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A World Wide Assessment of Rapid Prototyping Technologies

January 1994

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This paper describes the results of a worldwide assessment of commercial rapid prototyping technologies that was initiated in the Intelligent Manufacturing Systems IMS Test Case on Rapid Product Development. Additionally, this paper will highlight the development of university-led rapid prototyping technologies.

Objectives:

The objectives of this assessment are:

- Characterize and differentiate the commercially available rapid prototyping technologies by identifying their economic factors and technical capabilities
- Benchmark the pre-processing, building and post processing time to fabricate a common part
- Provide a document on commercially available technologies for potential purchasers to use to compare and contrast the many systems and models available and,
- Provide a brief overview of university-led rapid prototyping research and development.

NOTE: The information contained in this assessment is dated to the Winter of '93-'94. The Rapid Prototyping industry has proven to be dynamic and in continuous improvement.

Table 1 is a listing of commercial organizations that were solicited for participation in this worldwide assessment.

Company	Location	Process
3D Systems	Valencia, CA U.S.	SLA
BPM Technology	Greenville, SC U.S.	Ballistic Particle Manufacturing - Jetting
C-MET	Tokyo, Japan	Solid Object Ultraviolet Plotter SOUP
C-MET	Stuttgart, Germany	Solid Object Ultraviolet Plotter SOUP
Cubital	Raanana, Israel	Solider - Masked Printing
D-MEC	Tokyo, Japan	Solid Creation System
DTM Corp.	Austin, TX U.S.	Selective Laser Sintering
EOS	Planegg, Germany	Electro Optical Systems
EOS	Stuttgart, Germany	Electro Optical Systems
E-Systems	Falls Church, VA U.S.	Jetting Technology
Helisys	Torrance, CA U.S.	Laminated Object Manufacturing
Laser 3D	Nancy, France	Stereophotolithography
Light Sculpting	Milwaukee, WI U.S.	Masked Printing
Mitsui Engr&Ship	Tokyo, Japan	Colamm
Soligen	Northridge, CA U.S.	Direct Shell Production Casting
Sparx AB	Molndal, Sweden	Hot Sparx
Stratasys	Eden Prairie, MN U.S.	Fused Deposition Modeling
Teijin Seiki	Kawasaki, Japan	Soliform
Texas Instruments	Plano, TX U.S.	Protojet - Jetting Technology
Visual Impact	Windham, NH U.S.	Jetting Technology

Table 1. -- Listing of commercial organizations solicited for participation in this assessment.

In order to meet the needs of this assessment, two common test parts were created to provide a variety of geometrical features. Each part measures 6-inches long by 4-inches wide. See figure 1.

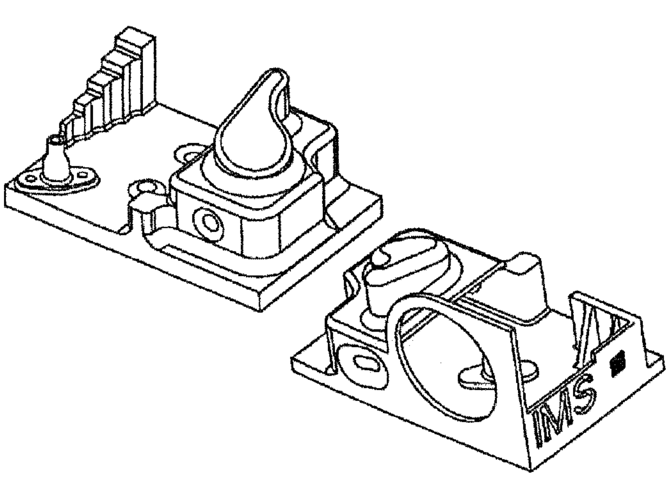

Figure 1 -- Isometric views of the test parts.

Background of Intelligent Manufacturing Systems:

The following background information was sent to the companies in Table 1to provide a basis for their decision to participate.

The principal objective of the IMS program is to conduct international pre-competitive R&D in advanced manufacturing. In 1993, the feasibility of such collaboration was tested by conducting six test cases on selected topics in advanced manufacturing. The organization of the IMS feasibility study has been put in place by an International Steering Committee, Technical Committee, and Intellectual Property Rights Committee, all composed of representatives from the six regions of IMS: Australia, Canada, European Community, European Free Trade Association, Japan and the United States.

Our test case on Rapid Product Development is focused on rapid prototyping, measurement and conversion technologies, the business practices associated with reduced product development cycle time, and multi-media communications. This work was conducted by 22 partners from four regions: Australia, Canada, European Community, and the United States. This project is being led by the following Coordinating Partners: Australia - Swinburne University of Technology, and the Queensland Manufacturing Institute; Canada - Pratt & Whitney Canada and Ecole de Technologie Superieure; European Community - Daimler Benz; and the United States - United Technologies Corporation.

