NATIONAL CENTER FOR MANUFACTURING SCIENCES
(NCMS)

A Collaborative Effort to Address Advanced Technology Needs of the U.S. Printed Wiring Board Industry

Printed wiring boards (PWBs) underpin the efficient manufacture of virtually all electronics products. PWBs provide the platform on which to mount integrated circuit chips, capacitors, and connectors for the manufacture of everyday products ranging from toys, toasters, copy machines, and pagers to computers. Circuit patterns in copper or another conductor are etched on the surface of an insulating material to make connections among components typically mounted on the fiberglass board. And because they are a component to any larger electronics assembly, PWBs are an essential component of many other U.S. technologies.

COMPOSITE PERFORMANCE SCORE
(Based on a four star rating.)
★ ★ ★ ★

U.S. Producers Loosing in Global Competition

Between 1984 and 1990, the U.S. world share in the manufacture of printed wiring boards declined significantly, from 42 percent to 26 percent, with lost market share captured by lower-cost foreign competitors using increasingly sophisticated technology. In 1991, the profile of the U.S. PWB industry was one of many small firms with little market power or research capability: 725 firms produced PWBs, but most had annual sales of less than $5 million in specific niche markets. These small firms lacked the resources to undertake R&D on a scale that would achieve technology breakthroughs, and could only support R&D that addressed particular and immediate product development goals. Meanwhile, users of PBWs were forecasting that in the near future they would have to procure an increasing share of PWBs from foreign producers whose technical advances were outstripping those of U.S. producers.

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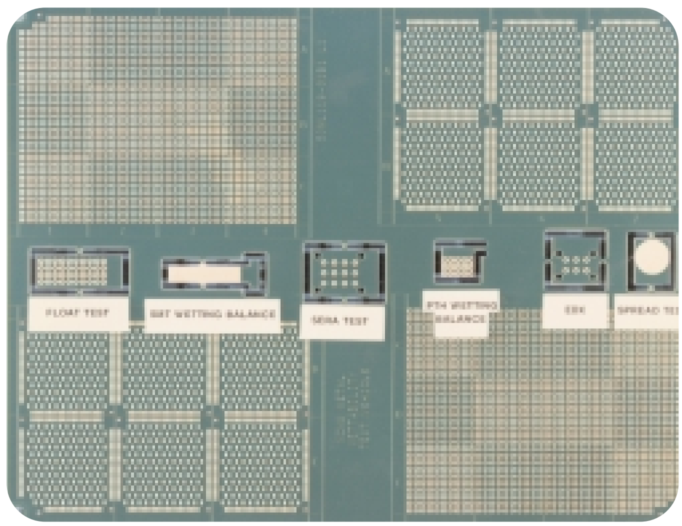

A printed wiring board test vehicle used by the surfaces finishes team, with different solderability test method coupons labeled.

ATP Supports Collaborative R&D Initiative for "Leapfrog" Technical Advances

A few leading equipment suppliers with advanced research capabilities, concerned with the decline of the U.S. domestic PWB industry, coalesced to form a research joint venture to address the technology gap faced by domestic PWB producers. These equipment producers, all major consumers of PWBs, utilized their membership in the National Center for Manufacturing Sciences, a nonprofit organization that specializes in brokering collaborative R&D projects, to organize the joint venture. The NCMS helped to organize the collaborative project among four of its member companies.

The joint venture, comprised of the four major companies, with NCMS as the coordinator, applied in the ATP's 1990 General Competition for a five-year project. The initial participants were AT&T, Digital Equipment Corporation (DEC), Hamilton Standard Interconnect

PROJECT HIGHLIGHTS

PROJECT:
To develop advanced processes and procedures for making printed wiring boards (PWBs), the backbone of all U.S. electronics products, that would leapfrog existing domestic and foreign technologies, thereby re-energizing the U.S. PWB industry in the face of severe international competition. The goal was to assist U.S. suppliers of printed wiring boards to become able to supply the boards of the future, through advances in materials, surface finishing, imaging, and overall product design.

