History of Cornell Injection Molding Program (CIMP)

Kuo K. Wang, 2012

ABSTRACT

CIMP is a pioneer of interdisciplinary research in engineering involving university, government, and industry. Started in 1974 and inspired by industrial needs, CIMP was first funded by NSF and then jointly supported by an industrial consortium of major corporations in 1978. The goal was set to study the feasibility of establishing a science base for analyzing the injection molding process which would have real impact on industrial practices. Due to the complex nature of both the material and the process, the mission was considered impossible by many at the time. By integrating and extending existing knowledge in the fields of non-Newtonian fluid mechanics, heat transfer, rheology, and with the invention of new instruments for material characterization, the dream became reality after more than a decade of concentrated group effort. In the early days, to develop a successful mold for mass-producing plastic parts used to take weeks or months of trial-and-error design and fabrication at a cost of hundred thousands of dollars for so-called mold trials. Now, it can be done not only better, but also in hours or days on computers using powerful and accurate simulation programs. The knowledge and technologies developed by CIMP are considered a game changer in the manufacturing industry overall because no similar results have been achieved for other processes. The main reason is that most manufacturing processes in the real world are too complex to analyze theoretically and thereby results are usually lack of accuracy. As a result, academic research in these areas have had very little impact on industrial practices. CIMP is acknowledged as a success both by NSF and the industry. In fact, the resulting commercial software for injection molding available today is widely used in industry, and it is a contributing factor toward the ability of industry to put new products to market faster and cheaper. This is particularly true as applied to the consumer electronics and automotive industries where product design changes more frequently. For instance, the bodies of cell phones, TV sets, and various types of computers are mostly made by injection molding of engineering plastics. Similarly, an increasing number of parts used in today's cars are made of high strength plastics in order to reduce weight and improve fuel efficiency.

Sibley School in the Late1960s

There were 3 departments in the Sibley School of Mech. Eng. in the 1960s: the Dept. of Thermal Eng., Dept. of Mechanical Design, and Dept. of Materials Processing. The third Dept. was the smallest (only 1 tenured faculty and 2 technicians) in late 1960's, but occupied the whole building of Kimball Hall with 3 floors of machine tools. Its main function was to teach a few shop courses for M.E. students, but it had also helped train a large number of technicians for US Navy during WWII. After a study by a special committee appointed by the Dean of Eng. to investigate how manufacturing processes should be taught in the M.E. curriculum, it was decided to merge the Materials Processing Dept. into the Dept. of Mech. Design, becoming the Dept. of Mech. Systems and Design. This would be done after the last faculty member, Roger Geer, retired the following year. In the meantime, an effort was made to recruit a new faculty member who not only would have a PhD degree, but also some industrial experience and could teach science-based material processing courses and initiate research projects in the field.

How Did CIMP Get Started?

In the fall of 1970, Kuo-King (K.K.) Wang was hired by the Department of Mechanical System and Design when Prof. Howard McManus was the Head and Prof. Dick Shepherd was the Director of the Sibley School. Around that time, the Eastman Kodak Co. in Rochester, NY was developing a revolutionary new product which was a reusable, low-cost (around $10 apiece), pocket-size camera. The product was mainly made out of plastics by using the injection molding process. The prototype product was successfully developed after years of effort using experimental molds with either single or double cavities. While in production, however, a multi-cavity (typically 30 or even 40 cavities) mold had to be used to achieve the goal of low cost. It was found then that most cavities far from the gate (where the molten polymer enters) either could not be filled or the molded parts contained severe defects. At the time, there was no quick-and-easy solution to the manufacturing problem other than continuously using the trial-and- error method. As a result, Kodak management had to put on hold the official announcement of the new product to the Wall Street while waiting for the solution of this manufacturing problem.

This story was told by the then CEO of Kodak who is a Cornell alumnus serving on the Advisory Board to the Dean of Eng., Prof. Edmund Cranch, at Cornell. The Dean was asked whether it would be possible for academia to help develop some scientific basis for mold design and process control so that they would not be "at the mercy of a handful of so-called experts at Kodak the next time a similar situation may arise again". The message was passed on to Howard McManus and then to K. K. Wang for consideration. The challenge was taken seriously and internal discussions were started with colleagues in the School of Chem. Eng. as well as the Dept. of Material Science & Eng. Through the effort of Don Gordon, Director of Industrial Liaison in the Dean's office, a number of mutual visits and discussions were held with the technical persons at Kodak. A formal proposal was submitted to Kodak and reviewed and agreed upon by their technical personnel but was finally rejected (See Exhibit 1) by its management primarily due to problems of patent rights and ownership of other intellectual properties possibly generated by the research. As a result, it was decided to submit a proposal to NSF for possible support.

First Support from NSF/RANN Program

In the early 1970s, right after the first oil shock, the nation was facing three major problems: energy, the environment, and productivity. To study these problems, the Engineering Directorate of NSF initiated an exploratory program named RANN (Research Applied for National Needs) with very limited funding. Apart from traditional NSF funded projects for basic research, the RANN program also invited industrial participation in its review and monitoring processes. Once starting, it didn't take long for the RANN program to realize that energy and environmental problems were so large and basic that separate agencies in the government might be needed to handle them. In fact, that subsequently led to the government decision of establishing the DOE and EPA to deal with those problems separately.

The problems of productivity, however, were of a different nature. The annual rate of productivity increase in the U.S. after WWII had been around 3% or slightly above. However, the rate in our competing countries, particularly Germany and Japan, was much higher. Although the absolute values of productivity in those countries were still much lower then, it would not take long to catch up or even surpass us. Nevertheless, after a few hearings held at the US Congress with the participation of industrial executives, it was concluded that productivity was a problem for the private sector to cope with and there was no need for government intervention. As a result, most research projects supported by RANN were all related to productivity problems such as production automation, basic research on manufacturing processes, or production systems.

Along with researchers from industry, K. K. Wang was invited (primarily because of his background in industrial automation) to participate in the review process of a few early projects supported by RANN. In 1974, Wang was invited to attend the first grantees conference (Named as: the "Industrial Automation Conference") held at Stanford University with a relatively small group of attendees (See Exht. 2) from universities as well as industries. After that conference, McManus and Wang decided to submit their own proposal on injection molding to RANN. The objectives of the proposal were somewhat similar to the one sent to Kodak before, but with much more technical detail in its contents. In the meantime, a number of other companies who were heavily involved in using the injection molding process were also visited, including

Xerox, Ford, Whirlpool, and a few others. The purpose of having more industrial participation was to gain better understanding of the problems as viewed from the scientific perspective, and in the meantime, searching for their possible support (such as conducting experiments, etc. in the early stage) in case we did receive funding from NSF. The responses from them were mostly positive, and two of them (Kodak and Xerox) were willing to write a letter of support attached to the proposal.

The proposal was accepted by NSF and the project started on July 1, 1974 under Grant # 7411490. Unfortunately, Prof. Howard McManus passed away suddenly even before the award was granted. In his place, Profs. S.F. Shen of MAE and James Stevenson of Chem. Eng. were invited to be Co-PI's of the project. The NSF/RANN grant was continued through 1979 with total funding of $541,100. After that, the project was continually supported by the newly established Division of Manufacturing and Systems within the Engineering Directorate of NSF. With several slightly different project titles, the program was uninterruptedly supported by NSF under a total of 11 grants with a total funding of over 3.6 million dollars from 1974 through 1998 (See Exht. 3). The exceptionally long support for a single project at NSF's Engineering Directorate was due to the fact that CIMP was the first project which was receiving broad industrial support and producing results significantly affecting industrial practices. In fact, NSF treated CIMP as a role model for guiding future projects in the design and manufacturing area during that period of time.

Goals and Approaches Set for the Program

From the very beginning, our goal has been to establish a scientific base for the injection molding process. With that, one would be able to handle the mechanics of the process, and thereby, a mold used in the process could be designed and the process be controlled based on scientific laws rather than only past experience. However, like most material-forming processes used in industry, the material undergoes rapid transformations from its original form to a final shape. The mechanics of transformation are usually not well understood from a scientific viewpoint. Injection molding starts with solid plastic particles being first heated in the barrel of the machine through primarily external heating and mixing by a rotating screw inside of the barrel. They become a homogeneous but highly viscous fluid accumulated in front of the screw. The polymer melt, a viscoelastic fluid, is then injected rapidly by the screw unit into a cooled mold cavity. In a matter of seconds, the part is solidified, the mold opened and the part is ejected from the mold. The molded parts are all in final net shape without the need of any secondary operation.

Unfortunately, the transient property changes of polymeric materials undergoing the injection process are too complex to understand. The existing knowledge on the science of rheology and non-Newtonian fluid mechanics were not able to analyze and make predictions of the process behavior with any accuracy. Because the properties of polymer melts are viscoelastic and changing very rapidly during the molding process, there is no constitutive equation which can accurately represent the characteristics of the material so that the process behavior can be accurately predicted. At the outset, therefore, we took the approach to make full use of all existing knowledge and techniques in thermal sciences and rheology, and extend them with the help of knowledge gained through a series of specially designed experiments. Through these experiments, we gained insight as to whether some assumptions made in theory are justifiable or should be modified. All theoretical analyses had to be verified by experimental results. During this process, we developed two instruments which are necessary to characterize the basic material properties needed for flow analyses. One is to determine the thermal conductivity of polymer melt as a function of temperature (US Patent No. 4,861,167), and the other is to determine the viscosity of reactive polymers as a function of temperature, shear rate, and pressure (US Patent No. 6,023,962). These instruments along with associated simulation software are used regularly by injection molding industry today.

CIMP Industrial Consortium

To follow up the idea of working with industry closely, we had numerous contacts with a number of companies (in addition to Eastman Kodak) who have shown strong interest in injection molding research. Such contacts included visits and technical discussions before and after the NSF grant was awarded. Once the NSF funding started in July 1974, a Project Steering Committee was formed to provide suggestions to the research group as to the-state-of-the-art of the technology at the time, and what was needed for the research. Initially, the Committee consisted of only a handful of companies including Ford Motor (See Exht.4), Kodak, Xerox, and Cincinnati Milacron. The first three were heavy users of the technology and the last was the largest injection molding machine manufacturer in the U.S. In fact, Milacron successfully developed a mini-computer controlled injection molding machine at the time. By transferring the CNC (Computer Numerical Control) technology used in machine tools for metal cutting processes to injection molding, the Milacron injection molding machine could control as many as 35 parameters simultaneously with a mini-computer. Unlike metals, however, the properties of polymers during injection molding change continually. There were no rules or methodologies which could be used to set up only 2 or 3 key parameters so that consistent part quality could be guaranteed. As a result, they were convinced that there was no way the process could be controlled properly without basic and scientific understanding of the process dynamics.

In 1978, the CIMP Industrial Consortium was established. The main purpose for that was to seek deeper commitment from the industry in support of the research. Each member company was required to pay an initiation fee of $10,000 and an annual membership fee of $10,000. The membership was only committed for one year, but renewable annually. The annual membership fee was later raised to $15,000. The founding members were Eastman Kodak, Cincinnati Milacron, G.E., G.M., and Xerox. In 1980, Prof. Wang was invited to give a seminar on CIMP at the Hokkaido University in Japan. One of the attendees in the audience was Mr. J. Akiyama who was the General Manager of Technology Center of Sony Corp. He was apparently very impressed by the talk and immediately invited Wang to pay a visit at three operations of Sony around the Tokyo area. The visit involved all aspects of injection molding, from research to production. After the visit, they immediately asked if they could join CIMP Consortium as a member. Upon his return, Wang checked with both NSF and all U.S. members, particularly RCA and GE who are competitors to Sony. They all agreed to let Sony in with the main motivation to find out how Sony could produce TV sets cheaper and better. As a result, Sony became the first foreign CIMP Consortium member (Exht.5). After that, a flood of major companies from Japan and Taiwan joined the consortium. The annual membership grew steadily over the years and reached a peak of 35 companies worldwide in 1986. In the same year, the Advanced CAE Technology, Inc. (commonly called C-MOLD) was established by a former CIMP student with the help of CIMP principals. This helped CIMP reduce some of its burden supporting the experimental software (a byproduct of basic research, written by students and staff) for the consortium members. As a result, a few members dropped out of their membership and switched to using the software by C-MOLD which was of commercial quality, more user-friendly and well maintained. However, most members stayed on until the consortium ended in 1994, when K. K. Wang officially retired.

The format of CIMP Ind. Consortium was set to have two consortium meetings each year. At each meeting, CIMP students and staff reported their work (with a preprinted proceedings) and followed by detailed discussions. Members were entitled to receive a copy of all technical reports (published and unpublished) and source codes of simulation software after signing a Non-disclosure and Non-transfer agreement (Exht.6). Since all work done at CIMP was pre-competitive, there was plenty of time at the meetings for the participants to mingle, even though many of them were business competitors. A complete list of CIMP Industrial

Consortium members is included in Exhibit. 8, and also available at the CIMP website www.plastemart.com/cimp/, under the subtitle of Industrial Consortium Members.

Technology Transfer via AC Technology, Inc. (or C-MOLD) in 1986

As usual, computer simulation programs are byproducts of basic research. They are typically used as tools to test or verify the theoretical analyses. Due to their usefulness for real-world applications, however, they became the most desired results by CIMP Consortium members. Many of them began to use the software as a tool to help them design molds because they were fairly accurate and powerful. In fact, it was considered by some that CIMP had come "from dream to reality" as described in its brochures published in celebration of its 15th and 20th anniversaries (See Exhts.7 & 8). As a consequence, it happened quite often that users of the software called in CIMP for help when they were using those programs. That became a significant burden for CIMP staff and students to cope with such a situation.