Assessment of Rapid Prototyping Technologies:

We asked the rapid prototyping companies to fabricate four (4) copies of the test part with the IMS-T2 STL (see figure 1), file that was provided to them on 3-1/2" floppy disk. We also provided a fully dimensioned engineering drawing of the test part. In our evaluation, we conducted a dimensional inspection of the parts which they produced and shared the inspection results of their parts with them. However, the inspection results are to be held as proprietary information to the Coordinating Partners of the IMS test case listed above. The inspection results will not be publicized, nor will they be shared with other IMS test case participants. Additionally, we asked that the rapid prototyping companies complete the questionnaire forms and to provide a signature of a company officer in the validation section. The parts and the Rapid Prototyping Technologies Questionnaires were displayed at the IMS International Conference in Stuttgart, Germany on 31 January to 2 February 1994.

We provided the following conditions to maintain consistency among the companies in fabricating the test parts:

1. The 4 parts are to be fabricated directly from the STL files provided - no machining or manual polishing beyond removal of supports, bases, etc.
2. If the companies are required to *calibrate* their rapid prototyping process for the parts by making some iterative trial runs, we asked that they limit them to deliver the best 4 of 6 trials; however, we asked that they identify if and how many trial runs were required.
3. If their processes have "offset" capabilities to compensate for inaccuracies such as material shrinkage, laser beam-width compensation, etc., then we asked that they identify the parameters and numerical amounts (in all directions) used to produce the parts. We also asked that they identify the thickness of each layer.

4. We suggested that if they were unable to fabricate the parts, to please consider completing the questionnaire.

Participating companies in this assessment

Table 2 shows a listing of the responses from the solicited companies with a brief comment if they did not provide full participation.

Company	Location	YES	NO	Comments
3D Systems Inc.	Valencia, CA U.S.	■		1 test part provided
Helisys Inc.	Torrance, CA U.S.	■		2 test parts provided
Soligen Inc.	Northridge, CA U.S.	■		2 molds made at P&W
Stratasys Inc.	Eden Prairie, MN U.S.	■		
Cubital Ltd.	Raanana, Israel	■		
Laser 3D	Nancy, France	■		Questionnaire only
EOS GmbH	Planegg, Germany	■		Parts paid for by DB
C-MET	Sindelfingen, Germany	■		By Mercedes-Benz
D-MEC Ltd.	Tokyo, Japan	■		
Teijin Seiki Co.	Kawasaki-City, Japan	■		
BPM Corp.	Greenville, SC U.S.		■	
C-MET	Tokyo, Japan		■	
DTM Corp.	Austin, TX U.S.		■	
E-Systems	Falls Church, VA U.S.		■	
Light Sculpting Inc.	Milwaukee, WI U.S.		■	
Mitsui Engi&Ship Building	Tokyo, Japan		■	
Sparx AB	Molndal, Sweden		■	
Texas Instruments	Plano, TX U.S.		■	
Visual Impact Corp.	Windham, NH U.S.		■	

Table 2. -- List of responses from the commercial organizations solicited for participation in this assessment.

System and Maintenance Costs

The major economic factor associated with rapid prototyping is the cost of purchasing and maintaining the equipment. Currently, these rapid prototyping systems range in cost from $75,000 for a Stratasys FDM-1500, to $750,000 for a D-MEC JSC-3000. Table 3 shows a listing of available systems from the participating rapid prototyping companies including their system prices, annual maintenance fees, and training costs.

A series of charts are provided to compare the variety of issues related to these systems. The charts are annotated to assist in identifying the systems. Figure 2 shows a bar chart of the purchasing costs, and figure 3 shows the maintenance fees. Note that most of the companies offer a variety of options. For example, six machine options are available from 3D Systems, 3 from EOS and D-MEC, and 2 from Helisys, Stratasys, Cubital and Teijin Seiki. It should be noted that both Soligen and Laser 3D do not market their devices for purchase, but offer a licensing arrangement. Soligen provides their license in the U.S for $350,000 and for $450,000 in other world regions. Instead of a maintenance fee, they provide for a usage fee

Table 3

Company Name	Systems Available	Price USD	Annual Maintenance	* Notes	Training Days	Training Fees	Warranty Months
3D Systems Inc.	SLA-190/20	135k	5-10k	1	5	Included	12
	SLA-250/30	215k	5-18k		5		12
	SLA-250/40	250k	5-18k		5		12
	SLA-400	425k	5-30k		5		12
	SLA-500/20	495k	5-40k		5		12
	SLA-500/30	540k	5-40k		5		12
Helisys Inc.	LOM-1015	130k	12k	6	5	2.5k	12
	LOM-2030	230k	18k		5		12
Soligen Inc.	DSPC-1	350k	Usage fee	7	12	Included	Unlimited
Stratasys Inc.	FDM 1500	75k	5k	8	5	Included	3
	3D Modeler	198.3k	7k		10		3
Cubital Ltd.	Solider 4600	325k	67k	3	MPM -10	Included	6
	Solider 5600	550k	67k		DFE - 3		6
Laser 3D	SPL 1000/LSA	50k	0	9	5	0	
EOS GmbH	STEROS 300	290k	25k	5	5	Included	12
	STEROS 400	380k	30k		5		12
	STEROS 600	500k	40k		5		12
C-MET	SOUP-600	600k	80k	2	5	4.4k	12
D-MEC Ltd.	SCS-1000HD	500k	15k	4	6	12k	12
	JSC-2000	500k	15k		6	12k	12
	JSC-3000	750k	15k		6	12k	12
Teijin Seiki Co.	Soliform-300	350k	90k	5	3	Included	12
	Soliform-500	500k	90k		3		12

