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The Future of Organic Electronics Manufacturing

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Executive Summary

E.1 Summary of Organic Manufacturing Methods

Organic semiconductors (OSCs) are promising candidates for a number of large-area electronic and electro-optical applications. Two major properties differentiate organic semiconductors from their inorganic counterparts. First, light absorption and emission is an efficient process in many thin-film OSC materials; and second, because OSCs are held together via van der Waals bonds, which are relatively weak, OSCs can be deposited and manipulated using minimal energetic investment. These two properties allow organic semiconductors to be applied to a range of electronic devices on a variety of substrate materials. Thermal evaporation and solution processing of active electronic materials is now a reality, and many systems can be built using economical process steps on substrates unthinkable a decade ago.

E.1.1 Printing vs. Blanket Deposition

The molecules in OSCs are primarily van der Waals bonded, which allows manipulation of these materials using a relatively small energetic investment. The relatively weak inter-molecular bonding of soluble or solubilized materials can be disrupted by the introduction of a solvent, and these materials can be deposited in a solution carrier, which evaporates leaving the semiconductor behind. Small molecule materials can also in most cases be thermally evaporated in a vacuum environment. The ability to use thermal evaporation and solvent-based processes represents a significant processing advantage over covalently bonded solids, like amorphous silicon (a-Si), which requires enough energy input to break the covalent bonds to manipulate the material and is kinetically disadvantaged against the formation of an ordered bonding structure.

Patterning of OSCs is often a challenging process, and printing technologies have been identified by many groups as a strategy for reducing costs and increasing throughput in manufacturing. Printing combines the deposition and patterning steps for a material; it simultaneously transfers the material only to where it is required, leading to both process and material utilization efficiencies. The ultimate goal for many groups is the development of roll-based high throughput manufacturing processes with an economy of scale similar to that seen for other roll-based mass produced products like printed paper products and food packaging (e.g. potato chip bags). Many of these example products incorporate some of the same unit operations, such as metal evaporation and aligned and patterned solution printing that are needed for OSC device fabrication.

Solution deposition can add some complications in device fabrication process flows. Despite these complications, there has been significant investment in technology development and establishment of a large installed equipment base for patterned solution deposition using techniques developed for the printing and coating industries. Many research and development groups working in the OSC space have decided that the benefits associated with printing outweigh the complications and are vigorously pursuing all or mostly printed solutions. Most commercial or near-commercial OSC-based products, however, incorporate at least one non-printed definition step as part of the process flow because of material, device, or process limitations.

E.1.2 Major Deposition Methods

A number of approaches have been proposed for the deposition of organic semiconductor materials. Small molecule materials have a low molecular weight and can be deposited via evaporation in a vacuum or, if they are soluble, can be deposited from a solution. Polymeric organic semiconductors need to be functionalized so that they are soluble and can be deposited using printing or blanket deposition techniques.

Current processes approaches for small molecules rely on thermal deposition techniques. Thermal deposition, however, suffers from several drawbacks that can make it uneconomical. Vacuum equipment is expensive and has a relatively long tact time for batch processing. It can also be challenging to control of the deposited material morphology, material utilization, and patterning.

To address these challenges a number of improvements have been developed which significantly improve the throughput and quality of material deposited using thermal processes. Roll-to-roll vacuum equipment allows for deposition over large areas to occur using only one pumpdown time, which significantly improves throughput and decreases process cost. Roll-to-roll and inline feed systems can also take advantage of line deposition sources, which address the material utilization and uniformity problem by providing a geometry that uniformly deposits material on the substrate while it is moving past and sweeping out a uniform deposition cross section.

Several improvements on batch evaporation have also been engineered. Most thermal evaporation is traditionally performed from a point source, which is straightforward to heat and control from a crucible. A point source acts more or less like a Knudsen cell, which has a Lambertian emission plume. A rectangular substrate placed on top accumulates more material in the center, where the solid angle subtends more of the plume, than on the perimeter, and increased uniformity can only be achieved by using substrate rotation and increasing the separation of the substrate and source, wasting much of the material in the periphery of the plume. Advanced thermal source chimney structures that re-shape the deposition plume into one more suitable for rectangular substrates (such as those produced by Advanced Neotech Systems) can improve the uniformity of a material that is deposited from a point source on a rectangular substrate. This allows existing equipment to be upgraded for larger substrates, and offers better uniformity.