In 1986, one of CIMP's early PhD students, Dr. V.W. Wang, was interested in starting a company to develop commercial-quality software to serve the industry. One of the main reasons for him to do this was that the CIMP version of the mold-filling program was a byproduct of his thesis. After turning down a few job offers from CIMP member companies, he decided to start a company aiming at transferring and extending the basic technologies from CIMP to serve the industry with high quality products and services. To avoid any possible conflict of interest, he first donated the source code, copy-righted in his name, in his thesis to Cornell Research Foundation (CRF later licensed the software to Graftec, Inc., an early CIMP member and an engineering software company). He then rewrote the mold-filling program, named C-FLOW, as the first product of AC Technology. Several CIMP member companies quickly acquired the commercial software while maintaining as CIMP members. Subsequently, AC Technology further developed C-PACK and C-COOL packages to handle the simulation of packing and cooling phases of the entire injection molding process. Furthermore, the company's materials laboratory provided material properties data for any specific grade of polymer which are necessary for using the simulation programs. As a result, C-MOLD, as it was called in business, became the technology leader in the field worldwide. They were one of the earliest spin-off companies from Cornell as listed in the pamphlet, "Small Business Development" published by Cornell University in 1997 (Exht. 9).

As the accuracy of the simulation programs was proven very satisfactory for handling most industrial applications, popularity of using C-MOLD as a mold design tool grew very quickly. Early practices based on trial-and-error experiences through numerous mold trials were not only costly, but also time consuming. Developing a production mold for a laptop computer casing typically took at least 3 to 6 months. A large plastic part like a bumper or an instrument panel for a car would take 6 months to a year and could cost millions of dollars. With the simulation tools, the task has been reduced to days or even hours, and a physical mold trial is often not necessary. This is why many plastic parts, particularly used today in consumer electronics like cell phones, laptop computers, or TV sets, can be produced so quickly and cheaply. As a result, C-MOLD started from a one-man operation in 1986 to a global company with branches and agents all over the world. In year 2000, C-MOLD was merged to Moldflow, Inc., a company originated from Australia and then bought by a Boston-based venture-capital company. Moldflow was later acquired by Autodesk, Inc., a major engineering software company.

Projects in Later Years of CIMP

After his official retirement in 1993, Professor K. K. Wang continued working at CIMP for another 10 years. There were three major projects (all extensions of early work) during that period: the first was the "Net-Shape Die Casting of Complex Parts" (a new process later named as Rheomolding), the second was the "Pressurized Underfill Encapsulation of Flip Chip on Board", and the third one was named IMS (Integrated Molding System). The first two were supported by NSF with two separate grants while the last one was supported partly by a subset of a few CIMP Consortium members with strong interest in process control. They include Moog/Japan, United Technology Research Center, and Philips DAP from the Netherlands.

Die casting of metals has been a well established mass-production process for making metal (with relatively low melting temperature) parts. However, because the molten metal flows like water (a Newtonian fluid in a technical sense) it has to be injected into the die very quickly before it freezes. The so-called turbulent flow taking place in the die cavity often causes porosity problems in the part which are not acceptable. A common remedy to the problem is to over-feed the die cavity by pushing the porous portion out first, and then remove them later by a second operation. Therefore, die-casting is not a "net-shape" process like the injection molding of plastics. In the late 1960's, researchers at MIT's Material Science Dept. came up with the idea of so-called "semi-solid" metals. They found that when the molten metal is slowly cooled down through its melting point while being mechanically agitated, small particles are gradually formed and suspended in the fluid which then becomes a mushy semi-solid state. The fluid in this state has much higher viscosity than molten metals, and its viscosity depends on the solid fraction in the fluid which could be controlled by the cooling process. CIMP's idea and new invention in this regard was to extend the idea of injection molding to treat the semi-solid metal fluids like polymer melts. The new invention uses existing injection molding machine configurations, but modified by changing its heating elements around the machine barrel into cooling jackets. Therefore, instead of heating the solid polymer particles as in injection molding when they enter the machine barrel, the molten metal are moved forward by a rotating screw while being cooled gradually by the cooling jacket. During the process, solid particles are continually formed and transported to the tip of the screw before being injected into the mold. Because of the relatively high viscosity of the semi-solid fluid, the injection speed is much lower. As a result, it is a laminar flow which pushes all air out of the mold cavity to achieve a net-shape and precision part without the need for a second operation. The new process was named as Rheomolding and details are given in the US Patent No. 5501266, entitled “Method and apparatus for injection molding semi-solid metals”, awarded in March 1996 to Cornell Research Foundation. The patent was later licensed to the Industrial Technology and Research Institute (ITRI), a government-supported research organization in Taiwan.

The Pressurized Underfill Encapsulation of Flip-Chip-On-Board is another extension of injection molding technology. It was developed at the time when the semiconductor industry was advancing its packaging techniques from wire-bonding (signals in and out from a micro-chip through a series of fine wires around the edges of the chip) to Flip-Chip where all the I/O connects come out from the bottom of the chip which can be directly inserted onto the board. However, the high-density matrix of the fine pins also need protection by filling the gap with polymer encapsulates. The traditional encapsulation process lets the liquid reactive polymer be sucked into the gap primarily by the forces of gravity and surface tension. After filling, the boards are put in an oven for curing. The whole process is very time consuming and costly. CIMP’s idea was to enclose the chip into a closed mold first, and then inject the encapsulate under pressure and cure it in place. It was estimated that the total cycle time could be reduced by almost two orders of magnitude. The process is detailed in the US Patent No. 5817545 entitled “Pressurized Underfill Encapsulation of Integrated Circuits”, granted to Cornell Research Foundation in Oct. 1998.

The intent of IMS, or the Integrated Molding System, was to complete our idea of having the production of plastic parts, from design to manufacturing, fully integrated and automated. It was hoped that the computer-based system could produce plastic parts automatically without the attendance of a machine operator. In essence, IMS was built based on the concept of Concurrent Engineering. Once the design of the part is finalized, the preferred initial process condition can be generated via process simulation which in turn could be used to set up the machine controller. A system has been developed and tested successfully for simple parts like a flat plate or disk. By monitoring online the momentary mold-separation at micron level during the packing phase of the process, the variation of part thickness, or weight, due to the batch-to-batch material property change and other uncontrollable process conditions was drastically reduced. Details are given in the Technical Report, TR-92. For parts of complex shape, however, the challenge remains to find an effective way of monitoring part quality online which is necessary for feedback in a closed-loop control system.

Impact on Industry

CIMP was a pioneer of university research in close collaboration with industry aimed at solving a real-world manufacturing problem. It was known then and still is true now that manufacturing processes in the real world are hard to analyze and predict based on first principles. This is particularly true for polymeric materials for which the properties are too complex to model during processing. By extending existing knowledge in such fields as non-Newtonian fluid mechanics, heat transfer, rheology, and with inventions of new instruments for characterizing material properties, CIMP succeeded in achieving that goal. Today, commercial software based on CIMP results can predict the behavior of injection molding process accurately, and is used by industry extensively throughout the world. Now, the so-called mold trials which used to take weeks or months in the mold shop can be done in hours or days on computer with better results. In fact, CIMP research has resulted in great impact on such industries as consumer electronics, automotive and many others who can put their new products on market cheaper and faster.

CIMP Website

After K. K. Wang's final retirement in 2004, the CIMP Website was moved out of the Cornell University site and linked to Plastemart.com as, www.plastemart.com/cimp/. Plastemart.com, founded by a former CIMP student, is an Internet portal based in India and specializes in plastics. They provide maintenance of the site and the site has been used as a platform of communication among all CIMP alumni and friends.

Exhibits 1 – 9 follow

Exht I

H. McMasters

Pls advise K.C. Wang

EASTMAN KODAK COMPANY

ROCHESTER, NEW YORK 14650

PLEASE ADDRESS REPLY TO
KODAK PARK DIVISION

TELEPHONE
AREA CODE 716 458-1000

February 3, 1972

Mr. Donald B. Gordon
Director of Industrial Liaison
College of Engineering
Cornell University
Ithaca, New York 14850

Dear Don:

We regret that we have had to discontinue our discussions regarding cooperation between our Company and Cornell University on your project proposal in connection with the injection molding of plastics. Although our most recent discussions involved patent matters, the costs involved and the presence of on-going programs of similar nature here also played a part in the decision. Further exploration of the injection molding work being done here may reveal facets of the problem on which we might require assistance from you.

Our decision not to accept your project proposal does not imply a lack of confidence in your expertise. We were very favorably impressed by those whom we met during our discussions and with the problem definition and solution proposal. We will continue to seek ways in which we can cooperate to our mutual benefit.

Sincerely yours,

Gordon S. Rugg

Gordon S. Rugg, Director
Engineering Division

/gf

cc: Mr. A.G. Bailey
Dr. J.M. Calhoun

Kodak

INDUSTRIAL AUTOMATION CONFERENCE

Exh. 2

March 27-28, 1974

Attendees

ALCOA: E. Quade, K. Landsberg
AMP: Joseph Sweeney, Milton Ross, Dimitry Grabbe
ARPA: John Perry
BENDIX: Carl Ruoff, James Edmond
CAL TECH: Sidney Sternberg, Meir Weinstein
CASE WESTERN: H. W. Mergler
CINCINNATI MILACRON: Richard Messinger, Jim Gavin, Randy Holt
CORNELL: K. K. Wang
DOW: Paul Ramer
DRAPER LABS: James Nevins, Sam Drake, Albert Woodin, Daniel Killoran
DU PONT: Paul Gaither
EDGEWOOD ARSENAL: Edward Colburn
FORD: Sing King
GENERAL ELECTRIC: Paul Scott, Les Meyer
GENERAL MOTORS: Lothar Rossol, Robert Dewar
HARVARD: Jordan Baruch
IIT: Hsien-Hwei Shu, George Jacobi, J. V. Belcher
INDUS. ASSOC. MACHINISTS & AEROSPACE WORKERS: Angelo Cefalo
MARCOM: Thomas Patterson
MIT AI: Patrick Winston
MIT EE: J. Frank Reintjes
MIT ME: Daniel Whitney
NORTHROP: Bernard Gaiennie
NSF: Robert Lauer, Holt Ashley, A. F. Brewer, John Leech, Arthur Ezra, Bernard Chern
NASA AMES: Melvin Sodoff, James Jones
PURDUE: Moshe Barosh
SO. PACIFIC: Robert Byrne
STANFORD: Jerry Feldman, Lou Paul, Tom Binford, Bernard Roth
TELEDYNE RYAN: David Carnevale, Arley Parker
UNIMATION: T. H. Lindbom
U. ROCHESTER: Herbert Voelcker, Jr., A. Requicha
U. TEXAS: Richard Duda, J. K. Aggarwal
WESTINGHOUSE: Richard Abraham, J. C. McVickers, N. Yaroshuk, T. Brody
WHIRLPOOL: John Adams, Frank Skinner, Ed Barton, Eric Rembold
XEROX: William Newman
ZENITH: Vernard Price, George Roark
DEC: James Bell, Alan Davis

Exht. 3

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Plans & Pricing
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Researcher Detail

History
Kuo Wang

Kuo Wang

Total Projects:	11	**Rank:**	Account Required
Total Active Projects:	0	**Rank:**	Account Required
Total Awarded:	$3,621,666	**Rank:**	Account Required

E-mail Addresses

Address	Last Indicated	Status	Verified
Subscription Required	1998		12/10/2010

Organizations

Organization Name	Years Applied	Projects
Cornell University	1974-1998	11

Projects (11) | Publications* (0) | Patents (0)

Project Number	Project Title	Organization	Fiscal Year	Total Award
7411400	Computer Aided Injection Molding System	Cornell University	1974	$541,100
7818868	Computer-Aided Injection Molding System	Cornell University	1979	$555,285
8200743	Computer-Aided Design and Fabrication of Molds, and ComputerControl of Injection Molding (Mechanical Engineering)	Cornell University	1982	$616,053
8217107	U.S.A. -Sweden Workshop on Cad/Cam For Tooling and Forging Technology	Cornell University	1982	$11,900
8507371	Integration of CAD/CAM for Injection Molded Plastic Parts	Cornell University	1985	$977,232
8515501	US-Japan Cooperative Research: TIPS-1 Based CAD/CAM System for Tooling	Cornell University	1986	$11,626
8906015	Engineering Research Equipment Grant: Computer and Instruments for Material Characterization	Cornell University	1989	$56,800
8815855	Net-Shape Die Casting of Complex Parts	Cornell University	1989	$431,670

Share |

9412196	Small Grants for Exploratory Research: Development of a Screw-Pressure-Type Die-Casting Machine for Net-Shape Manufacturing of Semi-Solid Materials	Cornell University	1994	$20,000
9522929	Pressurized Underfill Encapsulation of Flip Chip on Board	Cornell University	1996	$200,000

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Exht. 4.

Manufacturing Staff
Ford Motor Company

Plastics Development Center
24300 Glendale
Detroit, Michigan 48239

June 13, 1975

College of Engineering
Cornell University
Ithaca, New York 14850

ATTENTION: Dr. K. K. Wang
Associate Professor and Director
NSF Injection Molding Project

Dear K.K.:

SUBJECT: Schedule for the Third Steering Committee Meeting

I would like to confirm our earlier conversations regarding subject meeting to be held at Ford Motor Company's Plastics Development Center on 24300 Glendale Avenue, Detroit, Michigan 48239.

The committee members should plan to be at the Plastic Development Center around 9:00 a.m. The meeting will follow the same format as the last one held at Xerox, but it will start in the morning and adjourn in the early afternoon.

I have enclosed a map to show you the location of the Plastic Development Center. Please advise how many you expect to have in attendance.

