systems ($K)			4,127.50
Number of Years for Amortization			7
Amortized Cost per Year ($K)			589.64

Annual material costs for the Microbattery operation is shown in Table 3. Based on the annual rate of 100,000 m^2, approximate annual masses for each film have been determined. These estimates are based on an approximate deposition efficiency which ranges from 40% to 60%, depending upon the material and deposition process. Present costs were obtained during the Phase 2 proposal activity and scaled accordingly. A 30% discount was assumed for all material costs in quantity. Consequently, total annual material cost is $1.889 M, or $18.89 per linear meter of substrate. Corresponding to the attached PV module, material cost is 19¢ per watt for CIS and 47¢ per watt for a-Si.

Table 3. Raw Material Costs for Estimating Production Cost of the Thin-Film Microbattery.

Area/ Year	100,000 m^2/yr									
Mat'l	**Density (g/cm^3)**	**Thick-ness (µm)**	**Areal Density (µg/cm^2)**	**Annual Mass (kg/yr)**	**Dep. Eff. (%)**	**Req'd Material (kg)**	**Present Cost ($K/m^2)**	**Volume Discout (%)**	**Material Cost ($K/kg)**	**Annual Cost ($K)**
Upilex	—	50.0	—	—	—	100000 *	0.03	70.0	0.02 **	1,785.00
Si_3N_4	3.440	0.5	1.72	1.72	40.0	4.30	2.07	70.0	1.45	6.23
Cr	7.200	3.0	21.60	21.60	60.0	36.00	1.01	70.0	0.71	25.43
TiS_2	3.220	2.0	6.44	6.44	50.0	12.88	0.90	70.0	0.63	8.11
Elect.	2.978	2.5	7.45	7.45	50.0	14.89	0.27	70.0	0.19	2.83
LiI	3.494	0.5	1.75	1.75	40.0	4.37	0.45	70.0	0.32	1.38
Li	0.534	2.5	1.34	1.34	40.0	3.34	25.85	70.0	18.09	60.39
Total Annual Material Cost ($K)										1,889.37
Total Annual Material Cost ($/m^2)										18.89
Total Annual Material Cost ($/ft^2)										1.76
Additional Material Cost to Coat 1W of CIS PV with Single-Thickness Battery ($)										0.19
Additional Material Cost to Coat 1W of a-Si PV with Single-Thickness Battery ($)										0.47

*** in m^2**
**** in $/m^2**

For our cost model, we assumed that the battery operation would be a part of our other operations (photovoltaics, thin-film coatings) to minimize the required direct-charge labor. Table 4 discusses the labor estimates for Microbattery production. Labor estimates assumes that a supervisory engineer is needed only on one shift while three technicians are needed in the three shifts to operate the equipment. Two technicians are needed during these three shifts for equipment maintenance. Other supervisory personnel would be carried on overhead. With a 125% overhead rate, total labor per year is $461 K.

Table 4. Manpower Estimate for Estimating Production Cost of the Thin-Film Microbattery.

Labor Class	Number	Annual Salary ($K)	Overhead (%)	Burdened Labor ($K)	Total Labor ($K)
Technicians	5	30.00	125%	67.50	337.50
Engineer	1	55.00	125%	123.75	123.75
				Total:	461.25

Table 5 summarizes the cost model data and the projected performance of the devices. Based on data presented in Tables 2, 3, and 4, a cost of $8.88 per linear meter was obtained. This corresponds to an additional 30¢/W for 10% efficient CIS or 74¢/W for 4% efficient a-Si. All of these costs are also based on a single thickness of battery, or a linear capacity of 56.9 mA•hr for each meter of device. It is possible to increase capacity by (a) increasing the thickness of the cathode and/or (b) stacking the battery into several layers as shown in Figure 27. Feasibility of battery stacking and/or thickening the cathode should be done in a Phase 2 effort.

Table 5. Cost Model Summary for Estimating Production Cost of the Thin-Film Microbattery.

Annual Production	100,000	m^2/yr
Material	1889.37	$K
Amortized Equipment	589.64	$K
Labor	461.25	$K
Misc. Cost	20.00	$K
Total	**2960.26**	**$K**
Battery Designed for	12.00	Voc
Voc Cell	2.50	V
# Cells	5.00	
Web Width	30.00	cm
Pad Width	0.50	cm
# Pads	2.00	
Pattern Width	0.32	cm
Active Cell Width	5.42	cm
Capacity	35.00	μA•hr/cm^2/cathode thickness (in μm)
Cathode Thickness	3.00	μm
Areal Capacity	105.00	μA•hr/cm^2
Linear Capacity	56,899.50	μA•hr/m
	56.90	mA•hr/m
Areal Cost	29.60	$/$m^2$
Linear Cost (30 cm width)	8.88	$/m
	0.30	Single layer cost per Watt of CIS ($)
	0.74	Single layer cost per Watt of a-Si ($)