Duration: 4/15/91 – 4/14/96

ATP Number: 90-01-0154

FUNDING (in thousands):

ATP	$12,866	48%
Company	13,771	52%
Total	$26,637	

ACCOMPLISHMENTS:
The project teams undertook many tasks in four technical areas and made a number of significant accomplishments. Accomplishments achieved by the team or following from those achievements include:

- demonstration that single-ply fiberglass could be produced with a sufficiently regular surface to allow for reliable electrical performance at a substantial cost savings, such that it has become the industry standard and the military has adopted it as a reliable product;
- broader applications for an imidazole treatment for copper that improves on the use of soldering as a way of preventing oxidation of copper surfaces, to which component leads must be connected;
- a test procedure for evaluating the process for producing PWBs, which allowed users of PWBs to conduct quality tests on sample boards, thus enabling them to evaluate the production methods used by PWB suppliers;
- demonstration of the effectiveness of thin copper plating in adhering to fiberglass in order to reduce the amount of copper used (saving resources) and lessening processing time (increasing productivity);
- a new interconnect structure—Multilayer Organic Interconnect Technology (MOIT) that may revolutionize the fabrication of PWBs, by achieving much higher wiring density than does current PWB technology;
- a plasma monitoring device which was, in turn, furthered by Sandia through a Sematech project, and eventually commercialized by a spin-off company—Peak Sensor Systems—formed by Sandia scientists;
- commercialization of single-ply glass technology by a leading supplier of glass laminate to PWB producers;
- commercialization of thin copper by Polyclad, a leading supplier of copper plating to PWB producers;
- further development of imidazole treatment for conducting surfaces (earlier patented), and licensing of it to LeaRonal, Inc., which supplies the treatment to PWB producers;
- formation of a new company, Conductor Analysis Technologies, Inc. (CAT), to commercialize the testing procedure developed by the imaging team and used by equipment manufacturers to verify that PWB shops have the technical capabilities necessary to build new high tech designs;
- 214 papers presented on the project;
- two best-paper awards at industry conferences;
- a patent on conductor analysis technology filed and received by NCMS, which then licensed the technology to a start-up company: "System and Method for Analyzing Conductor Formation Processes" (No. 5,659,483)
- a patent for prepeg bonding copper filed by NCMS but not yet received;
- development of novel PWB applications for block copolymer adhesion promoters, which facilitate lower copper profiles and thinner materials, by Sandia scientists working on the project, and a patent for a solder delivery method filed but not yet received by Sandia scientists;[2] and
- a patent for the test method developed to quantify capillary flow solderability was filed and received by Sandia National Laboratories "Solderability Test System" (No. 5,827,951).

CITATIONS BY OTHERS OF PROJECT'S PATENTS: See Figure 4.10.

COMMERCIALIZATION STATUS:
The different joint venture participants and their licensees have been able to successfully commercialize component technologies arising from this project. A leading supplier of glass laminate to PWB producers brought the single-ply fiberglass technology to market. Polyclad, a supplier of copper plating to PWB producers, has been able to commercialize thin copper. Joint venture member AT&T licensed the imidazole treatment that was developed earlier, but demonstrated for PWB applications in the project, to LeaRonal, Inc., which now supplies the treatment to PWB producers under the brand name Ronacoat OSP. It is used in large volume by leading board manufacturers such as Omni-Circuits, Inc., in Chicago, Illinois, and Pacific Circuits, Inc. (now part of TTM Technologies, Inc.) in Redmond, Washington.

Conductor Analysis Technologies, Inc. (CAT), the company created as a spin-off of research conducted by the imaging team, offers to leading equipment producers, such as Motorola and Hewlett Packard, rapid, reliable tests of sample boards. The testing services offered by CAT allow the equipment producers to evaluate the capabilities of PWB suppliers, thereby decreasing the amount of time and money spent moving new PWB designs into production. Faster market entry in turn translates into cheaper and better products for consumers of electronics.

OUTLOOK:
The adoption of project-related technical advances coincided in a turnaround in the performance of the U.S. PWB industry. According to the IPC's 1999 Report on the World Market for Printed Wiring Boards and Substrate Materials, world production of PWBs in 1998 posted a record high of $34.3 billion, up from $32.5 billion in 1997. Growth in the U.S. share of global PWB production has become positive, where it had been negative a decade ago. Recent IPC figures show that U.S. growth in the PWB industry is expected to be about 3.8 percent in 1999, and worldwide growth about 6.6 percent.[1] The outlook appears much brighter now for the U.S. PWB industry than it did at the beginning of the project. With further dissemination of the technology developed in the project, further strengthening is expected.