Another approach that improves material utilization of batch thermal deposition is organic vapor phase deposition (OVPD). OVPD, which was developed at Princeton University and is being commercialized by Aixtron, improves the traditional evaporation process by eliminating the need for line-of-sight deposition. In OVPD the evaporant is sublimed upstream and entrained by a carrier gas flowing through the source material. The gas is then distributed through a heated showerhead, which directs the material onto the substrate and uniformly distributes it. This approach allows direct areal deposition of the semiconductor and also overcomes the geometrical constraints of traditional point source evaporation processes.

Most organic semiconductor materials are not tolerant of solvent exposure (and in many cases are not tolerant of air exposure), so patterning operations often need to be employed that can structure the material without the use of photoresists or other conventional processes. When thermal evaporation is used, one popular approach is to use shadow masking during deposition, in which a structured foil is placed in the path of the emission plume to block material from depositing in unwanted areas and to allow for deposition elsewhere. Another popular approach is the creation of photolithographically defined shadow break structures on a panel, which allows a similar shadowing to be used to create discontinuous films.

Several alternatives that bring printing-like control to thermal evaporation have also been developed. A spatially patterned version of OVPD pulses the vapor stream allowing control over where the material is deposited. Another printing-like vapor deposition method is the molecular jet (MoJET) printing technique, which was developed at MIT and is being commercialized by TJet; this process allows inkjet-printing like control of vapor deposited materials at atmospheric pressures. Both of these techniques—by depositing material uniformly one point at a time—simultaneously solve the patterning, uniformity, and utilization problems inherent in typical vapor deposition.

OSC polymers and small molecules can be functionalized with solubilizing groups and can be deposited using a variety of techniques including on-demand drop and line printing, which are printing techniques that simultaneously pattern the material while depositing it. For many layers (e.g. large covered areas in OLEDs and gate dielectrics) blanket solution coating techniques such as slot and gravure coating are also extensively used.

E.1.3 Major Device Categories and Requirements

The major devices that are being commercialized have mostly grown out of university and industrial research labs over the past two decades. These devices have attracted commercial interest because they display system performance and/or cost that is believed to be superior to that of incumbent approaches; as such, there is interest in developing manufacturing processes and building capacity for these new devices.

Organic Light Emitting Diodes (OLEDs): Efficient OLEDs use at least one, but typically five or more, organic semiconductor layers to convert injected electrons and holes directly into excited states, which decay into emitted photons. OLEDs are the most efficient and highest performing large area electroluminescent light source currently known, and a great deal of effort and expense has been applied to developing the technology for active matrix and passive matrix display applications.

Full color displays typically operate by combining the three primary colors detected by the human eye—red, green, and blue—at each pixel to simulate the experience of seeing all possible colors. In order to create this color mixing illusion, however, and avoid seeing different color subpixels instead of a merged mixed color pixel, the red, green, and blue emitting regions need to be patterned very close to each other. The degree of separation required for these subpixels depends on the distance of the display to the observer, but is typically on the order of 150 microns for a desktop display and five or so microns for a near-to-eye microdisplay. It is the separate patterning of these three-color subpixels without direct photolithographic patterning of the semiconductor materials that is the most challenging issue facing OLEDs. Lifetime, brightness, and color point are also areas of concern, but there are established strategies and promising future developments for dealing with those problems.

OLEDs can be used in a passive matrix configuration in small panels, but for long lifetime and high image quality an active matrix backplane must be used. OLEDs are also now attracting a great deal of interest for lighting applications—they can be produced with a minimal energetic investment, can be highly energy efficient, are mercury free, and can emit light over a large area which has advantages for shadow-free lighting without complicated fixturing in many environments. Several processes for OLED-grade lighting have been developed which take advantage of the unique properties of organic semiconductors for low cost and high fabrication throughput. General Electric's lighting OLED process, for example, allows for the roll-to-roll fabrication of white OLEDs with a reasonable color rendering index, air-stable encapsulation, and avoids vacuum deposition of the organic semiconductors. The process deposits the anode and cathode conductors first in vacuum on separate substrates (which can in principle be done cheaply using a roll-to-roll coater), the semiconductors are printed, patterned (by wiping), and dried, and the two halves are laminated together. This is a level of process flexibility unknown in other technologies and holds the potential for significant cost savings. There are many firms, both large and small, which are working in the OLED space, but this report highlights several of the most influential that have integrated processes of note—Kodak, Universal Display Corp. (UDC), Sony, GE, and DuPont Display—along with some of the other players that have developed interesting manufacturing techniques or other unit operations.