Table 3. Listing of available systems including their costs for annual maintenance and training, and warranty period.
Notes: 1)Variable depending upon coverage level, hotline support, user group meetings, application consulting, modem troubleshooting, 24 hour response time & S/W updates; 2) Incl. Laser, H/W & S/W Support; 3) S/W upgrades, repairs; 4) Laser not incl.; 5) Laser not incl.; 6) Incl. Laser; 7) $40/cm - $12/cm per verticle cm built; 8) H/W maintenance only as an optional purchase; 9) System price includes terminal unit S/W only, annual rental includes laser maintenance, operator and resin.

per vertical cm of shell built on a sliding scale from \$40/cm to \$12/cm. Laser 3D only provides a terminal unit and software and, for additional fees, builds the actual parts at their facility in Nancy, France.

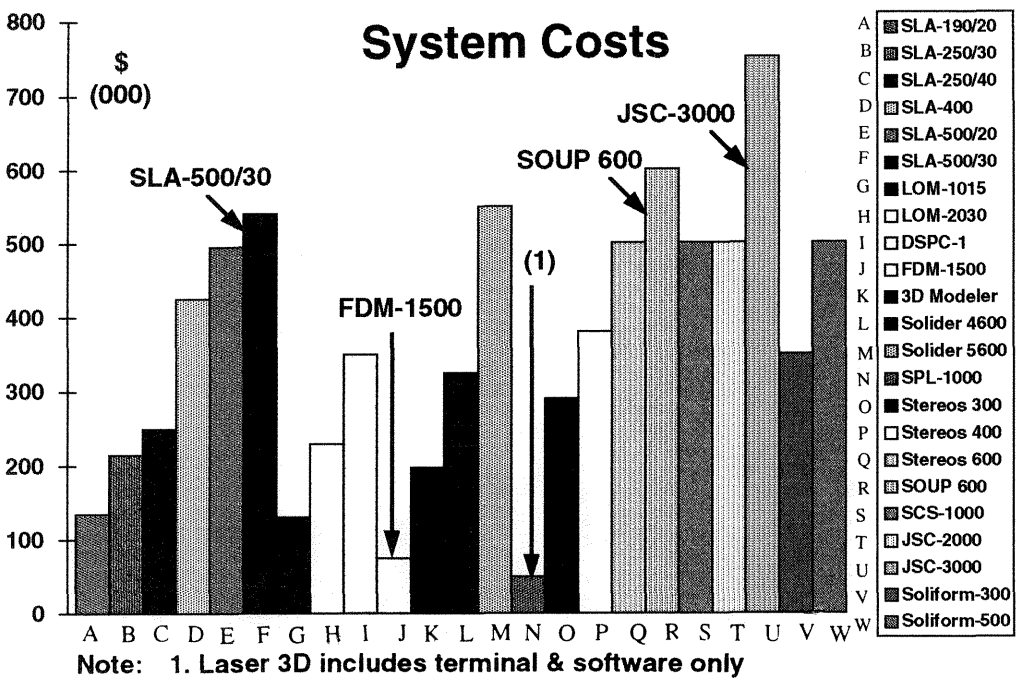

Figure 2 -- System costs are provided in thousands of U.S. dollars.

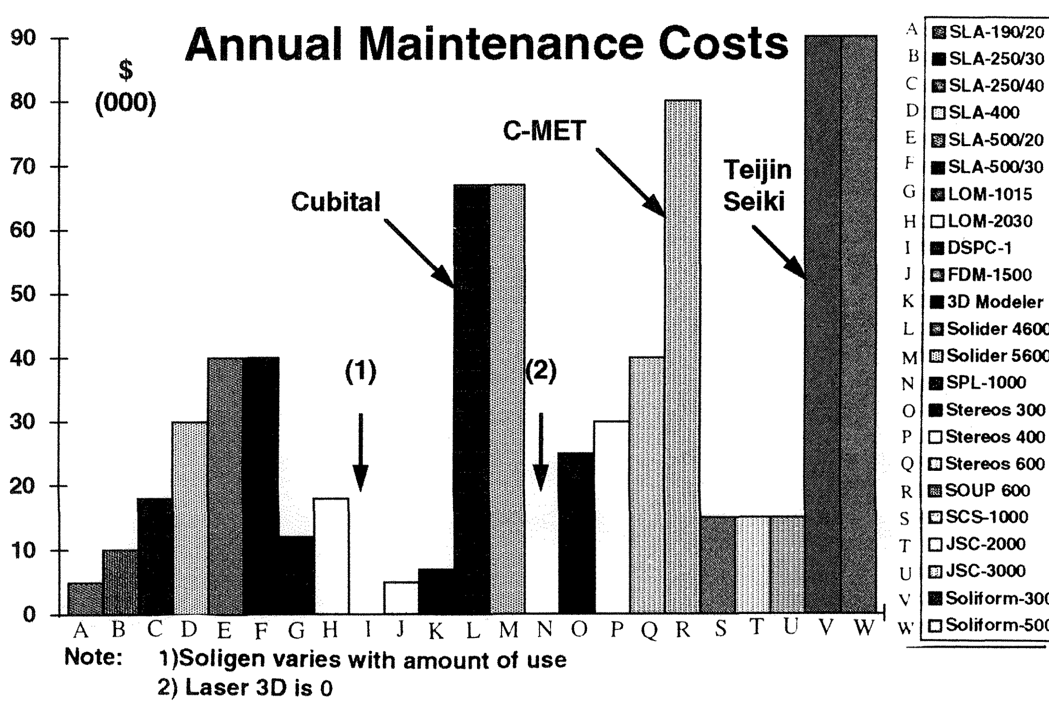

Figure 3. -- Annual maintenance costs.