The outlook for technologies developed under this project are manifold: some of the component technologies have already been absorbed and surpassed in an industry where any development is a moving target, or have become building blocks to further developments and sparked further research. Others, such as the single ply laminates, have become the standard for the industry. Some products based on the ATP funded technologies are available commercially, i.e., Ronacoat OSP and the CAT testing service. Some of the component technologies have yet to be fully explored, or are still being pursued independently by former project participants. Many benefits from this project have been and are being realized, and future benefits are expected.

Composite Performance Score: ★ ★ ★ ★

COMPANIES:
National Center for Manufacturing Science (joint venture lead)
Ann Arbor, MI

Contact: Edward Miller
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Joint Venture Participants: AT&T, Digital Equipment Corporation, Hamilton Standard Interconnect Systems, Inc., Texas Instruments, Sandia National Laboratories, Allied Signal, Hughes Electronics, and IBM.

Systems, Inc. (a division of United Technologies, Inc.), and Texas Instruments. Sandia National Laboratories joined the project shortly after it was formed.

ATP awarded the project $13.8 million. Industry participants matched ATP's funding with $14.7 million, with a total project budget of $28.5 million. Based on the proposal submitted by NCMS, ATP awarded NCMS $13.8 million toward the five-year project, scheduled to break ground in April 1991. Industry participants matched ATP's funding with $14.7 million, with a total project budget of $28.5 million. During the project, Sandia, funded by the Department of Energy, contributed an additional $5.2 million to the project.

Over the life of the project, membership in the joint venture changed. Eighteen months into the project, DEC decided to withdraw. During the next three years, Allied Signal, Hughes Electronics, and IBM joined, fulfilling the research agenda originally assigned to DEC.

This largely horizontally structured joint venture appears to have been unusually successful in achieving active collaboration among participants, substantive teaming to carry out major project tasks, and extensive sharing of information.

Successful Collaboration in a Horizontally Structured Joint Venture

Studies have shown that horizontally structured joint ventures of direct competitors may experience difficulties in establishing trust and sharing information.[3] And most of the participating companies produced PWBs. This largely horizontally structured joint venture, however, appears to have been unusually successful in achieving active collaboration among participants, substantive teaming to carry out major project tasks, and extensive sharing of information. There are several factors that seem to have contributed to its collaborative success.

One factor is that the companies, though producers of PWBs, were also consumers of PWBs and rarely direct competitors with each other. They utilized PWBs for significantly different products.

Another factor that appears to have contributed to the successful collaboration is the administrative and management arrangement. The NCMS, as project coordinator, handled the administrative tasks, including accounting, contract details, and legal and intellectual property issues. A steering committee, staffed by technical personnel from each joint venture participant, managed the technical aspects of the project.

Project Goals

The NCMS project sought progress in PWB technology and manufacturing in four areas: materials, soldering, imaging, and chemical processes. Research teams — staffed by technical personnel from each joint venture participant — were formed for each area.

Although there are two types of PWBs, rigid and flexible, rigid PWBs account for approximately 90 percent of global PWB production. Rigid PWBs are constructed from a fiberglass base, made by taking woven fibers of glass, filling the weave with epoxy resin, and applying pressure to form the sheets that harden and become rigid. The materials team focused on the construction of rigid PWBs, usually made from sheets of double-ply fiberglass, in turn made from two layers of woven glass. The materials team sought to develop cost-saving, single-ply boards. They had to overcome a commonplace obstacle presented by single-ply sheets: these tended to have surface irregularities that led surface metal circuits to meet and short out when the surface warped under heat or pressure. Thus, the materials team had to deliver a regular surface on a single-ply, rigid PWB.

Industry recognition of the successful research efforts of this project includes best paper awards to two of the many research papers that came out of the project.

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[1] The Sandia scientists received a patent for the concurrent technology supported by internal Sandia funding —"Block Copolymer Adhesion Promoters via Ring-Opening metathesis Polymerization," patent number 5,603,985.

[2] IPC, "Management Briefing on the Global Outlook for 1999," available by request from the IPC director of market research via e-mail <CarlaWehrspann@ipc.org>.