Kodak and UDC primarily have been developing materials and processes for vapor deposited small molecule OLED production. Both companies have an extensive intellectual property portfolio. UDC has developed a number of unique OLED stacks and holds the rights to phosphorescent material technology, which significantly increases the efficiency of OLED devices. The OLED was developed at Kodak, giving the firm a decade-long head start in the technology and allowing it to capture much of the foundational IP in the space.

Cambridge Display Technology (CDT), which was recently acquired by Sumitomo Chemical, was formed to commercialize polymer light emitting diode (P-OLED) materials and processes that allow the use of inkjet and other printing technologies to pattern the R/G/B areas on the display, avoiding the shadow masking which is typically used for small molecule process flows. CDT's technology has been used in a number of commercial devices, but is feeling pressure from soluble oligomer technologies being developed by DuPont and UDC. It is also suffering from an inferior blue material to alternative approaches, which has limited its applicability to TV and other high information content displays.

GE, along with Osram, Philips, and others, is looking at printed low-cost OLED lighting as a major future market. Most notable has been GE's development of a roll-to-roll pilot tool that prints lighting-grade OLED panels on flexible sheet substrates in a relatively high speed and continuous process. The design of this tool, the process used to assemble the panels, and the packaging infrastructure that has been developed alongside the tool are likely to influence other firms moving into the same space.

The major current capacity and revenue in OLEDs is in the OLED display market. It is expected, however, that OLED lighting will start to increase substantially in market size in 2010, starting with specialized units for shadow eliminating lighting (e.g. for photography) and architectural accents, moving into more mainstream applications starting in 2011 and beyond. OLED displays will continue to grow in market share and have already started to penetrate the TV market. It is expected by most industry watchers that OLED displays will start to displace currently dominant liquid crystal displays when cost parity is achieved and that the OLED infrastructure will have significantly lower costs overall, allowing for greater market penetration once volumes ramp up.

Organic Thin-Film Transistors (OTFTs): Organic thin-film transistor (OTFT) are devices that have performance that in many ways exceeds that of amorphous silicon, but can be produced using simple and straightforward processes such as thermal deposition and solution deposition strategies.

There are two major applications that companies have been pursuing for OTFTs—object level contactless identification (e.g. through RFID or capacitive signaling) and displays on flexible substrates. Because these devices can be printed or produced using other continuous flow processes at a low cost per unit area, it is conceivable that integrated identification (for product checkout, inventory control, document authentication, etc.) could be placed on virtually all objects at costs comparable with that of printing graphics using traditional ink. This would allow the development of substantial new markets, paralleling the influence that RFID has had on traditional retail markets.

Because OTFTs can be produced on plastic sheets they are attractive for use in electronic book readers using e-ink electrophoretic frontplanes. E-ink is mechanically flexible, and while the flexibility of OTFT-based backplanes is being emphasized by some end users (e.g. making rollable displays which can be stored at a size smaller than the display itself), perhaps the largest end market is that for ruggedized displays. E-book readers have been developed using thin plastic sheet-based displays that have significantly reduced weight and higher ruggedness by eliminating the glass and armoring required in traditional amorphous silicon backplane-based displays.

There are several companies that are scaling up production of OTFTs. Plastic Logic recently commissioned a US$80-million fabrication facility in Dresden, Germany to produce OTFT-based backplanes for e-ink based e-book readers. Plastic Logic uses a combination of photolithography and solution printing of the semiconductor and other device layers in order to achieve high throughput and adequate device performance.

Another major player in this space is Polymer Vision, a spin-out company of Philips Research, which also recently acquired additional fabrication capacity by buying out a subcontractor that has a silicon fabrication line in the U.K. Polymer Vision has also demonstrated an e-ink based e-book display based on a plastic sheet substrate. This display is notable because it takes advantage of its mechanical flexibility and can be rolled up for storage.