Regards,

Frank

Frank A. Pink
Plastics Processing Department

cc: Dr. B. Chern - NSF
Mr. W. J. Mueller - Xerox
Mr. D. H. Reber - Cincinnati Milacron
Mr. C. D. Simmons
Dr. W. J. Burlant

Exht. 5

SONY

SONY CORPORATION 7-35 Kitashinagawa 6-chome, Shinagawa-ku, Tokyo, 141 Japan

Mail Address P.O. Box 10 Tokyo A.P., Tokyo, 140 Japan
Cable Address SONYCORP TOKYO
Telex SONYCORP J22262
Telephone Tokyo (03) 448-2111

Prof. K. K. Wang
Upson Hall
Cornell University
Ithaca, N.Y. 14853
U.S.A

October 1, 1980

Dear, Prof. K. K. Wang

Thank you very much for your habitual consideration.
As to be attendance of C.I.M.P., we have decided to participate aggressively as a Full Member in consequence of investigation.
Enclosed is the application for taking part in C.I.M.P.
Injection molding involves lots of difficult problem, therefore, we have much expectation on the results of C.I.M.P.
Further kind consideration you may give us will be much appreciated.

Sincerely Yours,

J. Akiyama

Juzo Akiyama

General Manager
Production Technology
Center, SONY Corp.,
Tokyo

Exht. 6

Cornell University

Sibley School of
Mechanical and Aerospace Engineering
Upson and Grumman Halls
Ithaca, New York 14853-7501

AGREEMENT OF NON-DISCLOSURE AND NON-TRANSFER

THIS AGREEMENT, effective as of the 1 st day of June, 1985, is made by and between the Cornell Injection Molding Program (hereinafter "CIMP") of Cornell University, Ithaca, New York 14853, and The Goodyear Tire and Rubber Company, (hereinafter "Goodyear") whose principal place of business is Akron, Ohio U.S.A., an active member of the CIMP industrial consortium, sets forth the rights and responsibilities of the parties regarding the handling of the proprietary software and related materials developed by CIMP as follows:

1. <u>NON-DISCLOSURE</u>

CIMP holds all right and title to the software modules and associated documentation, including revisions, (hereinafter referred to as "Software") provided to Goodyear. Goodyear agrees to limit the use of the Software, in any form, to those of its employees who have a need to know, within the company, and agrees further that, unless prior written approval is obtained from CIMP, that it will not disclose or transfer the software in any form to any other third party. This non-disclosure obligation shall continue during membership in the consortium and for ten (10) years after termination of membership, unless a release in writing is given by CIMP at an earlier date upon request in writing from Goodyear.

This non-disclosure agreement shall not apply to Software: (a) which was already known to Goodyear prior to disclosure by CIMP, (b) which is now or hereafter becomes, through no act or omission of Goodyear generally known to the public, (c) which is received by Goodyear from a third party having no obligation to CIMP to keep the information confidential, or (d) which is approved by CIMP in writing for release.

2. RIGHTS TO USE

Goodyear shall have the full right to implement, use, test, and/or modify the Software received from CIMP during its active membership in the industrial consortium, subject to the confidentiality provision in section 1 above.

3. COPYRIGHT

The Copyright to the Software and the associated documentation is the property of Cornell University. The original Software package, together with any and all updates, remains the property of CIMP. However, all modifications and improvements to the Software designed by Goodyear shall be and remain the property of Goodyear, and Goodyear shall have the right to obtain copyright registration on its modifications and improvements. Goodyear shall have continuous use of the Software, subject to the provisions in sections 1 and 2 above.

4. SOFTWARE UPDATES

While Goodyear continues to be an active member of the CIMP consortium, it shall be entitled to receive all updates to the Software and any associated documentation whenever such shall become available for official release. The updates referred to in this section are subject to the same non-disclosure and non-transfer restrictions and right to use as set forth in sections 1 and 2 above.

IN WITNESS WHEREOF; the parties hereto have executed this Agreement on the dates written beneath their signatures and the effective date of this Agreement is the date first mentioned above.

Cornell Injection Molding Program (CIMP)	The Goodyear Tire and Rubber Company
By: K. K. Wang (printed name)	By: (printed name)
Title: Professor and Director, CIMP	Title: Vice President
Signature:	Signature: F J Kovac
Date: October 17, 1985	Date: October 29, 1985

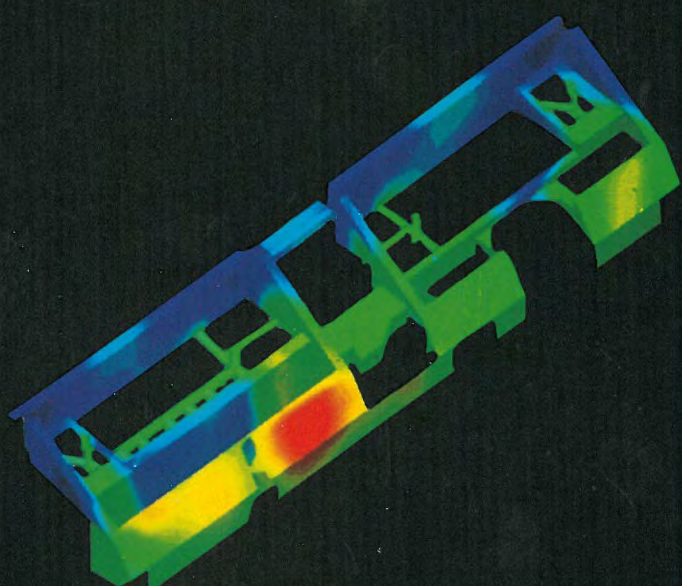
from dream to reality

A look at

CIMP

The Cornell Injection Molding Program

in its first fifteen years, 1974–1989



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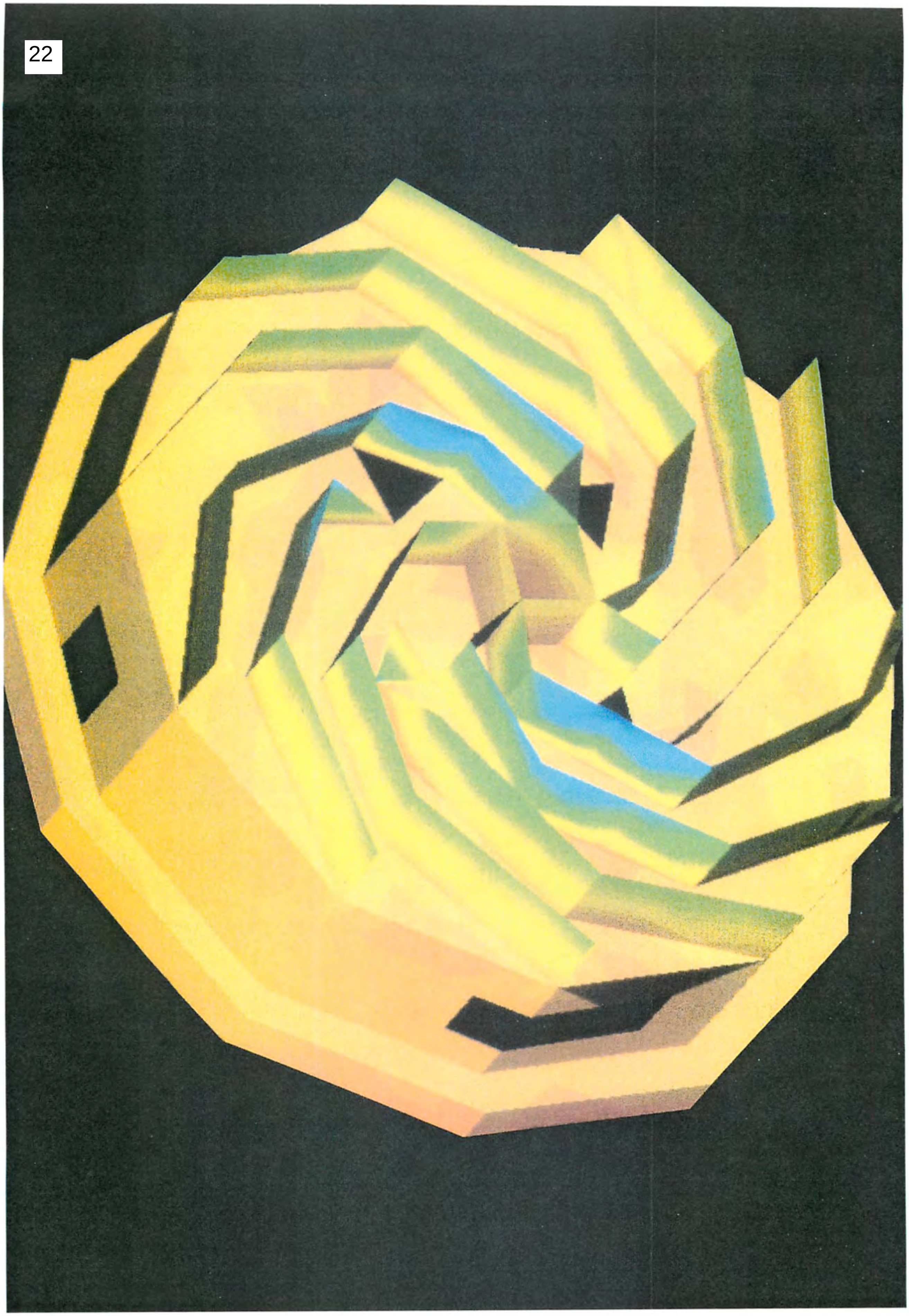


Fifteen years ago, a small group at Cornell began an innovative venture in which industry and academia would cooperate to advance an important area of technology. The Cornell Injection Molding Project (CIMP) began operations in 1974.

To celebrate those first fifteen years, the Cornell Injection Molding Program, as it has been called since 1979, is hosting a conference in the spring of 1989. It is appropriately titled "CAE for Injection Molding: From Dream to Reality."

The dream, back in 1974, was to place injection molding—then a "rule of thumb" technique—on a firm scientific basis. It was an ambitious dream, pursued by hard practical questions. Would it be possible to understand and predict the complex interactions that occur in the injection-molding process? And if so, could industrial practitioners be convinced to try the new scientific methods?

Today the dream has become a reality. CIMP is recognized not only as one of the organizations that took injection molding out of its dark ages, but as one of the most vigorous injection-molding research groups in the world. A look at the history of the program, its current activities, and its prospects is presented here.

The person with the original idea was K. K. Wang of Cornell's Sibley School of Mechanical and Aerospace Engineering, who has been the director of CIMP from the beginning. The project has been made possible by initial and continuing funding from the National Science Foundation. Many graduate students have worked on the project and gone on to advance the field in industry and academia. And a crucial element has been the support of industry, both financially and in the research. The CIMP Industrial Consortium, formed in 1979, now comprises thirty-four companies.

From the initial, relatively simple study of the filling of thin cavities to the current development of an expert system for handling a wide range of processes, CIMP has come a long way in its first fifteen years.

Cover illustration: A computer model showing predicted temperature distribution during mold-filling for a plastic part—an automobile dashboard.

Photo opposite: A display showing bulk temperature distribution of an impeller. (Courtesy of AC Technology.)

CIMP: Program Leaders

Cornell Injection Molding Program
Cornell University
256 Upson Hall
Ithaca, NY 14853–7501
607/255–5255

K. K. Wang, the director of CIMP, is the Sibley College Professor of Mechanical Engineering at Cornell's Sibley School of Mechanical and Aerospace Engineering.

He earned the B.S.M.E. degree at National Central University in China in 1947, and studied at the University of Wisconsin for M.S.M.E. and Ph.D. degrees. After two years of teaching at Wisconsin, he joined the Cornell faculty in 1970.

Wang has had many years of broad industrial experience related to design and manufacturing engineering, and has received many professional honors, including a TRW fellowship and awards from the American Society of Mechanical Engineers (ASME), the Society of Manufacturing Engineers (SME), and the American Welding Society. He is a fellow of the ASME and of the SME, and a member of the National Academy of Engineers.

Shan-Fu Shen, the John Edson Sweet Professor at the Sibley School, was one of the first participants in CIMP; he was a co-principal investigator from 1974 to 1988.

In addition to injection molding, his research interests include aerodynamics, fluid mechanics, and computational techniques.

Shen received a B.S. degree from National Central University in China in 1941, and the Sc.D. from the Massachusetts Institute of Technology in 1949. After a year at M.I.T. as a research associate, he taught at the University of Maryland and then joined the Cornell faculty in 1961.

Shen is a member of the National Academy of Engineers and a fellow of the Washington Academy of Sciences. His honors include a Guggenheim fellowship and a Humboldt Senior Award. He has been a visiting professor or researcher at institutions in Zürich, Vienna, Paris, and Tokyo.

Claude Cohen, a professor of chemical engineering at Cornell, has been a member of the faculty since 1977. His research centers on the thermodynamic and mechanical properties of gels, microgels, and polymers.

Cohen received a B.S. degree in 1966 from American University in Egypt, and a Ph.D. in 1972 from Princeton University. Before joining the Cornell faculty in 1977, he was a Katzir-Katchalsky fellow at the Weizmann Institute in Israel and a research associate at the California Institute of Technology.

Donald L. Koch came to Cornell in 1987 as an assistant professor of chemical engineering. Soon afterward, he won a five-year Presidential Young Investigator Award from the National Science Foundation.

Koch earned B.S. and B.A. degrees at Case Western Reserve University in 1981, and a Ph.D. at the Massachusetts Institute of Technology in 1986. After earning his doctorate, he spent a year as a NATO postdoctoral fellow at Cambridge University.

His research includes study of the orientation of fibers in suspensions, a factor that affects the properties of composite materials.