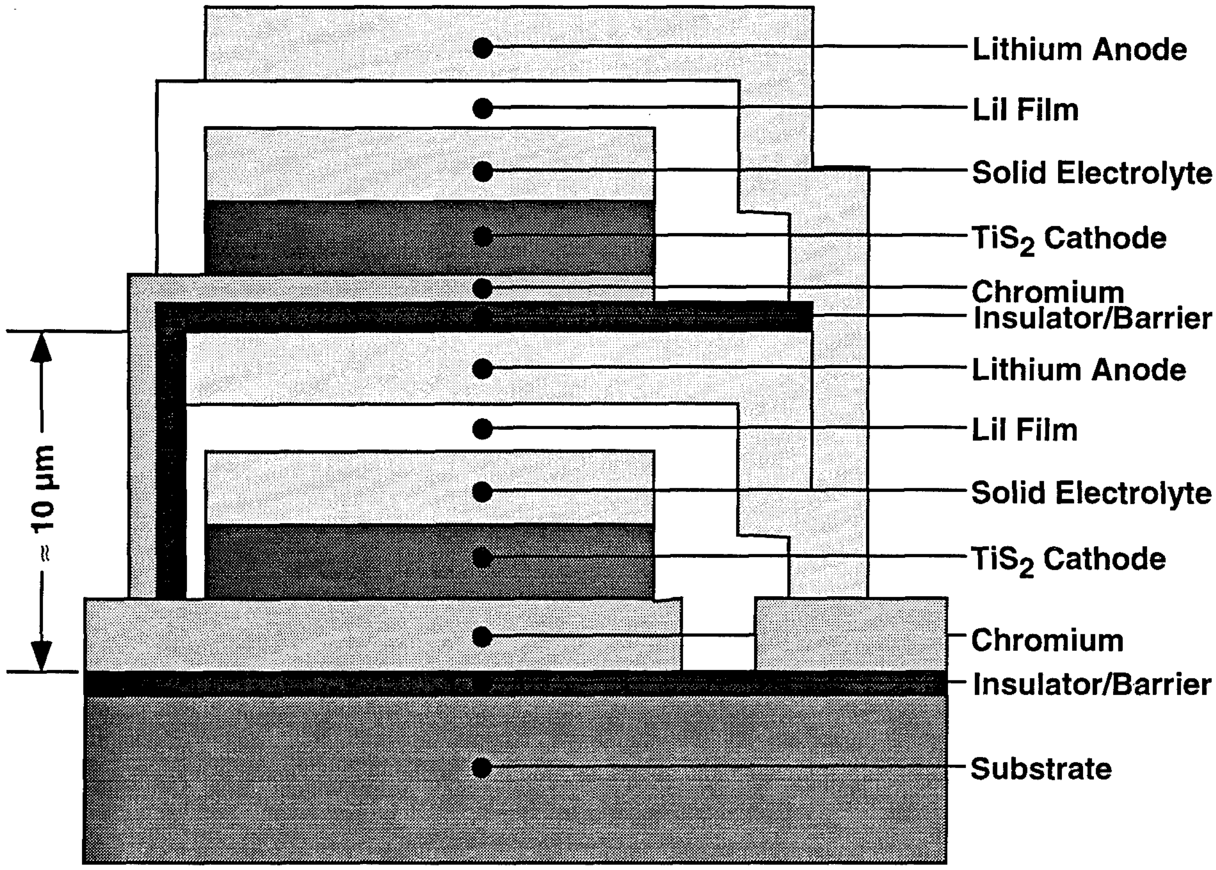

Figure 27. Schematic of a Stacked Microbattery for Increased Capacity

2.4 REMAINING PROGRAMMATIC AND TECHNICAL ISSUES

Many issues were raised during the Phase 1 effort to deposit Microbatteries onto flexible thin-film PV, both on a programmatic and a technical level. The most important of the programmatic issues is the need to bring all deposition steps directly under the control of ITN/ES. While we had anticipated this would occur during the Phase 2 effort, the lack of support from EBC throughout the project at their facility severely limited the success of this effort. Most of the difficulties were attributed to their internal workload. Issues such as substrate contamination could be handled almost immediately in the ITN/ES facility if it were capable of handling lithium-bearing compounds. Such a layout is shown in Figure 28. Three interconnected gloveboxes would be dedicated to target manufacturing, thin-film deposition, and post-deposition analysis and testing accordingly. An interconnected prototype system as described in Figure 28 would eliminate any possibility of contamination caused by bagging and transporting components outside the argon environment.