Sony has been exploring OTFTs, but primarily as drivers for flexible AMOLED. It has developed a sophisticated deposition and patterning process and demonstrated a flexible, full color AMOLED display. While there are no current plans to transition the process to manufacturing, Sony's future display roadmap has roll-up displays as a future element and sees this technology as one possible platform on which to build such a unit.

PolyIC is one of the more influential groups working on item tagging using OTFT materials. PolyIC and its partner organizations have demonstrated a number of RFID units and components, and PolyIC also has substantial expertise in continuous roll structuring of passive and active circuits. PolyIC's activities and plans in this space are profiled, along with its expectations for which milestones will lead to greater product adoption.

The greatest capacity in displays is found today at the Plastic Logic manufacturing facility, which can produce about a million displays a year. Most other firms are watching Plastic Logic closely to see how its product roll-out proceeds—if there is adequate demand and the product is well differentiated, it is certain that others will follow.

In the RFID space, PolyIC has substantial capacity for producing low frequency tags, and is already supplying these for some specialized applications. If groups are able to produce true standards-compliant RFID solutions at reasonable costs, there will be a significant opportunity for further growth especially in inventory control applications. It is also possible that RFID and RFID-like processes that can be implemented via printing will find applications in other structures, e.g. ticket and document authentication, where silicon-based RFID may be difficult to implement.

OTFTs have also been examined for other applications, such as chemical and mechanical sensing, but there is no substantial commercial activity at this time in those market areas.

Organic Photovoltaics (OPVs): OPVs take many of the advantages of OLEDs—low temperature and substrate-independent processing, and the ability to be printed on flexible substrates in a continuous process—and apply them to photovoltaic devices. Two major technologies have been developed that use organic semiconductors and dyes for photovoltaic applications. These are bulk heterojunction devices, which are produced using a solution deposition process and have a lower efficiency (currently around 6 percent), and dye sensitized solar cells, which use an inorganic cathode together with an organic dye and have a higher efficiency (around 12 percent) but are more complicated to produce.

The most influential firm in organic photovoltaics is Konarka, which was formed by the merger of three smaller groups working on organic PV. Many of these groups developed or had licensed work on a variety of OPV technologies, and as a consequence Konarka holds IP in many areas in which it does not have any commercialization activity, including much of the foundational IP for dye sensitized solar cells. Konarka has licensed many of its technologies to other firms, and one of these licensees, G24 Innovations (G24i), has developed a pilot line for dye sensitized solar cells that will likely serve as a model for other players in this space.

Konarka has recently leased the former Polaroid coating facility in New Bedford, Massachusetts, and is working on converting it to the production of continuously produced solar cells using Konarka's bulk heterojunction technology. This plant has a nameplate capacity (depending on the assumptions applied) of between 0.5 and 1GW a year of solar cell production. G24i's pilot line has been installed and is currently being qualified for limited production. At full capacity it will produce 30MW per year of solar cells. Many smaller companies are also developing new OPV technologies, but none have attracted the level of capital investment required to roll out substantial manufacturing capacity.

Organic Photodetectors and Sensors (OPDs): Organic photodetectors work on a similar principle to organic photovoltaics, but are instead applied to a variety of sensing devices that benefit from large area deposition. For instance, digital x-ray requires panels on the size scale of the item being examined, and microfluidic systems need to be instrumented at a number of reaction and detection sites distributed over a relatively large area. Both of these can be well served by large-area OPDs.

Several companies have publicly revealed interesting applications for OPDs, which take advantage of their unique properties. NANOIDENT[1] (and its subsidiaries) have been developing OPD-based sensors for microfluidic platforms that can be directly printed on the microfluidic substrates. These integrated sensors reduce system size and complexity, and potentially allow for more detection sensitivity by eliminating some of the loss and crosstalk associated with moving light off of the microfluidic element. Siemens has been working on using organic semiconductors to make indirect exposure digital x-ray panels using commercially sourced amorphous silicon backplanes. These panels show a noise level and sensitivity comparable with the best conventional panels, but with a substantially simplified production process.

PARC, the former Xerox Palo Alto Research Center, has been working on flat-panel photodetectors for many years primarily for flat panel x-ray and document scanning applications. PARC has examined the

[1] NANOIDENT has since filed for bankruptcy.

use of several OPD systems for photodetectors as well, including the use of photoconductors and bulk heterojunction devices.