[3] See, for example, Dyer, *Perspectives on the Determinants of Success in ATP-Sponsored R&D Joint Ventures: The Views of Participants*, NIST Contractor Report (In Press 2000).

The components on a PWB are connected by soldering component leads to the surface of the PWB. Soldering defects are a significant problem in the production of printed wiring assemblies, basically PWBs that are populated with components, such as integrated circuits. The soldering team aimed to develop ways to automate testing, to reduce the number of defects by identifying and using different materials in the soldering process, and to produce alternative surface finishes. The testing and repair of soldering defects provided an area of potential cost saving: most testing heretofore was performed manually.

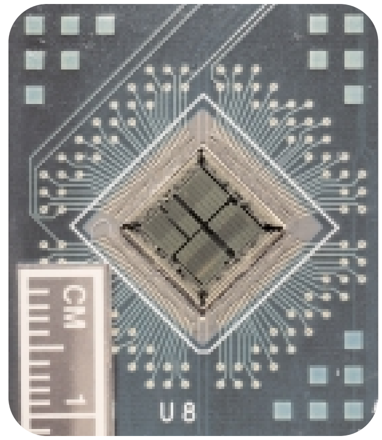
The soldering team also sought to develop an alternative to solder to prevent the oxidation of copper surfaces on PWBs in storage. Oxidation of the copper on the stored boards renders the contacts—the copper surfaces to which component leads are attached—unsolderable. In the past, contact surfaces have been preserved by solder. The use of solder, however, is messy and imprecise and limits the application of PWBs in circuit designs requiring increasingly fine connections. The goal of the soldering team was to develop a surface finish that would prevent oxidation, but at the same time would leave the copper surface free of obstacles to the etching of fine circuit patterns.

The imaging team sought to investigate and stretch the bounds of the imaging process to improve resolution, conductor yield, and dimensional regularity. It aimed to improve the projection of patterns along which circuits are placed to reduce the number of defects on boards.

The fourth team, originally known as the chemical processes team, later the product team, sought to advance the understanding of the chemical processes involved in producing the copper plating used in the PWBs to interconnect the components. The chemical processes team aimed to develop a thinner copper plating that would adhere to the PWB fiberglass base. This approach was seen as a way to save money by using less copper and reduce processing time. In cooperation with Polyclad, a copper plating supplier, they tested the performance of thinner copper plating. When the chemical processes team ran into difficulty securing financial support from joint venture participants for other copper research not considered high priority, the joint venture steering committee formed another team. The new product team had the more general goal of developing high-density interconnect structures, considered a high priority goal. In making this change, NCMS worked with ATP to redefine the research effort.

Research achievements

The efforts of the various teams paid off. The materials team achieved the noteworthy goal of developing and demonstrating the feasibility of single-ply fiberglass for



A close-up of an individual chip attached to a printed wiring board.

use in PWBs. They demonstrated that it could be produced with a sufficiently regular surface to allow for reliable electrical performance at a substantial cost savings. It has become the industry standard and the military has adopted it as a reliable product.

The materials team also developed a plasma-monitoring tool, which has a large potential for cost avoidance. Originally developed to monitor printed circuit boards, Sandia National Laboratories, in the post-project period, extended the application from PWBs to detect defects in microchips. If a defect in microchip manufacturing goes unnoticed after the wafer has undergone multiple processes — for instance, if circuits are etched to the wrong depth — it can translate into millions of dollars in expenses or lost sales after the ATP project was over, as part of a Sematech project. The effort resulted in a spin-off company formed by Sandia scientists, Peak Sensor Systems, which has filed 19 patents for related technologies, and has had 3 granted. Now in its third year, the company has three models of the Peak Propak plasma-monitoring device, and has achieved $1 million in sales. The research path is sketched out past the ATP project, in this case, to illustrate the complementarities that often exist across research efforts.

The materials team also developed PWB applications for a block copolymer that facilitates lower copper profiles and thinner materials. Scientists from Sandia, concurrent with the ATP project, developed a block copolymer technology under internal Sandia funding, which they were able to patent. The Sandia scientists as part of the materials team developed PWB applications for the block copolymer technology. Sandia also has a patent pending for prepeg bonding copper.