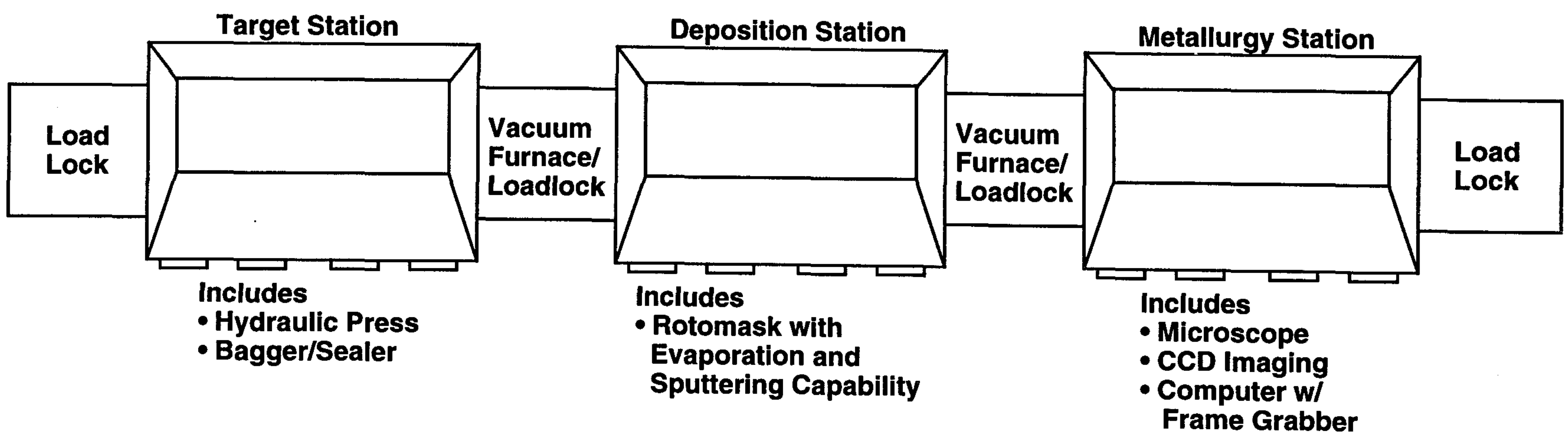

Figure 28. Schematic of an Integrated Prototype Thin-Film Microbattery Facility.

The process to be used in such a system is shown in Figure 29. For a prototype system, each deposition would be followed by a target change to facilitate using the same deposition system. Because the entire deposition system would be inside a glove box, no degradation to the device or the target material would be experienced. ITN/ES is acquiring gloveboxes to begin assembly of this facility.

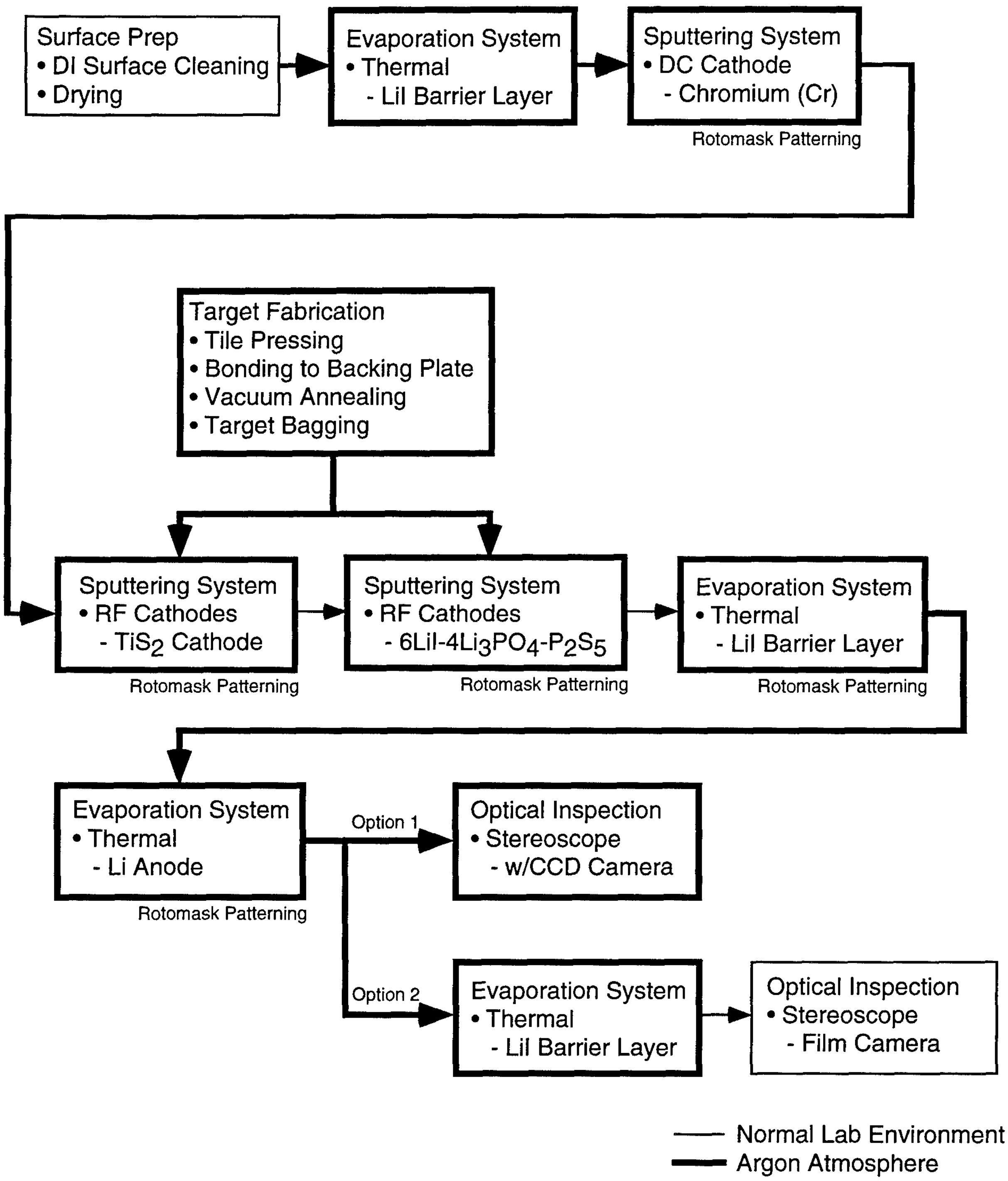

Figure 29. TOPS-PV Microbattery Process Flowchart Indicating Environmental Controls Required.