There is currently no substantial manufacturing capacity in the organic photodetector/sensor space. NANOIDENT has a research facility that is able to produce a variety of devices using printing and more traditional photolithography, but it lacks a commercial product to drive volume production. Research is continuing in flat-panel x-ray detection at Siemens, but there do not appear to be any plans in place for a commercial product. PARC generally looks to license the technologies that it produces, but has not actively pursued commercialization of its OPD technologies in a publicly visible way.

E.2 Opportunities for Equipment Producers

Much of the manufacturing capacity that has been rolled out to commercialize organic semiconductor devices is a combination of homemade and commercially available specialized systems (such as printers and cluster tools for evaporation), generic equipment (e.g. mask aligners and photoresist coating), and repurposed equipment from other applications (e.g. slot coaters). Part of the challenge of organic semiconductor device fabrication has been coordinating the operation of all of this equipment to ensure high yield and throughput. Defects that are tolerable in graphics printing, for example, can be catastrophic in electronic applications. Several opportunities exist for equipment manufacturers to apply their expertise to accessing these markets.

There is a clear opportunity for the development of new specialized systems for deposition and patterning. Especially as firms scale-up, the expertise required in material and substrate handling, control of deposition and etching processes, inspection, and quality control becomes more specialized and is more difficult and expensive to develop in-house.

Firms with existing generic or repurposed equipment that is being used in OSC manufacturing can upgrade their systems to better suit OSC processing. Improvements that customers are looking for include:

- Improved cleanroom compatibility: Adaptation of equipment to use non-particle shedding parts (such as switching plastic to metal housings), the isolation of cooling fans from the clean environment or switching to water cooling, good static electricity control, avoiding disruption of the laminar air flow in the room, and establishment of clean microenvironments in the process area.

- Expanded solvent tolerance: Many OSCs need aggressive solvents that can damage many of the fittings in graphic arts equipment, which is typically designed for aqueous or less aggressive solvent ink systems. This will require equipment with redesigned fittings, tubing, hardware, etc.

- Higher deposition quality (especially for solution deposition): Graphic arts processes can tolerate a level of defects, which are invisible to the eye but unacceptable for electronic applications. Better coatings, higher resolution, and a higher degree of perfection in deposition are necessary for electronic applications.

- Integrated defect detection: Because a higher degree of perfection is necessary (and mistakes are more expensive), equipment that can detect and either correct or flag production defects is essential for semiconductor processing to allow for equipment maintenance and avoid production of scrap pieces. An example of such defect detection is equipment that can monitor inkjet heads for clogging and either execute a cleaning cycle or compensate from another nozzle.

- Wider process windows: Off the shelf deposition equipment is designed for use with a limited universe of materials (e.g. aqueous graphic arts inks or a single metal in evaporation). Equipment can be redesigned to allow the use of new materials with different properties (e.g. allowing the use of reduced viscosity inks or replacing the thermocouples in a furnace to allow low sublimation point materials to be evaporated instead of a metal)

There also appears to be some advantage to developing pilot-scale systems as a way to drive market adoption of a product or process. Fujifilm Dimatix, Litrex, and Yasui, which are profiled in this report, have adopted this strategy. Once customers pilot the process and materials using the small-scale pilot tool, they are more likely to invest in a production scale tool from the same family. Pilot tools are sometimes acquired together with production tools for higher throughput material formulation, experimental production, defect repair, etc.

Another area of opportunity of note is the production of tools for roll-to-roll and in-line sheet processing. Many of the pre-commercial processes currently in use are batch processes that are only slightly adapted from their laboratory form. For reasons of capital expense and maximum experimental flexibility, research and development laboratories almost always use batch processing equipment. Once the process flow is set, however, significantly higher throughput and lower cost can be achieved in a tool, which performs several of the process steps (especially vacuum steps) together. The expertise required to build such tools is relatively specialized, and generally needs to be provided by tool vendors. Equipment that can enhance the throughput of OSC unit operations, especially in commodity markets like OPV and OLED lighting, can add significant value to the final product.

E.3 Opportunities for Materials Suppliers

Many of the firms in the OSC space have been developing proprietary materials, whereas others have been focusing on using materials that are commercially available or available under license.