The soldering team successfully developed better methods of testing solder and produced a surface finish that adequately protects the board in multiple soldering applications. The team also explored applications of the imidazole solution—originally developed by Bell Labs[4] — to prevent oxidation of copper surfaces in a solder-free manner, and to demonstrate its applicability for a wide range of uses. Joint venture participant AT&T subsequently licensed the technology to LeaRonal, Inc., which commercialized the treatment under the brand name Ronacoat OSP. The company describes its product as a "production-proven, low-cost, environmentally benign alternative" to substitute products.[5]

The imaging team was able to achieve PWB production process improvements. The imaging team developed methods to increase the yield of PWBs without flaws, and in fact, the yield on 3-mil board increased from 30 to 50 percent, and the yield for 2 mil boards from 10 to 50 percent. Another way the imaging team improved quality control was to introduce a test procedure for evaluating the underlying process used to produce PWBs, based on the analysis of a sample board. This development stimulated the creation of a spin-off company—Conductor Analysis Technologies. The company sells this testing service to equipment manufacturers and PWB shops.

The imaging team was also successful in demonstrating the feasibility of a new photolithography tool called Magnified Image Projection Printing. This tool has the potential to provide a contact-free way of printing PWBs, which could in turn eliminate problems caused by the current imaging-etching process. If successful, this technique could significantly improve manufacturing of the boards by allowing for finer, more tightly interconnected lines as little as three mils apart. The NCMS decided to pursue the development of the prototype tool as a separate project, without ATP support, and the final report of this research effort is now available from NCMS.[6]

Before it was regrouped as the product team, the chemical processes team developed thinner copper plating and tested its performance in cooperation with Polyclad. The chemical processes team was able to demonstrate the effectiveness of thin copper plating in adhering to fiberglass. The approach saves money because it uses less copper. It also reduces processing time, because less copper has to be etched away to make connections on the board.

Research efforts by the product team on high-density interconnect structures produced a novel interconnect structure—the Multilayer Organic Interconnect Technology (MOIT)—that has the potential to revolutionize the fabrication of PWBs. By radically increasing the number of connections to and from a device on the board by taking advantage of making connections from the bottom of the board, in addition to the standard surface connections, the MOIT offers the possibility of achieving much higher wiring density than current PWB technology. IBM Endicott is pursuing MOIT.

Public Recognition

Industry recognition of the successful research efforts of this project includes best paper awards to two of the many research papers that came out of the project. One of these awards was presented at the fall 1994 meeting of the Institute for Interconnecting and Packaging Electronic Circuits (IPC[7]).[8]

The president of NCMS, John DeCaire, also bestowed public praise on the project at a press conference in 1997. He stated that the ATP project had "quite literally saved the [then] $ 7 billion U.S. PWB industry—a key segment of the $20 billion domestic electronic interconnection industry that employs over 200,000 people."[9]

Technology Diffusion and Industry Impacts

The NCMS project achieved significant technical successes in each of the four areas targeted by the joint venture participants. Three of the efforts—single-ply boards, thin copper plating, and conductor analysis technology—delivered commercial advantages to the PWB industry and

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[4] Bell Labs patented the formula in 1983, patent number 4373656, and AT&T licensed the technology to LeaRonal, Inc. Viasystems is the successor owner of the patent.

[5] See LeaRonal's, website at <www.learonal.com> for a listing of products and their applications.

[6] See the NCMS website at <www.ncms.org> for a description of the report, *Magnified Image Projection Printing Project Final Report.* The MIPP project was dissolved prior to the completion of the illumination system design and building of the prototype due to the withdrawal of the system integrator, and no viable commercial integrator showed interest in participating in the project. The intent of the report is to preserve the knowledge generated during the project if any future efforts are undertaken.

[7] IPC is a U.S. based trade association of nearly 2,500 member companies representing all facets of the electronic interconnection industry, including design, PWB manufacturing, and electronics assembly.

economic benefits to the equipment manufacturers who are their customers.

The project's successes and the acclaim received have furthered PWB technology diffusion within the industry. Technology diffusion among industry suppliers was aided by the decision of project leaders to include suppliers to the PWB industry in the process of developing the technologies. In fact, over the life of the project, almost every team meeting involved working with suppliers across various industries such as glass manufacturers, weavers, laminators, resin manufacturers, equipment manufacturers, printers, and chemical suppliers.