Because Phase 1 involved deposition over small areas (1 cm^2), this prototype facility will be capable of scaling to a 15 cm wide web. For a commercially-viable product, large-volume processing dictates a large-area deposition process, probably in excess of 30 cm wide webs. Phase 1 showed that vacuum deposition processes can be used to manufacture flexible batteries. These processes are scalable to very large areas, even to continuous deposition of roll-to-roll (web) products.

A third issue is the back surface of the flexible PV devices. When processes were developed for the flexible a-Si which was used in this Phase 1 effort, no expectations were made as to using the back of the device for anything, other than possibly as a back contact. Rollers, masks, and platens all contribute to scratching of the back surface. As a result, none of the a-Si devices we obtained allowed for subsequent device deposition on its back surface. Attempts to deposit onto the back of an a-Si device whose stainless-steel backing was removed had not been completed by the end of the technical performance of this contract. However, we are pursuing this as one viable alternative.

Fourth, because EBC did not have access to any metallographic equipment capable of handling Li-bearing materials (other than stereoscopes), we were unable to conduct a thorough analysis of the film properties. Because EBC did not intend to manufacture these batteries, their depth of knowledge of the thin-film processes is sufficient only for the R&D level. Thus, the Phase 2 effort must include a fundamental aspect that will provide not only information for scaleup in Phase 2, but also provide sound fundamental data to decide upon the feasibility of a Phase 3 commercialization project. Discussions with Dr. David Olson at the Colorado School of Mines (CSM) indicated that such a facility could be established at the school where access to optical, scanning electron, transmission electron, Auger, and atomic microscopy would be available. This effort would be needed to assist scaleup and to improve producibility of the thin-film devices. Furthermore, this capability would be needed to assess the sensitivity to surface defects on the back substrate of the thin-film PV devices. CSM's experience in handling, processing, and analyzing Li-bearing compounds helped significantly in the preparation of the Phase 2 proposal.

Finally, issues regarding patterning for monolithically-integrated Microbattery must be studied. Part of Phase 1 required masking of individual layers to allow for two Cr contact pads with a lithium bridge. While the stresses in this area are still an issue, the ability to bridge this gap to connect to the other pad demonstrates the possibility of monolithic integration using a similar masking scheme. Monolithic integration eliminates the need for manual interconnecting, thereby reducing labor costs and improving reliability by eliminating heavy soldering joints and high-temperature bonding processes. However, monolithic integration could amplify stress-related issues and as such processing must be developed to control intrinsic thin-film stresses. Patterning of Microbatteries for monolithic integration, however, cannot follow the exact path used in the PV world. For instance, the last film, the Li anode, must be masked because the device would short out the fully-charged battery immediately without *in situ* patterning. For cost-effective roll-to-roll, or web deposition, the issues regarding patterning a moving substrate must be addressed. At present, ITN/ES is developing internally a method to pattern moving webs without dragging the sensitive thin films across stationary masks.

3.0 POTENTIAL MARKET FOR TOPS-PV TECHNOLOGY

3.1 SPACE MARKET

A great deal of interest has been generated in space applications for thin-film PV (Refs 27 and 28). Many of these projects could also utilize TOPS-PV as well. The potential market for a TOPS/PV technology lies mainly with the small spacecraft products where the limitations of spacecraft volume can become a major technology and program driver. Most significant in this category is the Teledesic program, where due to the sheer volume of spacecraft to be manufactured and launched, spacecraft size reduction is critical. Constellations of up to 940 spacecraft (including spares) are being considered. Other satellite markets are still available.

3.2 TERRESTRIAL MARKET

Terrestrial-based applications are numerous, including military-based markets (Ref 29). However, cycle life is critical here, but in a cost perspective. Many of the larger applications (e.g. housing, power plants) for PV and batteries require low system cost over the life of the system. High cycle life would eliminate the need for lead acid battery replacement every year or two. Both government and civilian applications exist for this product; in fact, ITN/ES is working with the U.S. Marines to build a rechargeable battery pack with a flexible PV array to eliminate the need for primary, disposable batteries for their radios. Such a system is shown schematically in Figure 30 and in a photograph in Figure 31. Microbattery technology on the back of the array is a perfect application for this technology. Similar projects from the Air Force and Army are possible as well. A poignant example of the importance of rechargeable batteries and their cost reduction in portable military PV power is military exercises where more is spent on batteries for radio communication than on munitions! These batteries are considered hazardous waste and expensive ($62.50 each plus $7 each for waste disposal). Furthermore, logistics for moving in and removing sufficient batteries for an operation are staggering.

Another terrestrial application is low-cost housing. One of the most pressing needs in our world is housing. One out of every four people in the world — 1.25 billion — live in unsanitary and unsafe shelter. Most of these conditions exist in developing countries, but not all; recent natural disasters — earthquakes, floods, hurricanes — have left many homeless in even the most affluent of countries. These two scenarios have much in common, in particular the need for low-cost, easily-installed housing.