One area of engagement has involved large suppliers offering scale-up expertise to small synthesis shops. UDC, Kodak, and CDT all have alliances with chemical firms that have scale-up experience to produce their proprietary materials. UDC, for example, has established a partnership with PPG in which UDC develops and markets new OLED materials, while PPG scales up and manufactures the materials in bulk. UDC handles most of the customer engagement, licensing, and technology development, while leveraging PPG's expertise in production, synthesis, material testing, product packaging, etc. CDT, until recently, had a similar arrangement with Sumitomo, in which a joint venture called Sumation formulated, qualified, and sold polymer inks which were produced by Sumitomo and licensed and supported by CDT.

Another approach to establish a market presence has been to formulate materials into formats that are more easily applied by end users rather than selling them one compound at a time. Several firms (e.g. Polyera and Plextronics) have been offering packages of materials that are "ready to use" in the application space. This allows the material supplier to capture more of the value of the material (and use their expertise in dispersing it, etc.), allowing the customer to focus on processing the materials into working devices and systems that their customers want to buy. Polyera is planning to offer, for example, pre-mixed inks for the semiconductor and pre-mixed formulations for gate dielectrics that are compatible with one another and qualified on their reference equipment. Plextronics offers a "solar cell ink" that has P3HT and PCBM pre-compounded and can, in principle at least, be dispensed by any user into a working solar cell or photodetector.

Of course, new materials with higher performance for device layers are always welcome in the marketplace. A great deal of attention has been given to the semiconductors in OSC devices, but many other layers are also necessary including patterning materials (e.g. photoresist), insulators, patternable conductors, planarization layers, color filters, optical cavity transparent layers, etc. In addition to the development of totally new material types, another route to adding value is the adaptation or reformulation of existing materials for photopatterning, continuous coating, or inkjet printing.

E.4 Major Equipment Suppliers

Generic equipment is supplied by many of the usual firms operating in the flat-panel semiconductor space, but it is worth mentioning some of the suppliers that have focused energy on the printed and evaporated organic electronics space including:

- Fujifilm Dimatix: Makes printers and heads for inkjet printers. Dimatix makes several popular piezo printheads that are used in a number of printers. Fujifilm purchased the firm in 2006. Dimatix also produces a relatively popular lab-scale R&D printer that sells for about $40,000.
- Xaar: Makes inkjet heads, primarily for the graphic arts industry. Xaar has also developed inkjet heads that are able to dispense organic semiconductors over large areas.

- Litrex: Makes inkjet printers, primarily using Dimatix heads (although other configurations are possible). Litrex has developed a popular lab-scale printing system as well as a large format LCD-glass scale (up to Gen 8) printing systems. Ulvac acquired Litrex in 2008.

- Pixdro: Makes inkjet printers and a proprietary head primarily targeted at the OLED and OSC industry. Pixdro has demonstrated devices jointly with a number of other device companies including Thin Film Electronics in Sweden.

- Applied Materials: Makes semiconductor fabrication equipment, and has recently created a new division to produce OSC and OLED equipment.

- Yasui: Focuses on coating, mostly for printing and converting markets (e.g. depositing adhesives, etc.). Most notably makes a lab-scale gravure printer that is popular for OSC coating.

- Tokki: Makes batch vacuum coating equipment, and has been focusing on OLED and OPV deposition and encapsulation.

- Ulvac: Makes vacuum coating equipment for vacuum deposited OLEDs, and has also acquired Litrex, which makes inkjet printers for color filter and OLED fabrication

- Doosan DND: Makes vacuum coating equipment for OLED fabrication

- Vitex: Licenses a process for OLED and OPV encapsulation. The encapsulation equipment is made by partner companies that specialize in equipment production.

- Dai Nippon Screen: DNS's engineering team has created several systems, which are suited for organic semiconductor deposition and patterning.

- Advanced Neotech Systems: Makes OLED deposition and encapsulation tools, as well as new evaporation sources.

Some of this equipment competes with homemade equipment, especially in pilot lines, and some (like inkjet printing and encapsulation tools) is challenging to make in-house and enables entire product categories.

E.5 Summary of Capacity Forecasts for Organic Electronics

Exhibit E-1 shows NanoMarkets' projections for the capacity in each of the major devices discussed in this report, while Exhibit E-2 shows the equipment roll-out value in each of these areas.