Training Duration and Costs

Some of these rapid prototyping systems have varying degrees of complexity that impact the time required to understand and efficiently operate the systems. Figure 4 shows the training time required to operate the systems. While a majority of the companies provide training at no additional cost, figure 5 shows which companies require additional fees.

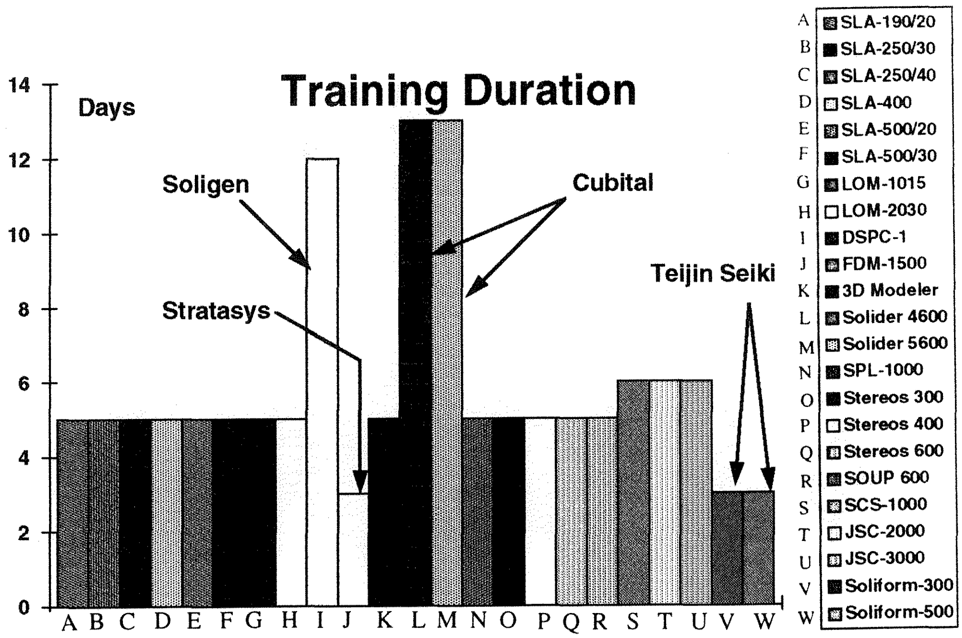

Figure 4. -- Time required for training in days.

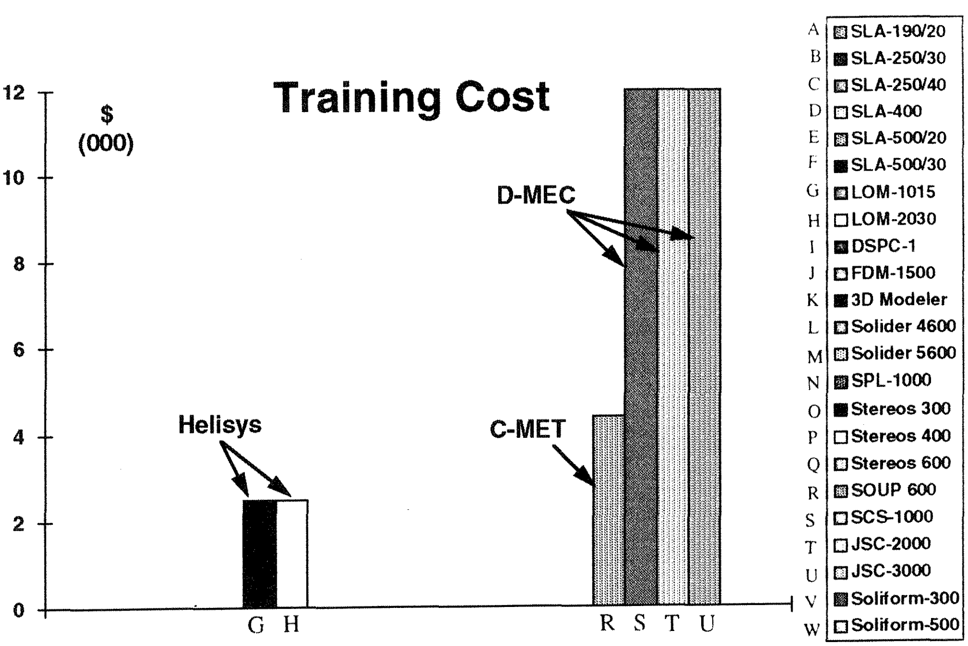

Figure 5. -- Companies requiring additional fees for training.