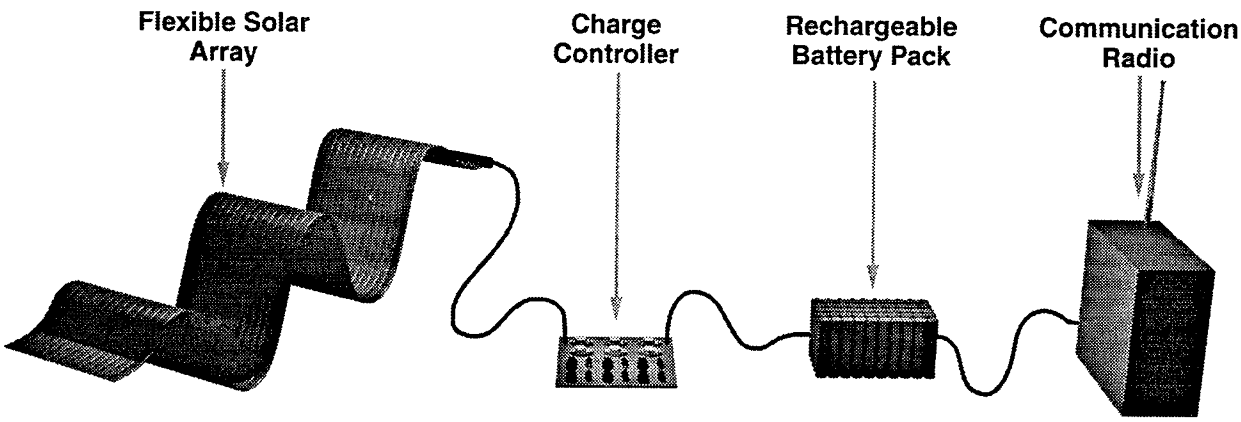

Figure 30. Schematic of ITN's Rechargeable Battery Solar Array System (RB-SAS).

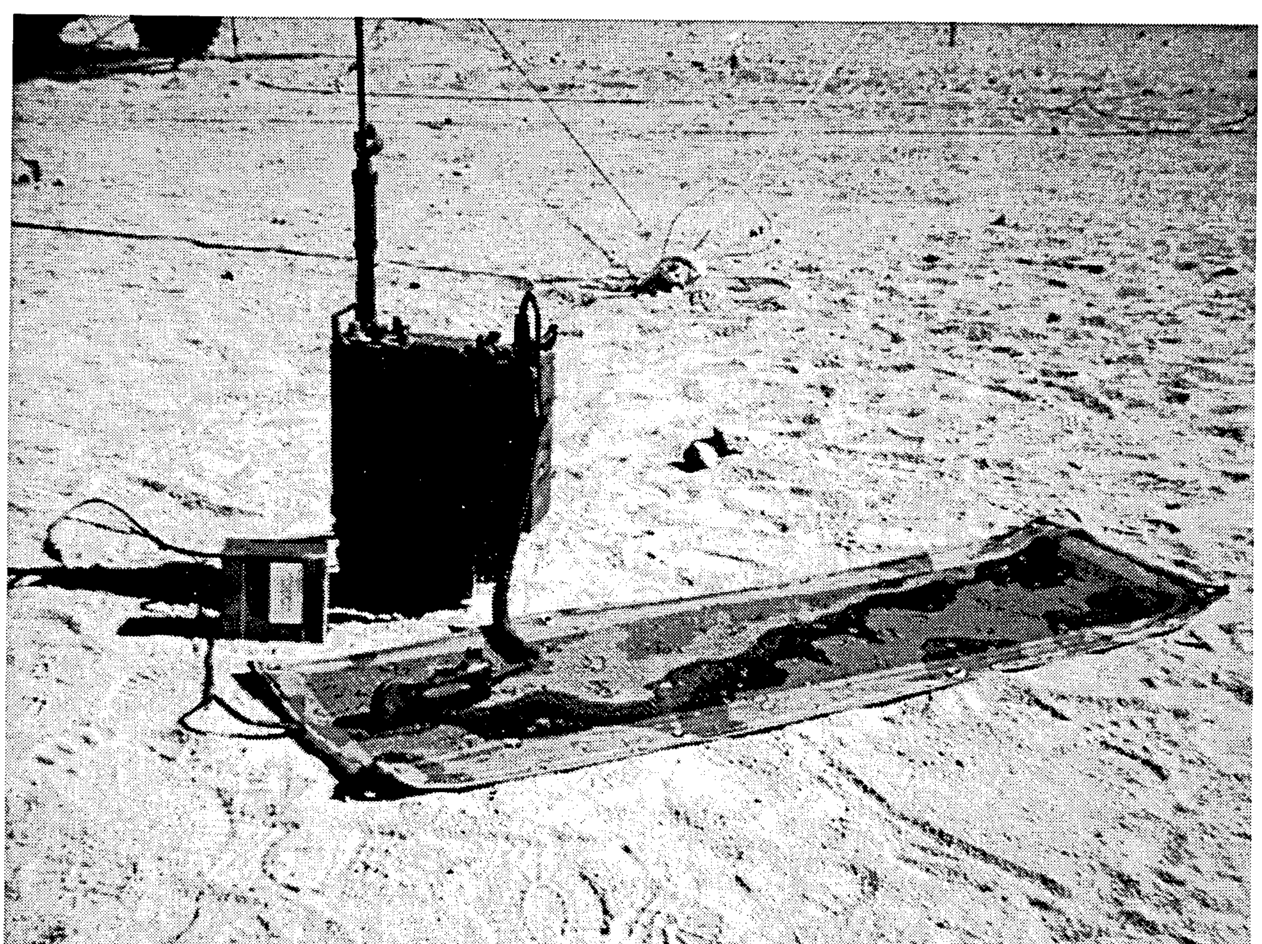

Figure 31. Photograph of ITN/ES' Current Rechargeable Battery Solar Array System (RB-SAS) in Operation.