C. A. Hieber, a senior research associate, is the associate director of CIMP and a member of the research team.

He holds three degrees in mechanical engineering: the B.M.E. from Cooper Union (1964) and the M.S. (1966) and Ph.D. (1970) from Cornell. He joined the CIMP staff in 1974 after teaching for four years at Clarkson College.

Hieber has published more than a score of papers in major journals, and serves as a reviewer for the *Journal of Heat Transfer*, the *International Journal of Heat and Mass Transfer*, and the National Science Foundation.

CIMP: Previous Participants

Co-Principal Investigators

Shan-Fu Shen, Professor of Mechanical and Aerospace Engineering; tenure at CIMP, 1974–88

James F. Stevenson, Associate Professor of Chemical Engineering; tenure at CIMP, 1974–77

Other Staff Members

Steven Emerman, Research Associate, 1985–86

Konathala Himasekhar, Research Associate, 1987–88

Avraam I. Isayev, Senior Research Associate, 1979–83

Tai Hun Kwon, Postdoctoral Associate, 1983–85

Hubert Lobo, Technical Assistant, 1986–87

Robert C. Ricketson, Research Associate, 1984–87

Eric Siegler, Laboratory Assistant, 1984–85

Ram K. Upadhyay, Postdoctoral Associate, 1982

Ven-Wei Wang, Postdoctoral Associate, 1985–86

David Zimmerman, Programmer, 1985–87

Visiting Scholars and Scientists

Toshihiko Akiyama, Asahikawa Technical College, Japan, 1979–80

Masashi Furukawa, Asahikawa Technical College, Japan, 1976–77

Hiroshi Kondo, Sony Corporation, Japan, 1983–84

De-Qun Li, Hauzhong University of Science and Technology, 1986–87

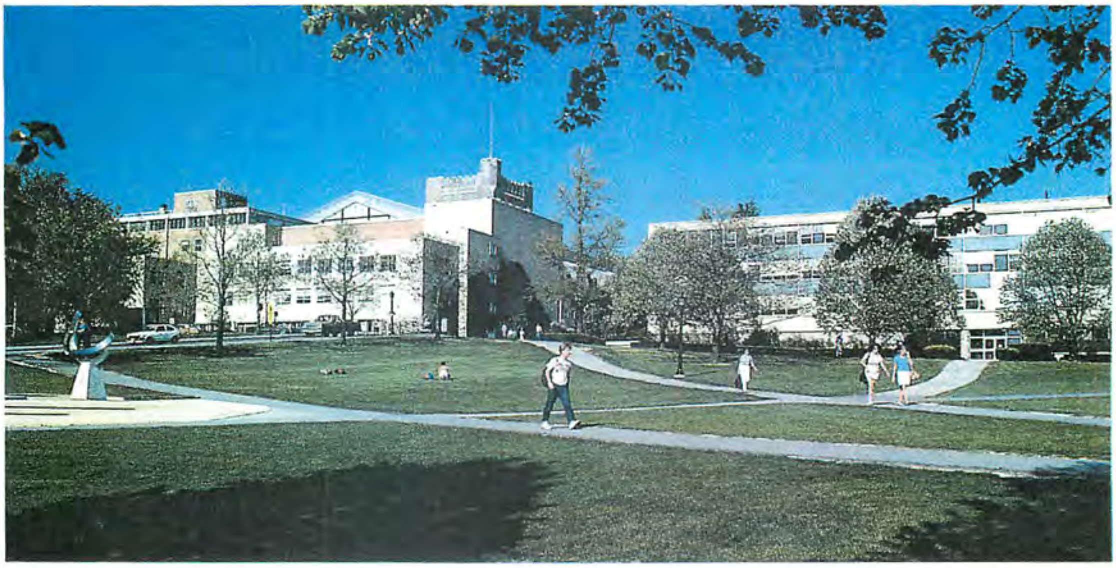
Shi-Jun Ni, Tianjing Institute of Light Industry, China, 1983–84

J. R. Ockendon, Oxford University, England, 1975–76

Shu Sengoku, Toyobo Company, Ltd., Japan, 1985–86

A. B. Tayler, Oxford University, England, 1977–78

Hsieng-Cheng Tseng, National Taiwan Institute of Technology, 1983–84



Consortium Members

AMP, Inc.
AT&T–Bell Laboratories
Becton Dickinson Research Center
B. F. Goodrich Company
David Sarnoff Research Center
E. I. du Pont de Nemours and Company
Eastman Kodak Company
Emerson Electric Company
Furukawa Electric Company, Ltd.
General Dynamics
General Electric Company
General Motors Corporation
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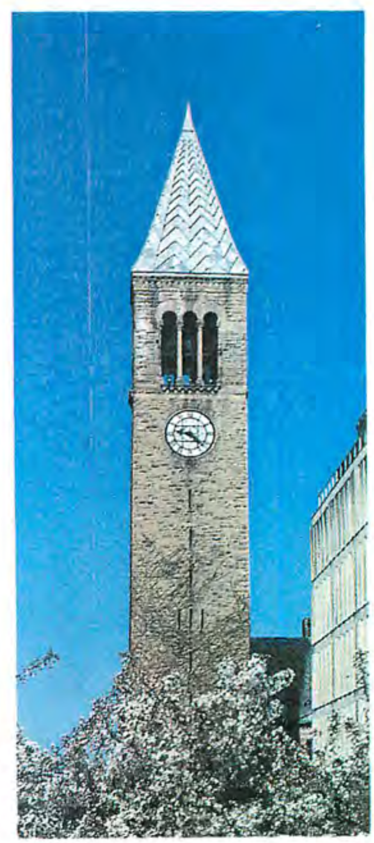
Idemitsu Petrochemical Company, Ltd.
Industrial Technology Research Institute (ITRI), Taiwan
Japan Synthetic Rubber Company, Ltd.
Lord Corporation
3M Company
Matsushita Electric Industrial Company
Mitsubishi Kasei (formerly Mitsubishi Chemical Industries)
Mitsubishi Electric Corporation
Mitsubishi Monsanto Chemical Company
Mitsubishi Petrochemical Company, Ltd.
Mitsubishi Plastics Industries, Ltd.
Mitsui Toatsu Chemicals, Inc.
Monsanto Chemical Company
Nippon Petrochemicals Company
Pitney Bowes
Polaroid Corporation
Rohm & Haas Company
Sony Corporation
Toyobo Company, Ltd.
Xerox Corporation



Former Consortium Members
Cincinnati Milacron, Inc.
Discovision Associates
Eaton Corporation
Ford Motor Company
Grumman Data Systems Corporation
McDonnell Douglas Automation Company
Moog, Inc.
NCR Corporation
Tatung Company
Unisys CAD/CAM, Inc. (formerly GRAFTEK)

CIMP: Degree Recipients

Name	*Engineering Field*	*Degree*	*Year*
Parvinder S. Ahluwalia	Mechanical	M.S.	1987
Hideho Ariyoshi	Mechanical	M.S.	1985
David I. Cahn	Chemical	M.S.	1978
Hwai Hai Chiang	Mechanical	M.S.	1987
Kwing-So Choi	Aerospace	Ph.D.	1983
David Chu	Mechanical	M.Eng.	1984
Winston Chuck	Mechanical	B.S.	1979
Bin Chung	Chemical	Ph.D.	1985
Simon C. K. Chung	Chemical	M.S.	1974
David Crouthamel	Mechanical	M.S.	1983
Ronnie G. Foltz	Mechanical	M.S.	1977
Alexandre Galskoy	Mechanical	M.S.	1977
G. Edward Grant	Mechanical	M.Eng.	1983
T. Hariharan	Mechanical	M.S.	1984
Richard A. Hauptfleisch	Chemical	M.Eng.	1976
Mark T. Holtzapple	Chemical	B.S.	1978
Sushant Jain	Chemical	M.S.	1980
Wen Ren Jong	Mechanical	M.S.	1988
Praveen Khullar	Mechanical	Ph.D.	1981

Name	*Engineering Field*	*Degree*	*Year*
Han Joon Kim	Mechanical	M.Eng.	1986
Tai Hun Kwon	Mechanical	Ph.D.	1983
E.-Cheng Lin	Mechanical	M.Eng.	1987
Hiro Maeda	Mechanical	MS.	1986
M. A. Morjaria	Aerospace	M.S.	1977
Paresh R. Patel	Chemical	M.S.	1976
Garry W. Perkins	Mechanical	M.Eng.	1979
Kumar Sambandan	Mechanical	M.S.	1988
Joseph A. Samluk, Jr.	Mechanical	M.Eng.	1988
Muneharu Sanou	Chemical	M.S.	1983
Avinash V. Sarlashkar	Mechanical	M.Eng.	1988
Lalit S. Shah	Mechanical	M.S.	1987
Pradeep Sinha	Mechanical	Ph.D.	1986
Lih-Sheng Turng	Mechanical	M.S.	1987
Ram K. Upadhyay	Aerospace	Ph.D.	1982
Gerald W. Vandenengel	Mechanical	M.Eng.	1984
Chalo F. Vorbeck	Mechanical	M.Eng.	1980
Kwang-Yu Wang	Mechanical	M.S.	1982
Weiping Wang	Mechanical	Ph.D.	1984
Ven-Woei Wang	Mechanical	Ph.D.	1985

CIMP: The Goals

From the beginning, the purpose of CIMP has been to apply scientific principles to the injection-molding process.

At first the researchers looked at simple problems involved in the injection molding of polymers.The initial objective was to understand the mold-filling stage; later the packing and cooling stages were considered. Soon the goal was enlarged to include the development of a comprehensive computer program to deal with all aspects of the process, from mold design to process control. The program was also expanded to include other technologies similar in nature to the injection-molding of plastics—specifically, ceramic injection molding and metal casting. The program continues to expand to keep up with current demands in manufacturing.

An important aspect of the program is the involvement of researchers from industry through the CIMP Industrial Consortium. Both the program and the consortium members benefit: CIMP receives economic support and the industrial members have access to proprietary software and publications and can call on the program staff for advice and consultation.

The program has also made contributions by generating a large number of papers that are frequently referred to by outside researchers in the field of injection molding.

An injection-molding machine in the CIMP laboratory.

Achievements

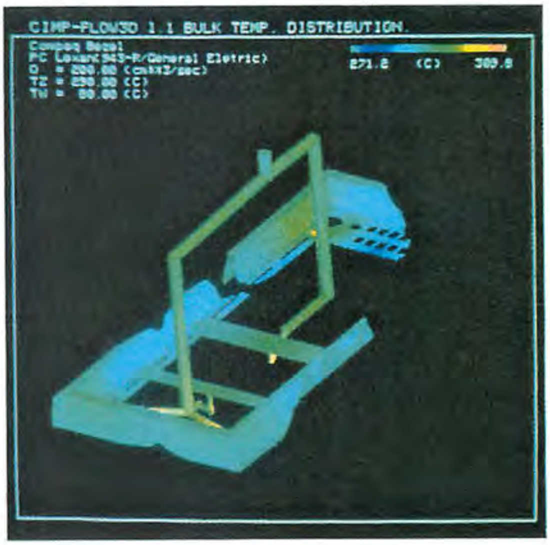
During the first four years, efforts were concentrated on the study of the dynamics of injection molding:

- Finite-element/finite-difference programs for simulating the filling of thin cavities of fairly arbitrary planar geometry were developed.
- The rheological behavior of thermoplastics was studied.
- The TIPS-1 CAD system was integrated with the mold-filling programs.

Throughout this period, the simulation packages were extended extensively and verified experimentally. The greatest confirmation was the ability to predict with fair success the injection pressures and clamp forces required for molding an automobile door-trim panel and a refrigerator liner.

Steady advances were made during the next four years:

- A systematic procedure for modeling the three stages of the thermoplastic molding cycle—filling, packing, and cooling—was developed.
- Cavity-filling programs were extended so that cavities with variable-gap thickness or with inserts could be simulated.
- A simple yet powerful "coupled-flow-path" modeling program applicable to multi-gated situations was developed.
- The effects of viscoelasticity on the injection-molding process were considered. In particular, efforts were made to determine the birefringence and the residual stresses in molded parts—a line of investigation that continues.
- Initial work on the simulation of orientation in fiber-filled materials was begun. Materials containing glass fibers were studied by means of injection-molding and capillary-rheometer experiments.



Simulations predicting pressure and bulk temperature distributions during filling.

• In work on the computer programs, an integrated CAD/CAM system, CADMOLD, was developed for use with minicomputers. In essence, CADMOLD is an interactive mold-assembly design program that helps the designer in the selection of standard commercial mold components. Contained within this initial version of CADMOLD are such constituents as the mesh-generation and cavity-filling programs and a simple program for designing cooling lines.