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Producers of PWBs report gains from project related advances that have been implemented into production. For example, 85 percent of the PWBs used by AT&T now incorporate single-ply technology, and this conversion to single-ply technology has saved AT&T at least $3 million per year. Another company reported a 50 percent decrease in solder defects, due to the soldering process improvements developed during the ATP project.[10]

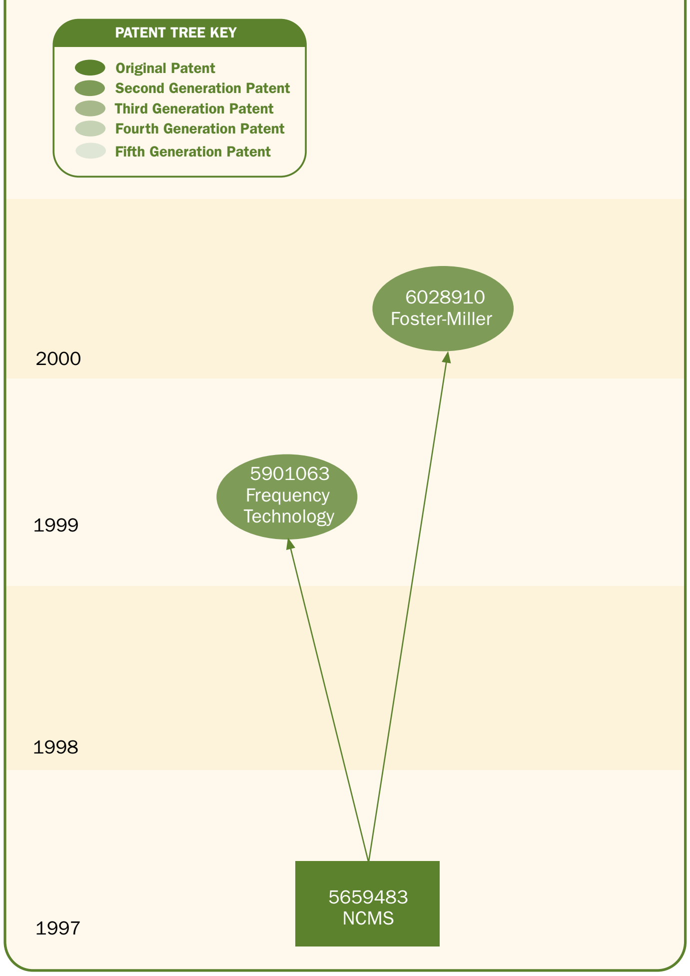
The ATP catalyzed a small group of companies with advanced research capabilities to undertake a wide-reaching project that would benefit the entire industry. The resulting NCMS-coordinated project conducted a research effort that would otherwise not have been pursued by the individual equipment manufacturers and PWB producers without the ATP, or only at a slower pace and in a far more costly way. The project encouraged the research teams to pursue two technologies—single-ply boards and thin copper plating—that challenged conventional wisdom, which held that these options were unfeasible.

An independent study undertaken on behalf of the ATP concluded that the ATP's presence supported and sustained research outcomes. The study's survey of joint venture participants found that "of the 62 research tasks completed by the PWB joint venture, about one-half would not have been undertaken at all in the absence of ATP funding, and the remaining one-half would have been delayed by at least one year without the ATP, in an industry where timing is critical."[11] In addition, the study found that by collaborating on the research, the companies

...a 50 percent decrease in solder defects

saved an estimated $35.5 million on those tasks they would have undertaken anyway, although at a slower pace. Savings resulted mainly from the labor efficiencies achieved and the duplicative test equipment avoided. (The study did not assess in a systematic way the benefits from the part of the research that would not have been done at all without the ATP.)

Figure 4.10 Patent Tree for Project Led by NCMS: Citations by Others of NCMS Patents



[8] Albert Link, *Early Stage Impacts of the Printed Wiring Board Research Joint Venture, Assessed at Project End* (1997), p. 28.

[9] May 13, 1997, NCMS News Release, "Landmark Collaborative Research Program Credited with Saving Domestic Printed Wiring Board Industry."

[10] Link, Early Stage Impacts p. 26.

[11] Link, Early Stage Impacts, p. iv.