In addition to the need for housing is the need for electricity. Lighting is necessary to increase productivity around the home and to promote education of the developing world's youth. Sources of running water, which almost seems second nature to those of us in the commercialized world, is scarce and as such is often the cause of much of the disease and famine in these areas. Refrigeration is also a critical need in developing countries to protect food and medicine. Thus, the needs of housing and power are inseparable for all practical purposes.

A typical low-cost home is shown in Figure 32. ITN/ES has found a significant market for PV and the TOPS/PV technology in low-cost housing and portable power for both military and civilian applications. At the present time, ITN/ES is pursuing a low-cost housing project with PV in Asia with a potential of 25,000 homes per year with options of up to 125,000 homes per year. While it may be impractical to rely solely on a TOPS-PV configuration for roof-mounted devices, additional storage can be placed in canisters from a continuous roll of Microbattery developed in a Phase 3 effort. Figure 33 shows a schematic representation of how a TOPS-PV power array can be laminated onto the roof of a typical low-cost home with easily attached leads that connect the self-contained powerpanel to the main DC bus. ITN/ES is pursuing this market to create a self-powered, low-cost home; a single order from China will result in 125,000 homes per year, each with about 500-1000 W PV systems installed.

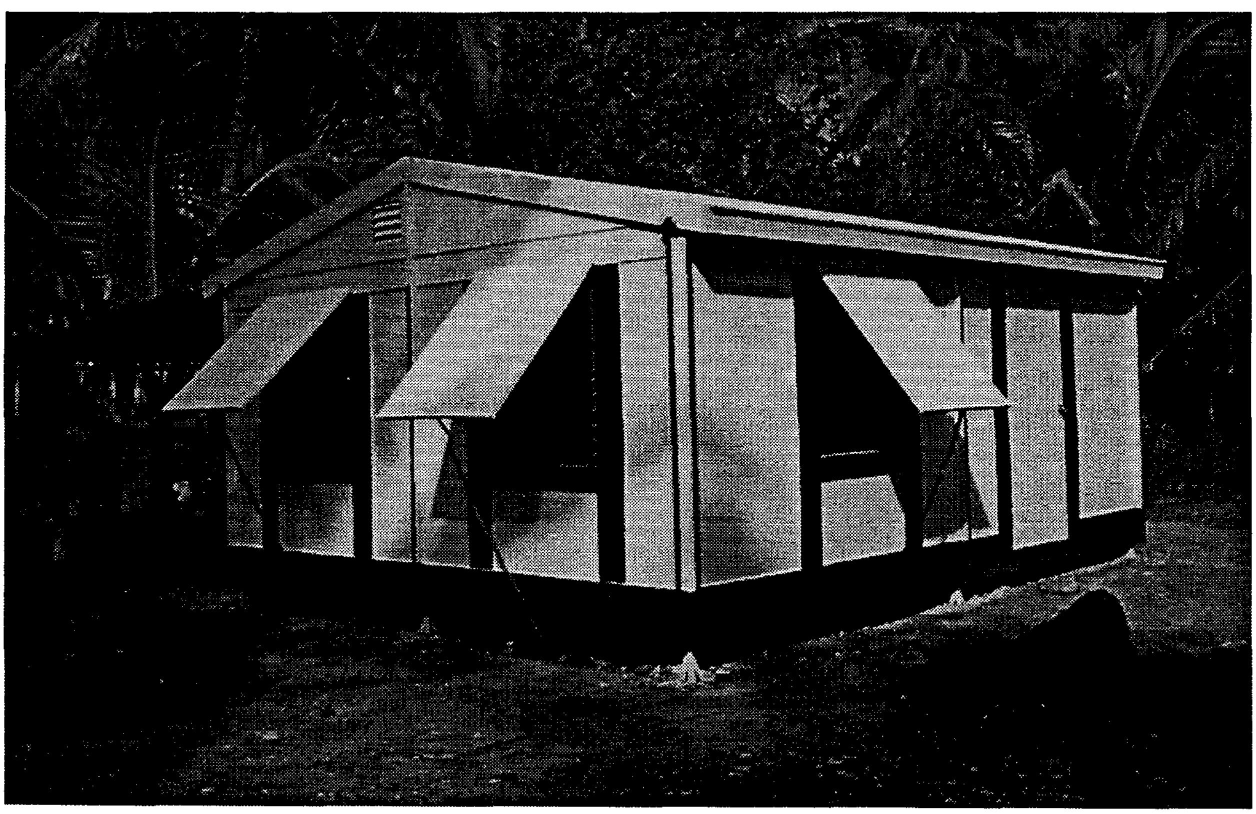

Figure 32. Photograph of a Typical Low-Cost Home.