Highlights of CIMP's third four-year period were:

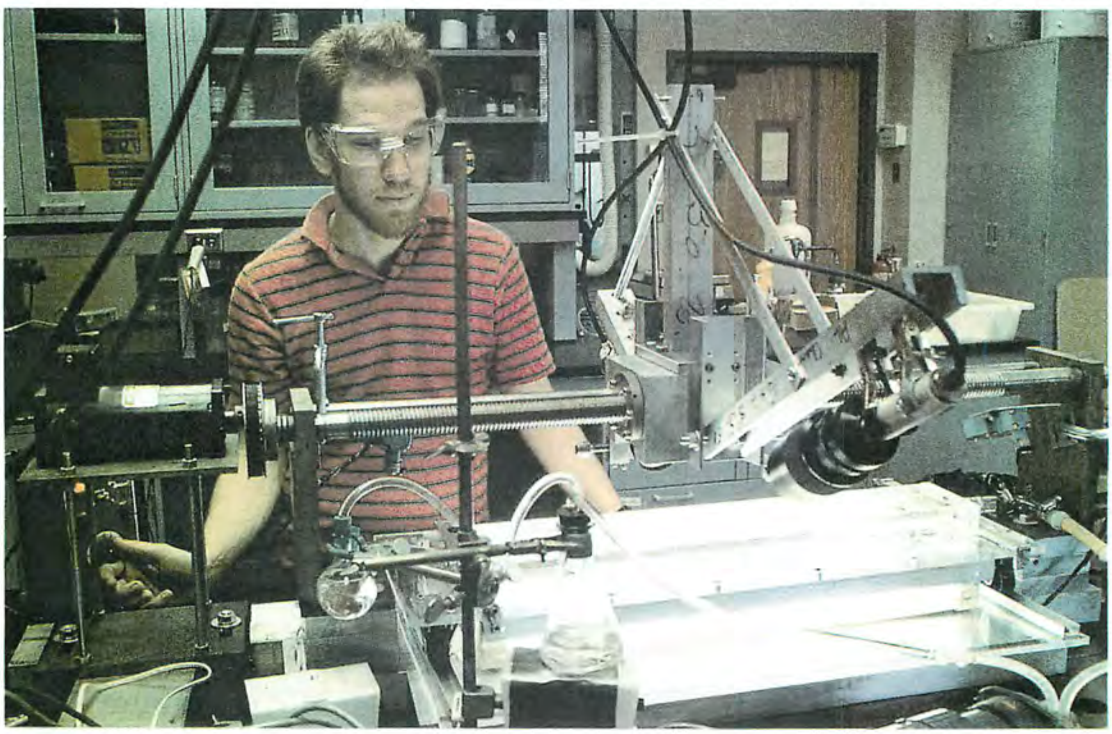
• The three-dimensional, "user-friendly" cavity-filling program CIMP-FLOW3D, needed by industry for the design of intricate commercial parts, was developed. Accompanying this was a much simplified, faster-running version, FLOW3DEZ, which is particularly useful for establishing gate locations during the initial design stage.

• Progress was made on cooling-line design programs that made use of finite-element and boundary-element formulations, and utilized commercially available software as pre-processors and/or post-processors.

• Substantial progress was made in developing a materials data bank. (Initially this consisted mainly of shear-viscosity data compiled from the literature.)

• Work on process control was initiated. The effects of certain operating conditions on part thickness were considered with the goal of developing real-time, microcomputer-based regulators for producing parts with consistent dimensions.

The fiber-orientation apparatus.



• Work was begun on a program for simulating the flow of thermosets and a flow-visualization apparatus for studying fiber orientation.

• A system for simulating NC mold machining, applicable to milling operations, was developed.

During the past three years, the research on injection molding of polymers has progressed very well:

• A two-dimensional packing simulation for amorphous polymers has been developed. It is currently being extended to allow three-dimensional simulation of thin objects, and to handle semicrystalline polymers.

• Progress has been made in predicting the frozen-in flow-birefringence for a center-gated disk, a problem of direct interest in CD technology.

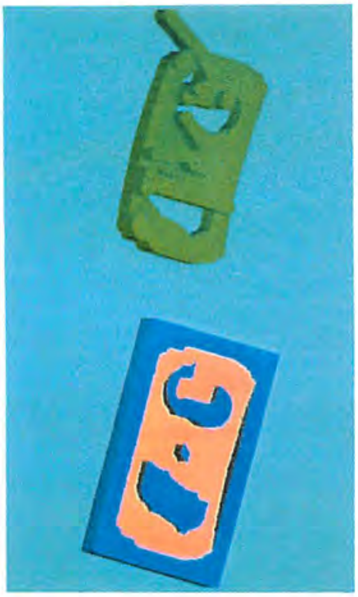
• A software package for cooling-line design has been developed and documented.

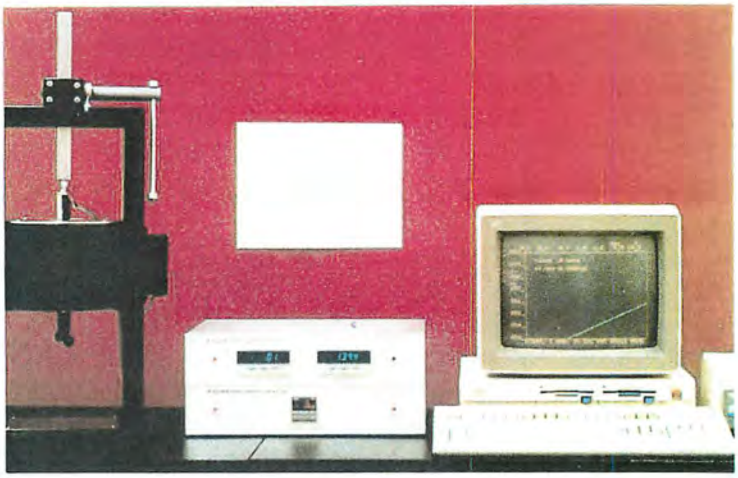
• In work on thermoset flow, kinetic and rheological experiments have been performed, and a one-dimensional cavity-filling program has been developed.

• The data bank has been greatly expanded, most notably with dynamic data from the literature.

• Ongoing work on parts molded from fiber-filled materials includes studies of the orientation of individual fibers undergoing steady shear, and the effects of fiber orientation upon the mechanical properties of the part.

The net-shape die-casting apparatus.





Above: Solid modeling of a mold design.

Right above: A system, developed by CIMP, for measuring the thermal conductivity of plastics.

A significant development is that CIMP has diversified to include work on materials other than polymers:

- Research has begun on injection molding of ceramic or metal powders and on net-shape metal casting. So far, the activity in these new areas has consisted mostly of rheological experiments, necessary for the eventual modeling of material flow.
- An ambitious project now underway is to develop an expert system that will encompass both the extensive data bank and the growing body of information on injection-molding techniques. The system will help designers find the optimal process conditions and material for a given job, and help process controllers in the time-consuming function of troubleshooting.

After fifteen years of steady progress, the Cornell Injection Molding Program has matured and is realizing its original objectives. But new challenges continually emerge and the scope of the program continues to expand. The completion of the fifteenth year is a time for looking back with satisfaction, but more importantly, it is a time for looking forward as early dreams become reality and new possibilities excite the imagination.

Opposite: The Cornell campus, viewed from the engineering quadrangle. Upson Hall, home of CIMP, is at lower right.

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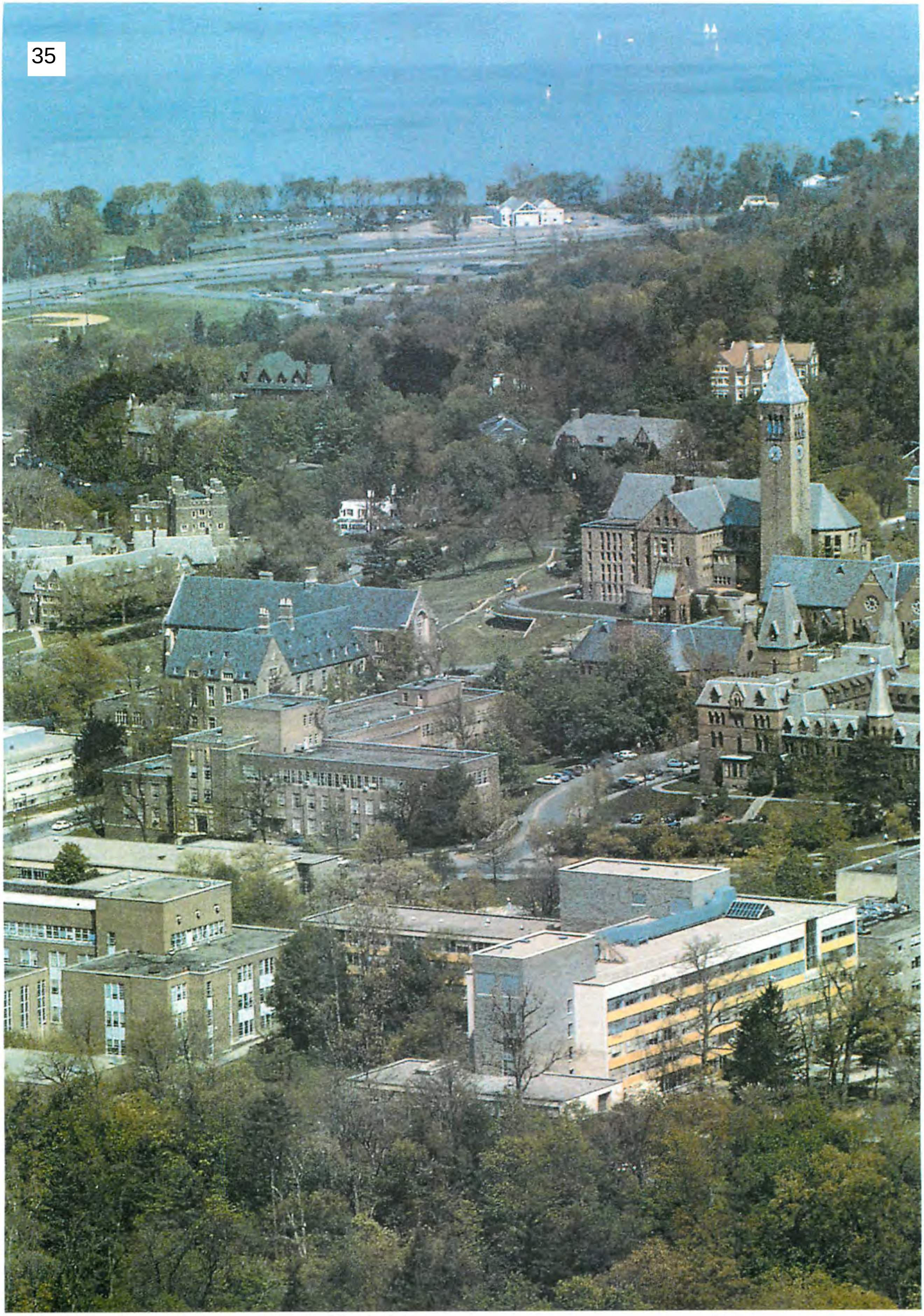
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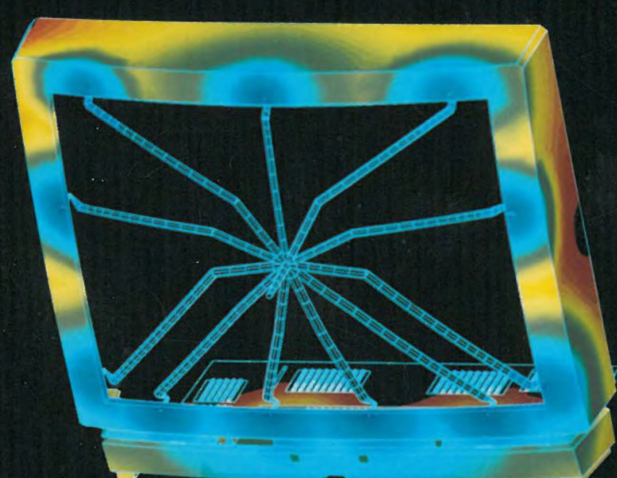
CIMP at 20

A look at the Cornell Injection Molding Program through its first twenty years



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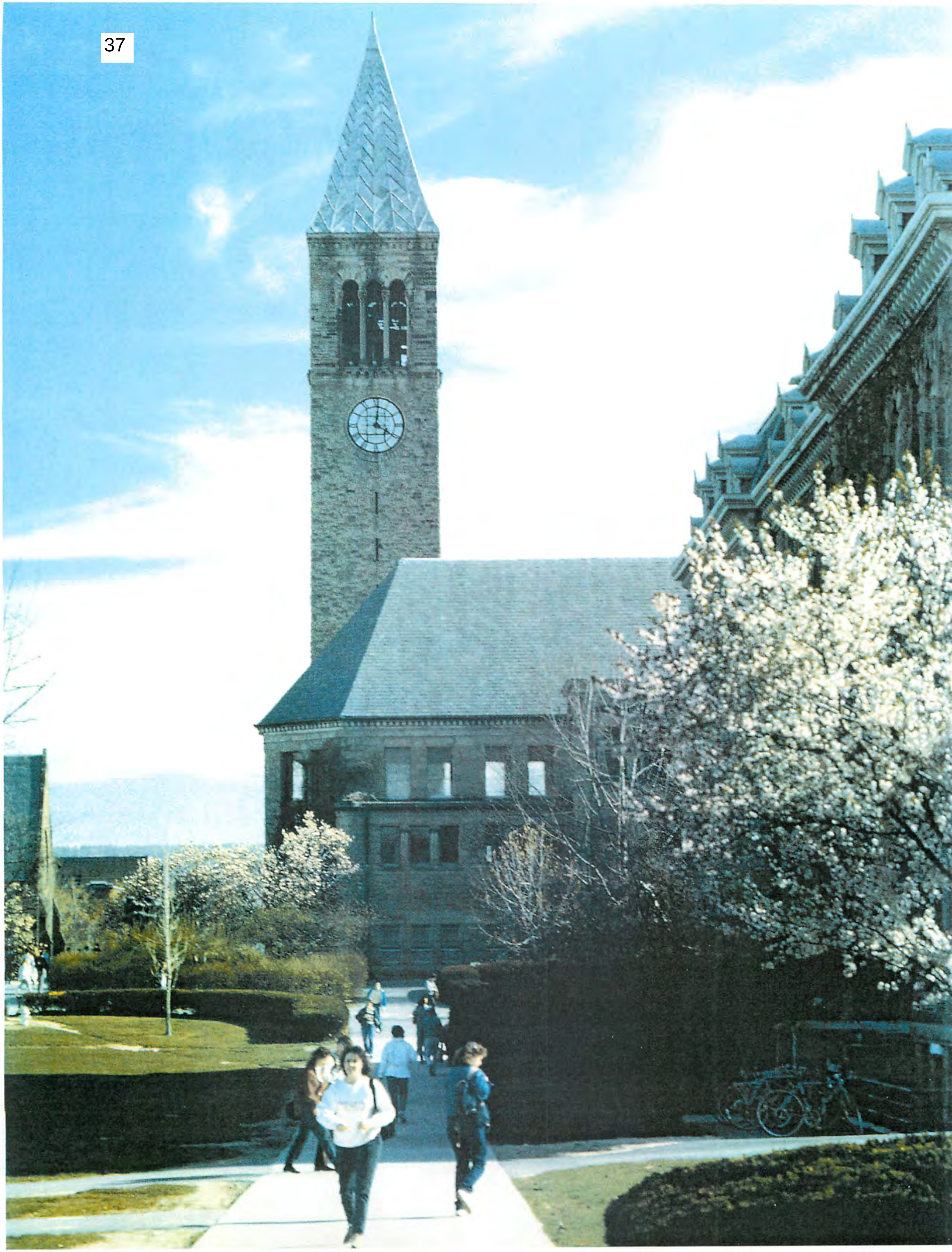

CIMP—from Dream to Reality

Twenty years ago, in 1974, a small group at Cornell began an innovative venture in which industry and academia would cooperate to advance an important area of technology. This was the origin of the Cornell Injection Molding Project (CIMP).