System Capacities and Limitations to Feature Sizes

The decision to purchase a particular model of a rapid prototyping system is often based on the size of parts it is capable of fabricating. Other factors that impact this decision are the capabilities to produce small internal feature sizes such as slots and holes, and fins or ribs for external features. Table 4 shows the various capacities and limitations to feature sizes for the different rapid prototyping machines. Figure 6 shows a chart of the maximum part building capacity in cubic centimeters.

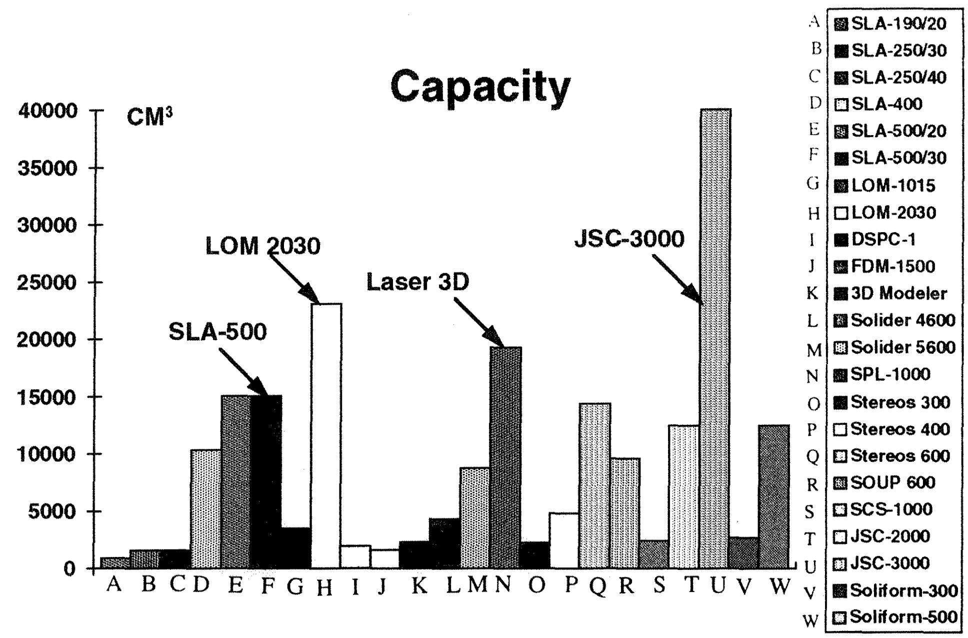

Figure 6. -- Maximum part building capacity.

Accuracy Issues

Accuracy is another key factor in deciding which rapid prototyping system to purchase. Experience has shown that the accuracy attainable in a particular part is often a function of its geometry. As can be expected, relatively small prismatic parts can be fabricated to a higher degree of accuracy than relatively large flimsy parts. The information on accuracy capabilities of the various rapid prototyping systems and models was provided by the manufacturers of the rapid prototyping equipment.

In the charts that follow on accuracy, keep in mind that the questionnaire requested "realistic accuracy expectations" on parts. The questionnaire listed a series of cubes ranging in sizes from small .5-inch, (1.27 cm) to large, 40-inches, (1m). Please note that the accuracies listed are "*claimed*" accuracies and are not related to the IMS test parts. Also note that the accuracy values are depicted in mm.

Figure 7 shows the accuracy expected to be achievable for a .5-inch (1.27 cm) cube part. Figure 8 shows the accuracy expected to be achievable for a 10-inch (25.4 cm) cube part. Note that some companies did not provide accuracy values.

Table 4

Company Name	Systems Available	Maximum Capacity mm	Minimum Ext.Feature Size mm	Minimum Int.Feature Size mm	Layer Thks Min/Max mm	System Resolution mm
3D Systems Inc.	SLA-190/20 SLA-250/30 SLA-250/40 SLA-400 SLA-500/20 SLA-500/30	1250/190/190 250/250/250 250/250/250 508/508/400 584/508/508 584/508/508	XY=.3-.4 Z. 1	XY=.05 Z .1	.1 -.9	XY=.007 Z .005
Helisys Inc.	LOM-1015 LOM-2030	254/381/355 559/813/508	.38	.25	..025 - 1.016	.0254
Soligen Inc.	DSPC-1	305/254/254	.38	.38	.177	.127
Stratasys Inc.	FDM 1500 3D Modeler	254/254/254 228/304/330	.254	.254	.05 - .76	.0254
Cubital Ltd.	Solider 4600 Solider 5600	350/350/350 500/350/500	XY=.6 Z.1	XY=.4 Z.1	.15 .1-.2	XYZ .1
Laser 3D	SPL 1000/LSA	500/550/700	--	--	.015 - .075	--
EOS GmbH	STEROS 300 STEROS 400 STEROS 600	300/300/250 400/400/300 600/600/400	.2x.25x.3 .2x.25x.3 .1x.1x.1	.1x.1x.1	..05 - .5	.01
C-MET	SOUP-600	600/400/400	XY=.2 Z.05	XY=.1 Z.6	.05-.3	XYZ .005
D-MEC Ltd.	SCS-1000HD JSC-2000 JSC-3000	300/300/270 500/500/500 1000/800/500	.1 .2 .3	.1 .2 .3	.03-.4	XY=.1 Z.01
Teijin Seiki Co.	Soliform-300 Soliform-500	300/300/300 500/500/500	.15	.3	.1 - .5	.254

Table 4 -- Listing of systems and their associated capacities for size and limits on feature size, etc.