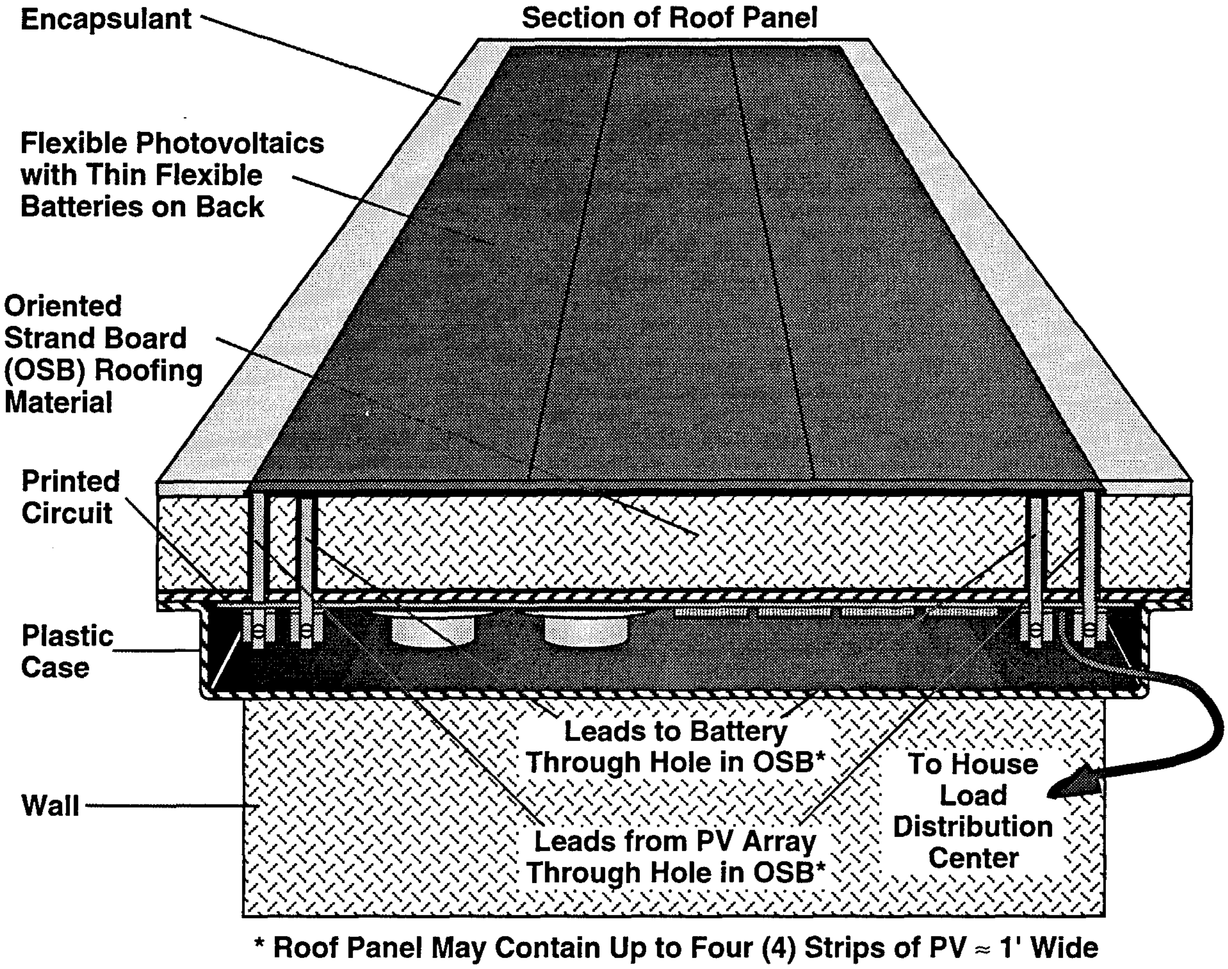

Figure 33. Schematic of TOPS-PV Product for Low-Cost Housing with Interconnect Scheme.

Other terrestrial applications with both commercial and governmental implications includes unmanned aerial vehicles (UAV) and powered gliders (Fig. 34). In these vehicles, space is at a premium and very little can be modified by way of the surface of the wing. TOPS-PV could conformally attach to the wing surface, thus providing electrical power and storage for onboard avionics, sensors, radar, and communication equipment.

Finally, ITN/ES has also identified uses for the Microbattery alone, including power tools and surgical tools. ITN/ES is presently developing intelligent power tools, such as screwdrivers and wrenches, in corded versions for assembly lines. Recent discussions with tool manufacturers indicate a tremendous need for a cordless version of this battery. Due to the flexible nature of the batteries, it is possible to construct a “hollow” cylindrical battery (Fig. 35), thereby allowing electronics, motors, gears, and other structural components to fit coaxially with the battery. Such a design would be a vast ergonomic improvement over existing products.