To celebrate these twenty years, the Cornell Injection Molding Program, as it has been called since 1979, is hosting a conference in the spring of 1994.

The dream, back when the initiative began, was to place injection molding—then a "rule of thumb" technique—on a firm scientific basis. It was an ambitious dream that presented hard practical questions. Would it be possible to understand and predict the complex interactions that occur in the injection-molding process? And if so, could industrial practitioners be convinced to try the new scientific methods?

Today, the dream has become a reality. CIMP is recognized not only as one of the organizations that took injection molding out of its dark ages, but as one of the most vigorous injection-molding research groups in the world. A look at the history of the program, its current activities, and its future prospects is presented here.

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From the initial, relatively simple study of the filling of thin cavities to the current development of an expert system for handling a wide range of processes, CIMP has come a long way in twenty years.

A four-roll mill is used to investigate the effect of polymer flow on fiber orientation.

CIMP Program Leaders

K. K. Wang, director of CIMP, is Sibley Professor of Mechanical Engineering Emeritus at Cornell's Sibley School of Mechanical and Aerospace Engineering.

He earned the B.S.M.E. degree at National Central University in China in 1947, and studied at the University of Wisconsin for the M.S.M.E. and Ph.D. degrees. After two years of teaching at Wisconsin, he joined the Cornell faculty in 1970.

Wang has had many years of broad industrial experience related to design and manufacturing engineering, and has received many professional honors. Among them are a TRW fellowship and awards from the Society of Manufacturing Engineers (SME), the American Welding Society, and the American Society of Mechanical Engineers (ASME)—including ASME's William T. Ennor Manufacturing Technology Award. He is a fellow of ASME and of SME, and a member of the National Academy of Engineers. He received the Distinguished Service Citation from the University of Wisconsin, Madison, and the Achievement Award from the Chinese Institute of Engineers.

Claude Cohen, a professor of chemical engineering at Cornell, has been a member of the faculty since 1977. He served as Director of the School of Chemical Engineering from 1990 to 1993.

He received a B.S. degree in 1966 from the American University in Egypt, and a Ph.D. in 1972 from Princeton University. Before joining the Cornell faculty in 1977, he was a Katzir-Katchalsky fellow at the Weizmann Institute in Israel and a research associate at the California Institute of Technology.

Cohen uses polymer science and engineering to interpret the physical properties of polymer systems and composites, and to understand structure-property relationships in these materials.

Donald L. Koch is an associate professor of chemical engineering. He came to Cornell in 1987, and soon afterward won a five-year Presidential Young Investigator Award from the National Science Foundation.

Koch earned B.S. and B.A. degrees at Case Western Reserve University in 1981, and a Ph.D. at the Massachusetts Institute of Technology in 1986. After earning his doctorate, he spent a year as a NATO postdoctoral fellow at Cambridge University.

His research includes study of the orientation of fibers in suspensions, a factor that affects the properties of composite materials.

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Hieber has published more than a score of papers in major journals, and serves as a reviewer for the *Journal of Heat Transfer*, the *International Journal of Heat and Mass Transfer*, *Polymer Engineering and Science*, and the National Science Foundation.

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Ithaca, NY 14853-7501

CIMP Staff and Visitors

Co-Principal Investigators

Shan-fu Shen, John Edson Sweet Professor, Emeritus, Mechanical and Aerospace Engineering; tenure at CIMP: 1974–88

James F. Stevenson, Associate Professor, Chemical Engineering; tenure at CIMP: 1974–77

Other Staff Members

Moustafa Aboulfaraj, Postdoctoral Associate, 1990
Tay-Yuan Chen, Postdoctoral Associate, 1991–92
Steven Emerman, Research Associate, 1985–86
Anath Fischer, Postdoctoral Associate, 1992–94
Hany Ghoneim, Consultant, 1993
Mahesh Gupta, Postdoctoral Associate/Research Associate, 1990–94
Sejin Han, Postdoctoral Associate, 1994
Oliver Harlen, Postdoctoral Associate, 1991
Konathala Himasekhar, Research Associate, 1987–88
Avraam I. Isayev, Senior Research Associate, 1979–83
Said Jahanmir, Faculty/Sibley School, 1977–80
Xiaoshi Jin, Postdoctoral Associate, 1993–94
Wern-Shiarng Jou, Postdoctoral Associate, 1991–92
Shinill Kang, Postdoctoral Associate, 1994
Leonid Kudryavtsev, Postdoctoral Associate, 1991–1993
Tai Hun Kwon, Postdoctoral Associate, 1983–85
Hubert Lobo, Technical Assistant, 1986–87
Kwabena Albert Narh, Postdoctoral Associate, 1992–94
P. T. Radulovic, Faculty/Sibley School, 1976–78
Byung Ohk Rhee, Postdoctoral Associate, 1992–1993
Robert C. Ricketson, Research Associate, 1984–87
Wei-Yan Shih, Postdoctoral Associate, 1992–94
Eric Siegler, Laboratory Assistant, 1984–85
Ram K. Upadhyay, Postdoctoral Associate, 1982
Shaupoh Wang, Postdoctoral Associate, 1992–94
Ven-Woei Wang, Faculty/Sibley School, 1985–86
Khungwan Yoon, Research Associate, 1989–1993
David Zimmerman, Programmer, 1985–87

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Isao Fukumoto, University of The Ryukyus, Japan, 1993–94
Masashi Furukawa, Asahikawa Technical College, Japan, 1976–77

Durn-Yuan Huang, National Kaohsiung Institute of Technology, Taiwan, 1993–94
Yong Jeong Huh, Korea Institute of Technology and Education, 1994
Yukinori Kakazu, Hokkaido University, Japan, 1986–87
Hiroshi Kondo, Sony Corporation, Japan, 1983–84
Hiroshi Kubo, Hokkaido University, Japan, 1979–80
Shi-Jun Ni, Tianjing Institute of Light Industry, PRC, 1981–84, 1990–93
Yi-Yong Nie, Shenyang Institute of Computing Technology, PRC, 1994
J.R. Ockendon, Oxford University, England, 1975–76
Tomaru Ogawa, Nisson Research Center, Japan, 1990–92
Norio Okino, Hokkaido University, Japan, 1979–80
Masanori Okubo, Idemitsu Petrochemical Co., Ltd., Japan, 1990–91
Jia Zhen Pan, East China University of Science & Technology, PRC, 1990–91
Sehyung Park, Korea Institute of Science & Technology, 1992–93
Tae-Suk Park, Korea Institute of Science & Technology, 1991–92
Shu Sengoku, Toyobo Company, Ltd., Japan, 1985–86
Kazunari Tajiri, Toyoda Gosei Co., Ltd., Japan, 1988–90
A. B. Tayler, Oxford University, England, 1977–78
Hsieng-Cheng Tseng, National Taiwan Institute of Technology, 1983–84
Nan Wang, Southeast University, PRC, 1993–94

Experimental results are discussed in meetings attended by CIMP staff members and industrial affiliates.

Companies Associated with CIMP

Over the course of its twenty-year history, fifty-two companies have been associated with CIMP. Those marked with asterisks (*) in the following list are users of C-MOLD software, developed by AC Technology.

McGraw Tower is a landmark on the Cornell campus.

Allied Signal, Inc.*	1990–1994
AMP, Inc.	1981–1991
AT&T Bell Labs*	1981–1992
B. F. Goodrich*	1980–1989
Becton Dickinson Research Center*	1987–1994
Cincinnati Milacron Inc.	1974–1985
Dainippon Ink & Chemicals, Inc.*	1990–1994
DiscoVision	1980–1982
DSM Research*	1990–1994
E. I. du Pont de Nemours Co.*	1984–1994
Eastman Kodak Company*	1974–1994
Eaton Corporation*	1982–1984
Emerson Electric	1984–1991
Exxon Chemical Canada	1993–1994
Ford Motor Co.*	1974–1984
Furukawa Electric Co., Inc.*	1987–1994
General Dynamics Corporation*	1979–1994
General Electric Company*	1974–1994
General Motors Corporation*	1982–1994
Goodyear Tire*	1985–1990
Graftek/Unisys	1981–1988
Grumman Data Systems	1981–1983
Hoechst Celanese Corporation*	1989–1994
IBM Corp.*	1984–1993
Idemitsu Petrochemical Co. Ltd.*	1986–1992
ITRI/MIRL*	1987–1989
Japan Synthetic Rubber Co., Inc.*	1988–1994
Kaneka Corporation	1991–1994
Lord Corporation*	1979–1989
3M Company*	1988–1994
Matsushita Electric Industrial Co. Ltd.*	1984–1994
McAuto	1982–1983
Mitsubishi Electric Corporation	1986–1994
Mitsubishi Kasei Polytech Co.*	1985–1993

Mitsubishi Petrochemical Co. Ltd.*	1985–1994
Mitsubishi Plastics & Industries Ltd.*	1984–1993
Mitsui Toatsu	1987–1993
Moog, Inc.	1982–1983
NCR Corporation	1979–1984
Nippon Petrochemical Co. Ltd.*	1987–1994
Nippon Steel Corporation*	1993–1994
Nissan Motors	1989–1993
Pitney Bowes*	1983–1991
Polaroid Corporation*	1985–1989
RCA/David Sarnoff*	1979–1990
Rohm & Haas*	1986–1989
Sekisui Chemical Co. Ltd.*	1991–1994
Sony Corporation*	1980–1994
Tatung Company*	1985–1988
Toyobo Co. Ltd.*	1987–1994
United Technologies Research Center*	1991–1994
Xerox Corporation	1974–1991

CIMP's headquarters are in the Engineering and Theory Center Building.

CIMP Degree Recipients

Over the years, forty-eight students have helped fulfill the requirements for their degrees through research conducted in the Cornell Injection Molding Program. Of these, one bachelor's degree, eight Masters of Engineering, nine Masters of Science, and sixteen doctoral degrees were earned in mechanical engineering; one bachelor's degree, one Master of Engineering, five Masters of Science, and five doctoral degrees were earned in chemical engineering; and one Master of Science and one doctorate were earned in aerospace engineering.

Name	*Engineering Field*	*Degree*	*Year*
Oscar Adiwidjaja	Mechanical	M.Eng.	1993
Parvinder S. Ahluwalia	Mechanical	M.S.	1987
Hideho Ariyoshi	Mechanical	M.S.	1985
David I. Cahn	Chemical	M.S.	1978
Hwai Hai Chiang	Mechanical	Ph.D.	1989
David Chu	Mechanical	M.Eng.	1984
Winston Chuck	Mechanical	B.S.	1979
Bin Chung	Chemical	Ph.D.	1985
David Crouthamel	Mechanical	M.S.	1983
Fearghal Downey	Chemical	Ph.D.	1994
Robert A. Ferstenberg	Mechanical	Ph.D.	1988
Ronnie G. Foltz	Mechanical	M.S.	1977
Alexandre Galskoy	Mechanical	M.S.	1977
Ulises F. Gonzales	Mechanical	Ph.D.	1991
G. Edward Grant	Mechanical	M.Eng.	1983
Sejin Han	Mechanical	Ph.D.	1994
T. Hariharan	Mechanical	M.S.	1984
Richard A. Hauptfleish	Chemical	M.Eng.	1976
Mark T. Holtzapple	Chemical	B.S.	1978
S. Ibrahim	Mechanical	M.Eng.	1980
Yoichi Iso	Chemical	Ph.D.	1994
Sushant Jain	Chemical	M.S.	1980
Wen Ren Jong	Mechanical	Ph.D.	1990
Praveen Khullar	Mechanical	Ph.D.	1981
Tai Hun Kwon	Mechanical	Ph.D.	1983
Hiro Maeda	Chemical	M.S.	1986
Kazuhiro Mimura	Mechanical	M.S.	1992
Kenjiro Takai Miura	Mechanical	Ph.D.	1991
M.A. Morjaria	Aerospace	M.S.	1977

Paresh R. Patel	Chemical	M.S.	1976
Garry W. Perkins	Mechanical	M.Eng.	1979
Mani Rahnama	Chemical	Ph.D.	1994
Kumaraguru Sambandan	Mechanical	Ph.D.	1990
Muneharu Sanou	Chemical	M.S.	1983
N. Santhanam	Mechanical	Ph.D.	1992
Lalit S. Shah	Mechanical	M.S.	1987
Pradeep Sinha	Mechanical	Ph.D.	1986
Carl Arthur Stover	Chemical	Ph.D.	1991
Lih-Sheng Turng	Mechanical	Ph.D.	1990
Ram K. Upadhyay	Aerospace	Ph.D.	1982
Gerald W. Vandenengal	Mechanical	M.Eng.	1984
Chalo F. Vorbeck	Mechanical	M.Eng.	1980
Ging-Li Wang	Mechanical	M.Eng.	1994
Kuang-Yu Wang	Mechanical	M.S.	1982
Pei-Jen Wang	Mechanical	Ph.D.	1991
Shaupoh Wang	Mechanical	Ph.D.	1993
Ven-Woei Wang	Mechanical	Ph.D.	1985
Weiping Wang	Mechanical	Ph.D.	1984

Many physical processes are modeled with numerical simulation.