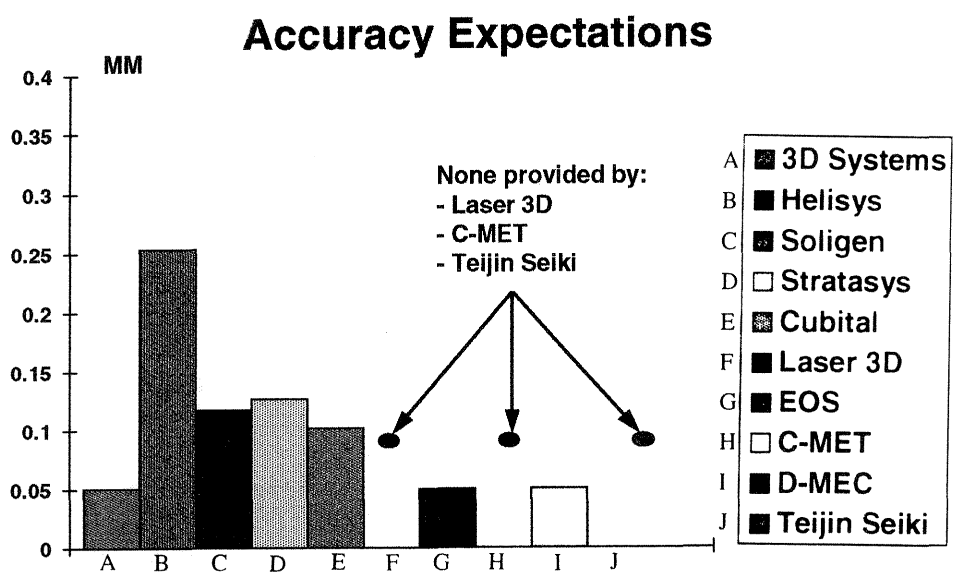

Figure 7. -- Accuracy expectations for a theoretical part measuring .500 inch cube or 12.7 mm cube.

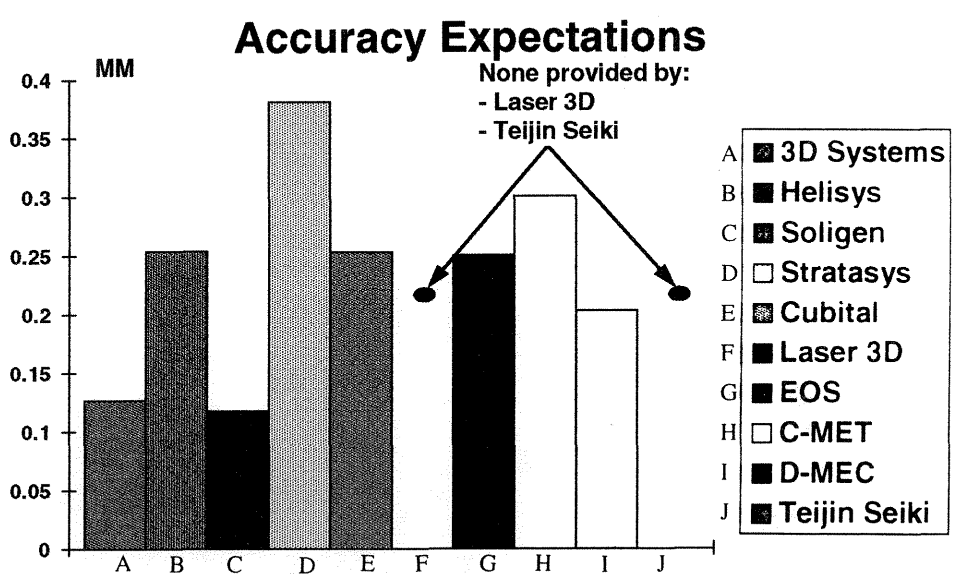

Figure 8. -- Accuracy expectations for a theoretical part measuring 10 inch cube or 254 mm cube.

<u>Specific Part Building Issues for Processing the IMS Test Parts:</u>

Pre-Processing Times

There are typically three phases to processing rapid prototype parts: 1) pre-processing, 2) building, and 3) post processing. During the pre-processing phase, the computer model, usually rendered in a 3-dimensional tessellated or faceted file format called a "STL file" from the originating CAD system, is read into the rapid prototyping device and reduced to very thin 2-dimensional sliced layers. These sliced layers are then used during the next "build" phase.

The following charts identify the "*actual*" pre-processing, building and post processing times required to fabricate the IMS-T2 test part. The time listed is in hours and the numbers on top of the columns indicate the number of parts processed in the given time. Figure 9 shows the actual pre-processing time. Note that all of the participating companies processed the IMS-T2 test part with the exception of Soligen. Pratt & Whitney processed a ceramic shell (mold) of the IMS-T1 test part at 1/2 scale on their Soligen "alpha" machine for Soligen. Also note that the C-MET time is long because of problems experienced at Mercedes Benz in processing the STL files.