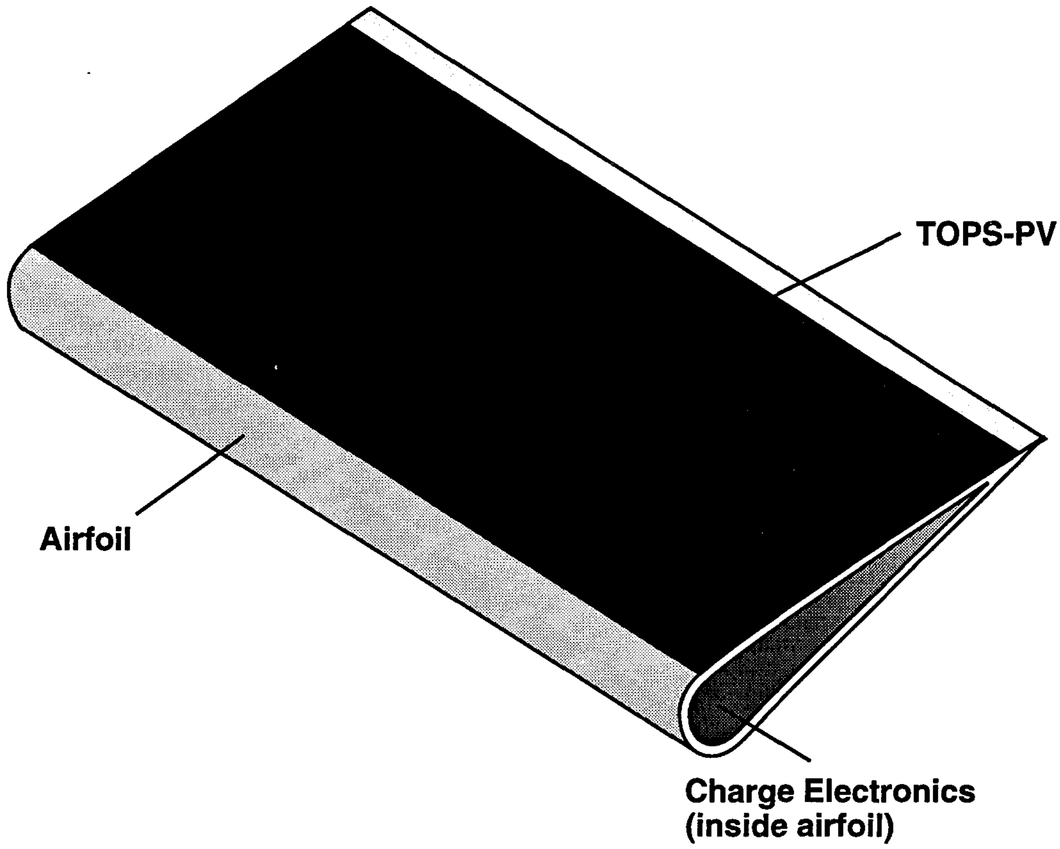

Figure 34. Schematic of a TOPS-PV Product for Use in Powered/Unpowered Gliders and Unmanned Aerial Vehicles.

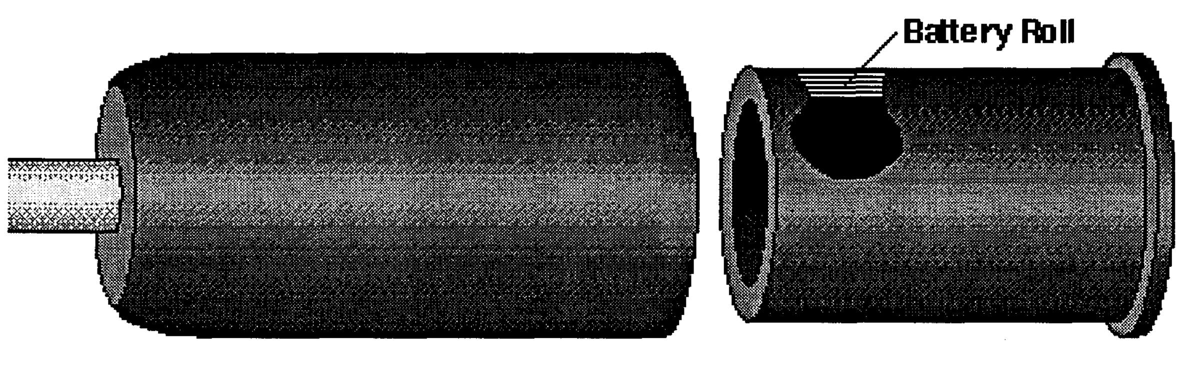

Figure 35. Schematic of Hollow Cylindrical Battery Possible Due to Microbattery Technology.

4.0 SUMMARY

During the past six months of the TOPS-PV program, we have demonstrated the feasibility of depositing the Microbattery onto a flexible substrate, namely polyimides. While the number of batteries produced did not allow us to conduct extensive analyses, they did nonetheless demonstrate the potential for these technologies. Contamination issues involving moisture and other contaminants from the polyimides, particularly the Kapton, can be resolved with proper pretreatment of the substrate prior to deposition. Difficulties with stresses in thin films is a common problem with multilayer thin-film stacks and are all resolvable through process variations. One possible solution is to replace the existing evaporation process with a lower-temperature sputtering or PECVD, if necessary, to minimize thermal mismatch issues.

Due to time constraints at Eveready Battery Company, we were unable to complete the deposition of the battery onto the back of a flexible PV substrate. However, there is no reason to believe that this stacking could not be done, provided that the back of the devices was sufficiently smooth after processing to prevent battery shorting.

ITN/ES has identified numerous markets, both in space and terrestrial applications, that not only can use the TOPS-PV technology, but in some cases, require it. In particular, portable power for communications and space arrays are the most immediate applications. While some of the identified applications represent rather high-volume production, scaleup issues are parallel to those under investigation for the photovoltaic technologies. Such a synergy can only benefit the microbattery/PV technology.

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