CIMP's Goals

From the beginning, the purpose of CIMP has been to apply scientific principles to the injection-molding process.

At first the researchers looked at simple problems involved in the injection molding of polymers. The initial objective was to understand the mold-filling stage; later the packing and cooling stages were considered. Soon the goal was enlarged to include the development of a comprehensive computer program to deal with all aspects of the process, from mold design to process control. The program was also expanded to include other technologies similar in nature to the injection-molding of plastics — specifically, ceramic injection molding and metal casting. The program continues to expand to keep up with current demands in manufacturing.

An important aspect of the program is the involvement of researchers from industry through the CIMP Industrial Consortium. Both the program and the consortium members benefit: CIMP receives economic support and the industrial members have access to proprietary software and publications and can call on the program staff for advice and consultation.

The program has also made contributions by generating a large number of papers that are frequently referred to by outside researchers in the field of injection molding.

Birefringence is measured with an optical microscope.

CIMP's Achievements

Process Modeling, Simulation, and Control

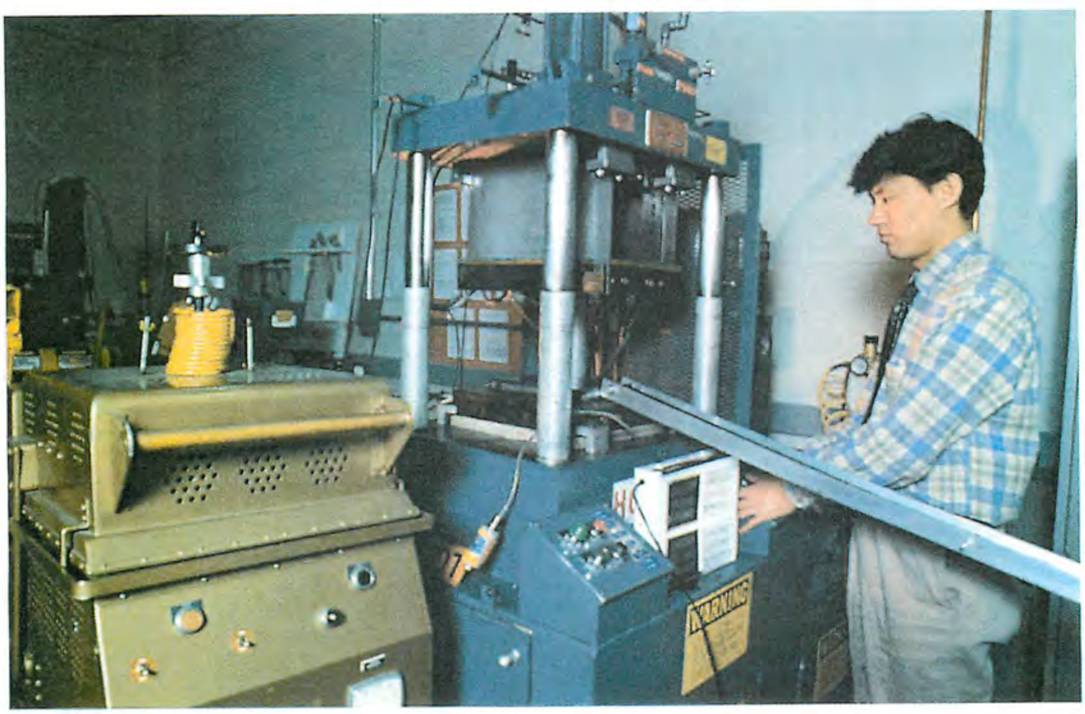
• During the initial stage of the research, effort was concentrated on the study of molding dynamics. A finite-difference numerical scheme was developed for simulating the filling of thin cavities based on 1-D flow analysis. A simple yet powerful "Coupled-Flowpath" modeling program applicable to multi-gated situations, completed during this stage, rationalized the so-called "lay-flat" approximation of cavity-filling simulation.

• The cavity-filling program was extended by developing a hybrid finite-element/finite-difference numerical scheme to handle the filling of fairly arbitrary planar geometry with variable thickness and inserts. A systematic procedure for modeling the three stages—filling, packing, and cooling—of a molding cycle was developed.

• By 1985, the three-dimensional, user-friendly, mold-filling program CIMP-FLOW3D, needed by industry for producing intricate plastic parts, was developed. Since then, the finite-element/finite-difference/control-volume numerical scheme has been adopted as the technical standard by most researchers and software developers in the field.

• The program was subsequently extended to account for the compressibility of the material over the entire molding cycle of filling, packing and cooling, resulting in CIMP-PACK3D in 1989.

• A separate effort was launched to aid the design of mold-cooling systems. Starting with a simple 1-D heat-conduction calculation, the simulation progressed to a 2-D heat-transfer program using the boundary-element method. The CIMP-COOL3D program that finally evolved couples a 3-D steady-state boundary-



The mechanics of chip encapsulation is studied with a transfer molding machine.

element calculation for the mold with a transient 1-D finite-difference calculation in the cavity, matching the temperature and heat flux at the mold/polymer interface on a cyclic-averaged basis.

- The effect of viscoelasticity on injection molding has been investigated starting from the early stages of the program. In particular, effort has been devoted to measuring and predicting flow-induced birefringence and residual (thermal and flow-induced) stresses. Current effort includes the calculation of juncture pressure losses using viscoelastic modeling.
- Considerable progress has been made toward a basic understanding of the behavior of short fibers in flow fields relevant to injection molding. Work on theoretical predictions and experiments regarding fiber orientation and fiber-fiber interaction have been carried out. A somewhat simplified program that has been developed predicts fiber orientation and resulting mechanical properties of injection-molded parts that are reinforced with fairly high concentrations of short fibers.
- Similar work on simulation of mold filling with thermosets has been carried out. Significant progress has been made in numerical/experimental studies on encapsulation of microelectronic chips with epoxy-molding compounds. A special slit rheometer was built to determine viscosity as a function of degree-of-cure as well as of temperature and shear rate. Good results have been obtained in predicting wire deformation due to wire sweep in the filling process.
- For warpage analysis of thin-walled parts, a dedicated and very efficient structure-analysis program, SHELL10, has been developed. Comparison with a high-end, general-purpose FEM code shows that SHELL10 gives comparable accuracy while requiring considerably less execution time and memory.

An instrumented mold is installed to study warpage of injection-molded plastics.

• Work on process control was also initiated at an early stage. Characteristics of a typical process controller were investigated and modeled. An on-line adaptive-control algorithm for controlling part thickness based on an empirical model was developed. Similar results were obtained by incorporating a predictive model into the control loop based on a 1-D packing calculation.

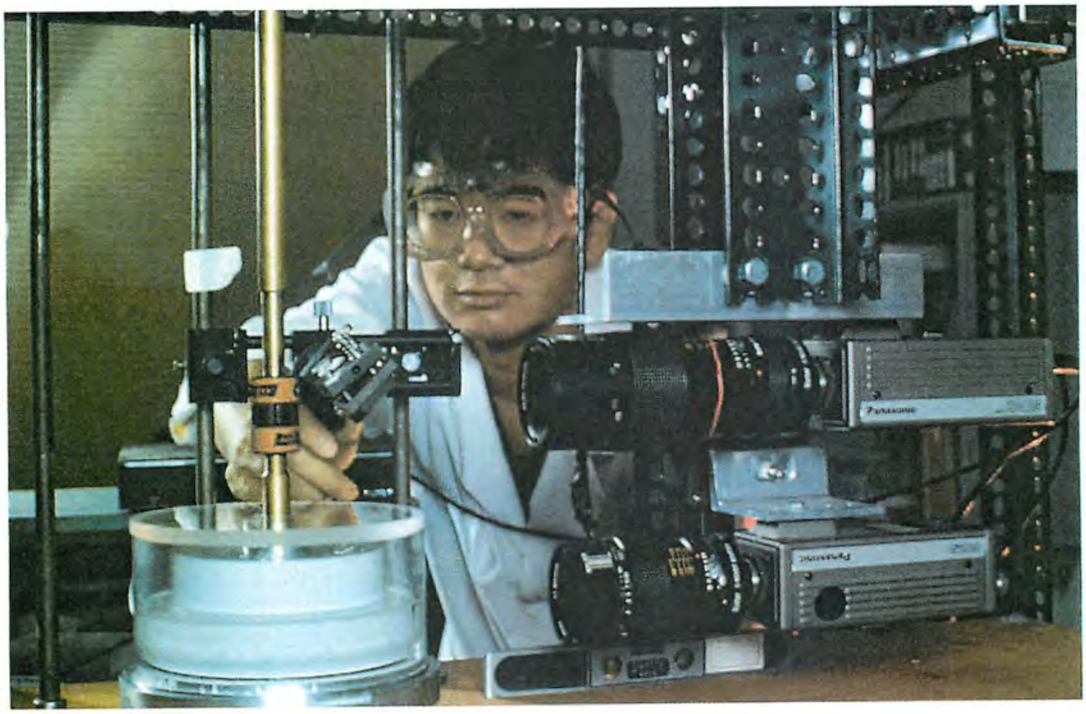
Material Characterization, Modeling, and Properties of Molded Parts

• The study of the rheological behavior of polymers has been an essential and continuous effort of the program. Various methods of measuring and modeling the viscosity of polymer melts have been critically assessed. Substantial experimental work has been done in this regard with a variety of rheometers.

• A substantial materials data bank has been developed consisting of shear-viscosity data from capillary and dynamic measurements. A new and patented instrument (K-System) using a line-heat source was developed to measure the thermal conductivity of polymers as a function of temperature.

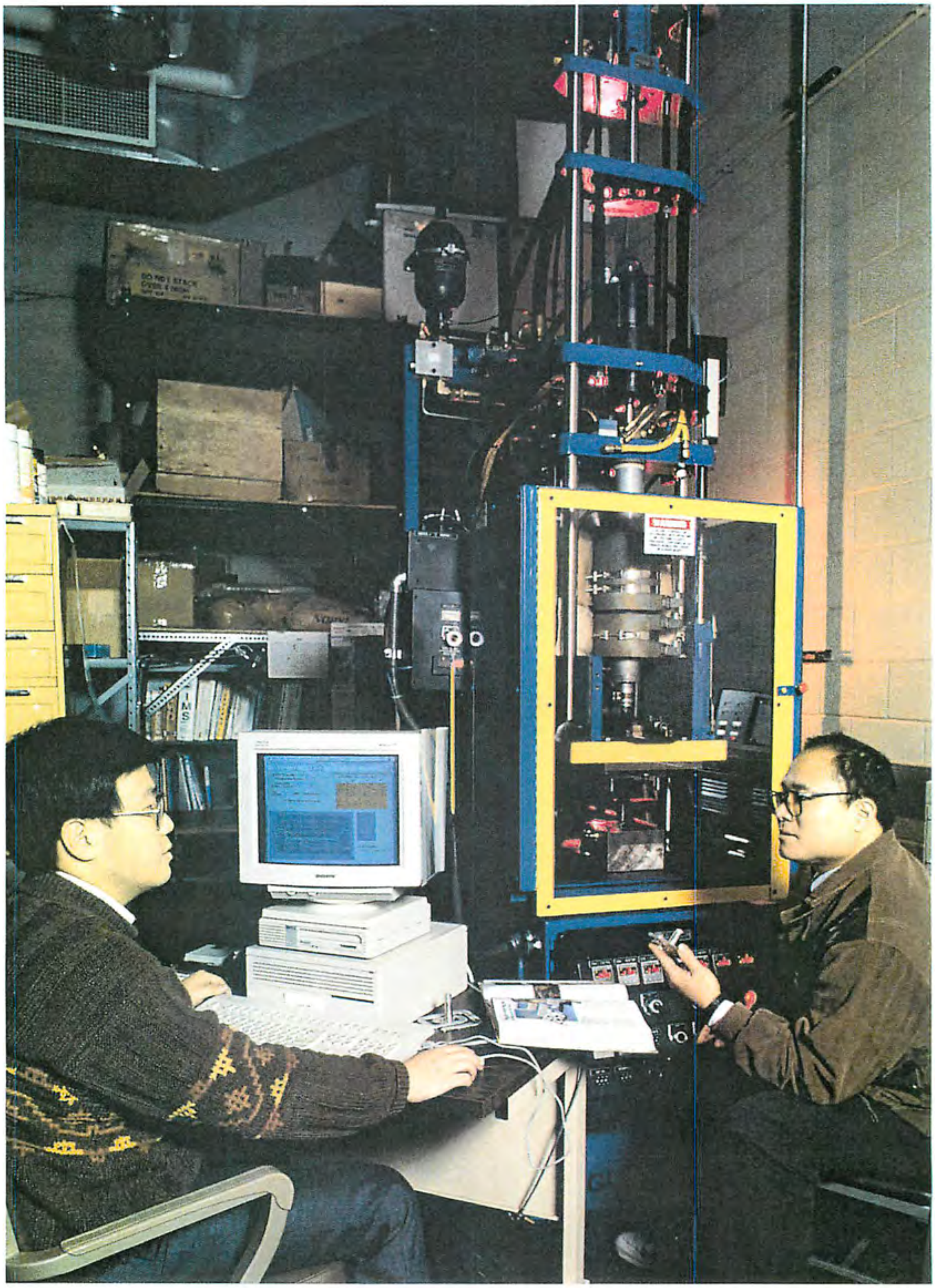
• A dual-vessel PVT device was designed and built to measure the density change of polymers over a wide range of temperature and pressure. The new device is inexpensive, easy to calibrate and operate, and environmentally safe. An apparatus was developed and used to assess the possible effects of thermal-contact resistance in injection molding.