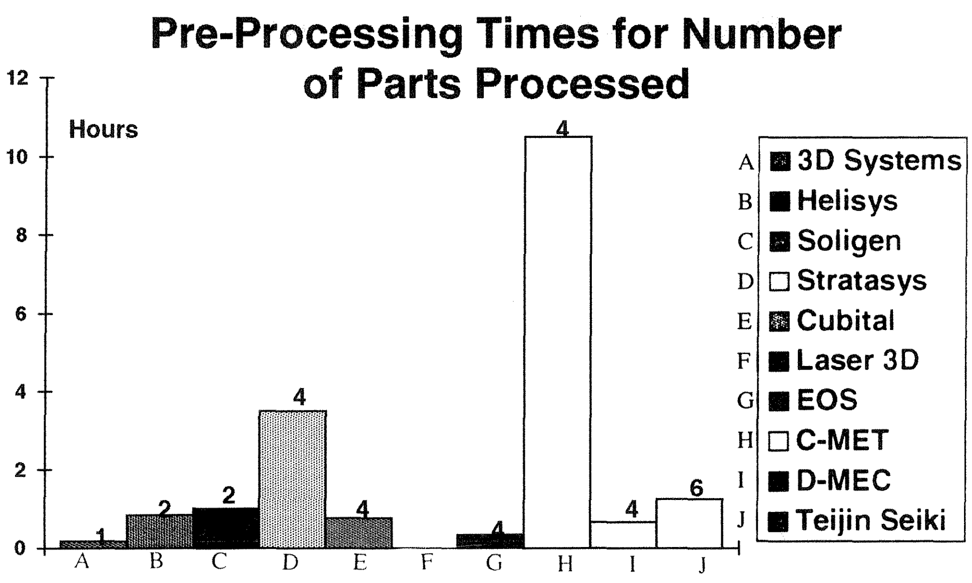

Figure 9. -- Actual pre-processing time for the IMS-T2 test part with the numbers of parts processed indicated on the columns.

Part Building Times

Building time is the time required to physically fabricate the part in the rapid prototyping system from the sliced data generated by pre-processing. In should be noted that in addition to building the part, additional structures such as supports may be required to support cantilevered features or "islands," which are later removed in the post processing phase.

Most of the systems including: 3D Systems (Stereolithography SLA), Laser 3D Stereophoto-lithography); Electro Optical Systems (EOS); C-MET (Solid Object Ultraviolet Plotter - SOUP); D-MEC (Solid Creation System, SCS); and Teijin Seiki (Soliform), produce parts using the computer controlled light from a laser to "draw" the outline of each sliced layer onto a vat of liquid photopolymer, thus causing a chemical reaction in the liquid photopolymer resin to change it to a solid wherever touched by the light, thus producing parts in photopolymer plastics.

The Cubital process also uses photopolymer plastic, but uses an ultraviolet flood lamp as the light source and a computer generated mask to localize the light where it's required. The Cubital process also includes a machining step to mill each layer flat, and uses a layer of wax as a support material for each layer, thus eliminating the need for additional support structures.

Helisys uses the heat from a laser to cut layers of paper in their Laminated Object Manufacturing (LOM) process, thus producing paper parts that look like wooden parts. Because each layer is fully supported, no additional support structures are required.

Soligen incorporates a jetting technology to "print" a liquid binder on a ceramic powder bed in successive layers to produce ceramic shells or molds for the investment casting of metal parts. The Soligen process is called Direct Shell Production Casting (DSPC).

Stratasys uses a heated nozzle to extrude a thermoplastic material in a layer by layer succession. This process lends itself to the use of a variety of materials, but also requires additional supports.

Figure 10 shows the actual building times required to fabricate the IMS-T2 test parts. Note that the wide variation can be due to the number of parts fabricated.

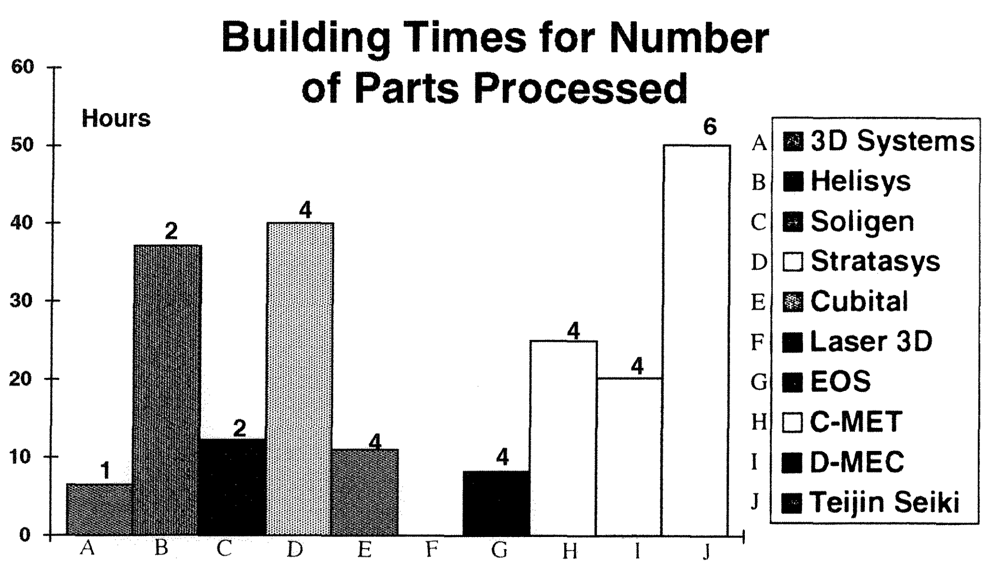

Figure 10. -- Actual building time for the IMS-T2 test part with the numbers of parts processed indicated on the columns.