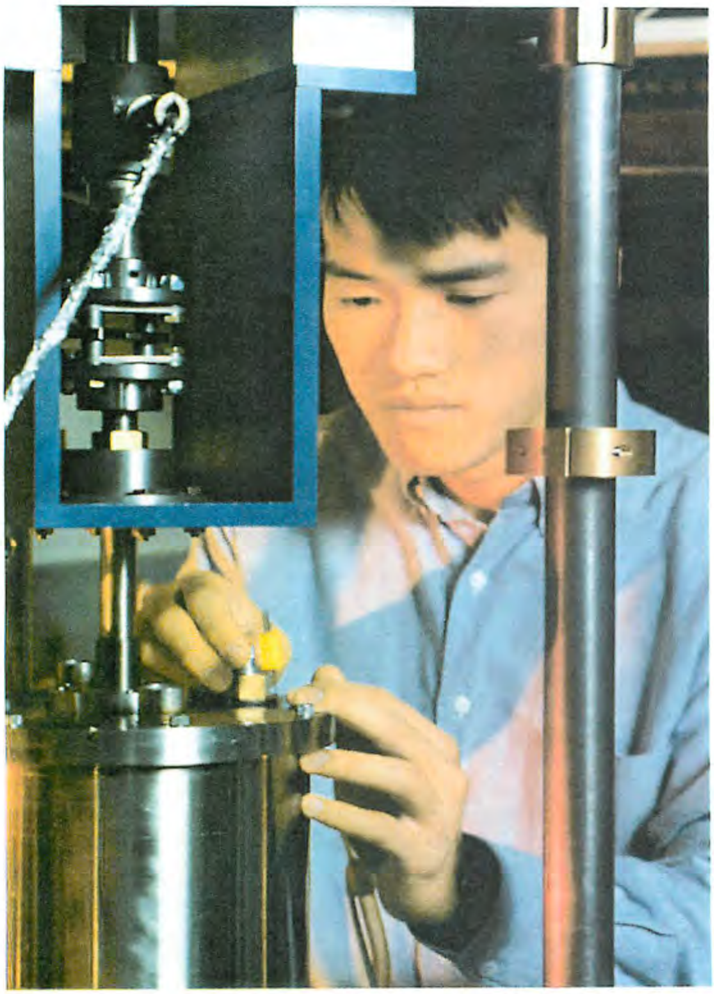
• Experimental and modeling studies have been conducted on semicrystalline polymers under both quiescent and flow conditions in order to investigate the effects of nonisothermal and stress-induced crystallization kinetics in injection molding.



Interaction among fibers is studied optically.

Semisolid metals are processed in an experimental rheomolding machine.





A specially designed apparatus is used to study the viscosity of semisolid metals.

Nonpolymer Materials Processing

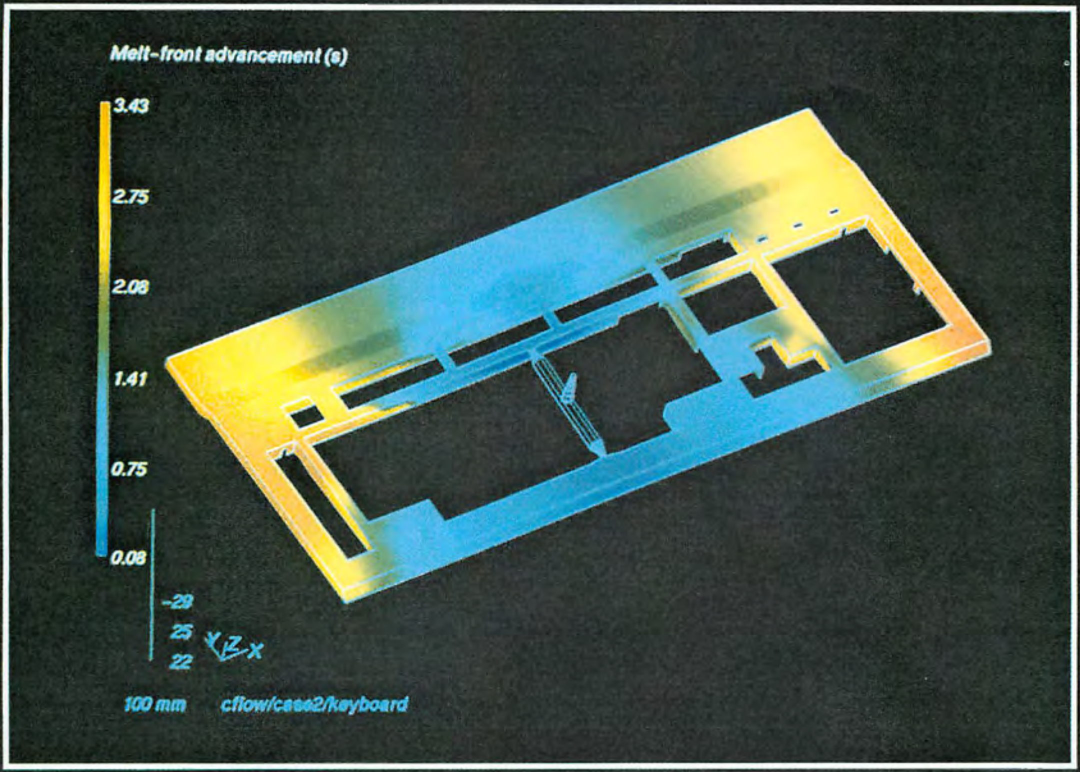
- A new research effort was launched in 1989 under a grant from the National Science Foundation to develop a novel process for net-shape manufacturing of semisolid materials (SSM). The idea was to make die-cast metal objects in a manner similar to the injection molding of plastics. The new process, named "rheomolding," makes use of a vertical injection-molding machine. Screw rotation and a controlled temperature profile along the barrel of the prototype machine have successfully produced the semi-solid state of a low-temperature metal alloy.
- Considerable work on rheological experiments and viscosity modeling of a tin-lead alloy has been done. A new finite-element procedure, called the net-inflow-method (NIM), has been developed to simulate incompressible viscous flow with inertial effects and moving free surface. NIM has also been applied to improve the numerical stability and efficiency in the filling simulation of the injection molding of plastics.
- Work has been done on rheological experiments with a ceramic-powder fill material, including the injection molding of such a material in a spiral-flow mold.

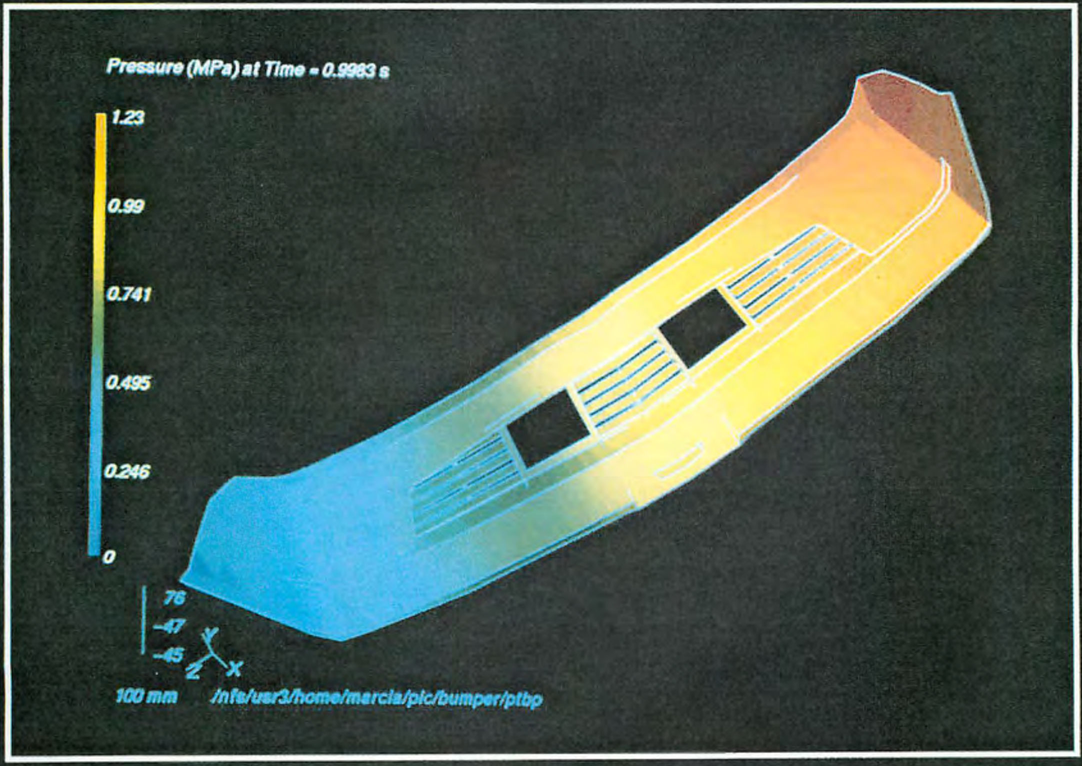
CAD/CAM Related Activities

- In the early stages of the program, an integrated CAD/CAM system, CADMOLD, was developed to help the mold designer to interactively select standard mold components. The TIPS-1 CAD system was integrated with the mesh-generation, cavity-filling, and a simple cooling-line design program.
- A system for simulating NC mold machining, applicable to milling operations, was developed. The NC simulation (NCS) program was the first software with color-shaded display that could be used for NC-toolpath verification.
- An algorithm and corresponding computer code were developed to more accurately compute the intersection of free-form surfaces. This pioneering work has evolved into a powerful geometric tool kit, SHAPES, which is commercially available.
- Work on the development of a feature-based design system for injection-molded parts was carried out. A library of features commonly encountered in plastic-part design was established to facilitate the design process. An algorithm was developed to extract midsurfaces of thin-walled parts created from a CAD system, which can be used directly for mold-filling analysis.

After twenty years of steady progress, the Cornell Injection Molding Program has matured and is realizing its original objectives. But new challenges continually emerge and the scope of the program continues to expand. The completion of the twentieth year is a time for looking back with satisfaction, but more importantly, it is a time for looking forward as early dreams become reality and new possibilities excite the imagination.

A feature-based CAD system is developed for injection-molded parts.





Simulation results produced with software developed at CIMP and licensed to AC Technology, Inc.

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Exht. 9

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Cornell's Small research Business serves the Development region:

Cornell University

Office of the Vice President for Research and Advanced Studies

Cornell, New York State's land-grant university, is committed to the integration of knowledge discovery and knowledge transfer to the public. Through the concept of outreach, Cornell seeks to extend research-based knowledge for the direct benefit of individuals, groups, and the public at large. One explicit form of outreach is the implementation and support of regional economic development. The collective efforts of numerous groups—such as the Cornell Research Foundation (CRF), Cornell Office for Technology Access and Business Assistance (COTABA), Cornell Business and Technology Park, Cornell Cooperative Extension, the Center for Advanced Technology in Biotechnology (CAT), Cornell's research centers and colleges, and the Tompkins County Area Development Inc. (TCAD)—contribute significantly to the process of moving advances in research from the university to the public. Many university–corporate partnerships have formed as the result.

Cornell, with more than $321 million expended for research in FY 1996, and its partnerships with industry have a significant impact on the regional and state economy. This directory of small businesses illustrates some of the relationships between Cornell and small business development and how economic development is fostered. The directory covers three types of connections between Cornell and small businesses.

- *The company was founded by Cornell faculty, staff, students, or alumni with an identifiable transfer of university technology;*
- *Cornell technology provided the major impetus for the company's creation;*
- *A close proximity to Cornell's intellectual resources is significant to the company's formation and retention in the region.*

***Cornell's Research Serves the Region: Small Business Development 1996-97** highlights 60 companies with more than 2,800 employees in the Ithaca area and annual revenues greater than $292 million. Many companies are in the start-up phase and, therefore, do not report revenues. Others have not provided data on revenues.*

This is the third annual documentation of regional small business development evolving from Cornell research. Since the first publication in 1994, the number of companies included has grown from 34 to 60. The number of employees has increased by more than 800. These increases reflect both new companies and recent identification of previously established companies. Small companies continue to emerge, thus demonstrating how Cornell research promotes the entrepreneurial spirit.

We thank each company for their collaboration in documenting growth in small business development in the region.

Norman R Scott

Norman R. Scott
Vice President for
Research and
Advanced Studies

Cornell University

Contents

AC Technology

C-MOLD

AC Technology licenses the technology developed at the Cornell Injection Molding Program (CIMP) that applies scientific principles to the plastic injection molding process. The company maintains an active research and development group and cooperative development agreements with industrial and academic research institutions. The company's technology, C-MOLD, is used worldwide by polymer suppliers, automakers, electronics manufacturers, mold and toolmakers, and molding machine manufacturers to design and produce high-quality plastic parts while minimizing time-to-market.

Cornell Connection

AC Technology was originally established to commercialize technology developed at CIMP. The company's president and many of its employees are Cornell graduates.

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V. W. Wang, Ph.D.

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1986

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