Post Processing Times

The parts are removed from the rapid prototyping device and processed further during this phase. Typically, this includes the removal of supports that were required during the building of the parts, and can also include further curing, cleaning and perhaps hand finishing and polishing. Figure 11 shows the required post processing time to further cure and/or clean the parts after fabrication. As shown in figure 11, Cubital required more time then the others because of the need to wash away the suporting wax that is used in their process.

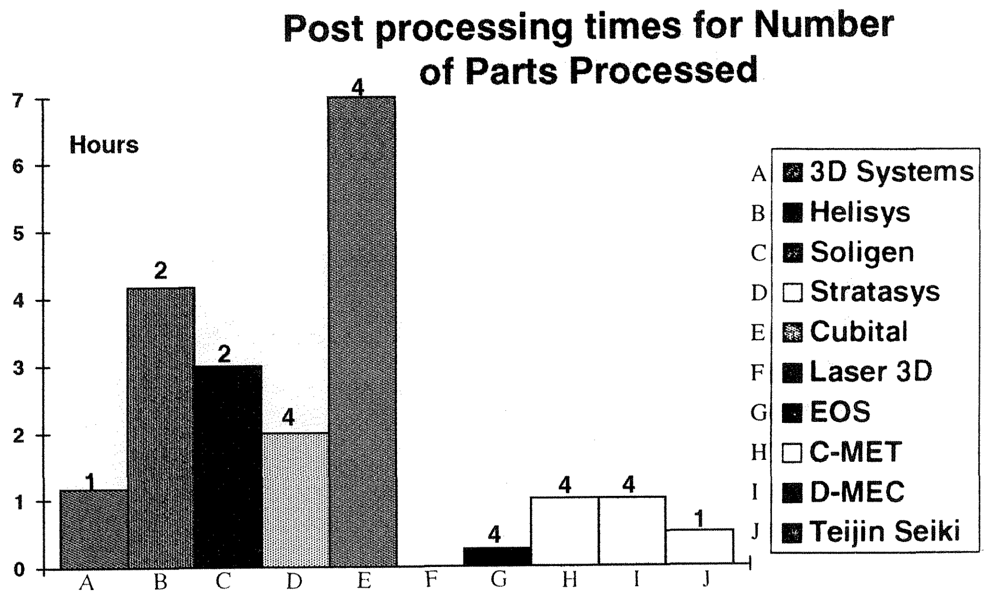

Figure 11. -- Actual post processing time for the IMS-T2 test part with the numbers of parts processed indicated on the columns.

Total Time to Fabricate the IMS Test Parts

Figure 12 shows the actual total time required to fabricate the test parts.

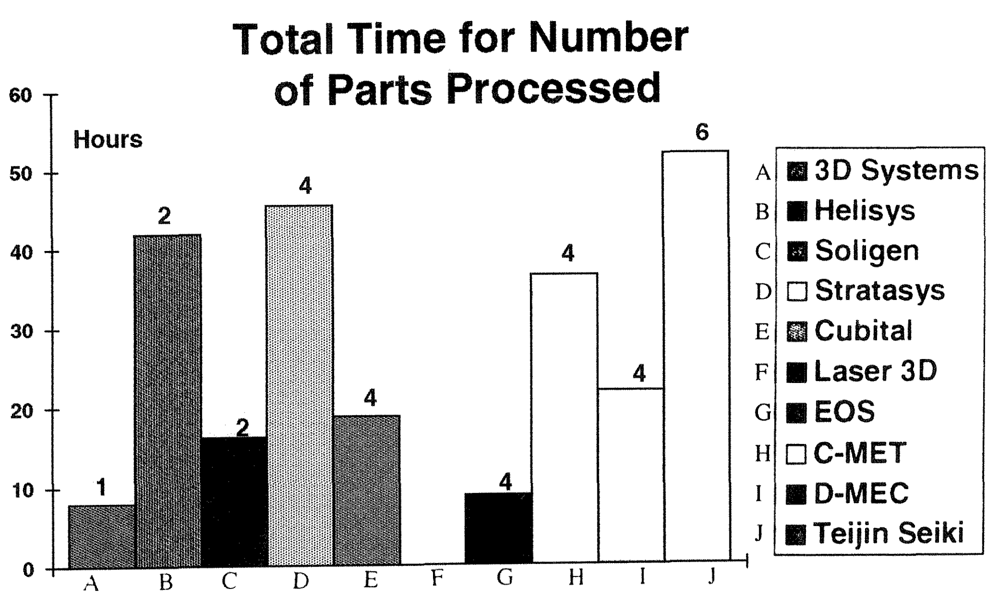

Figure 12. -- Actual total time for the IMS-T2 test part with the numbers of parts processed indicated on the columns.

As highlighted in figure 13, which captures all of the times required for the fabrication of the IMS-T2 test parts, the majority of time is required during the building phase.

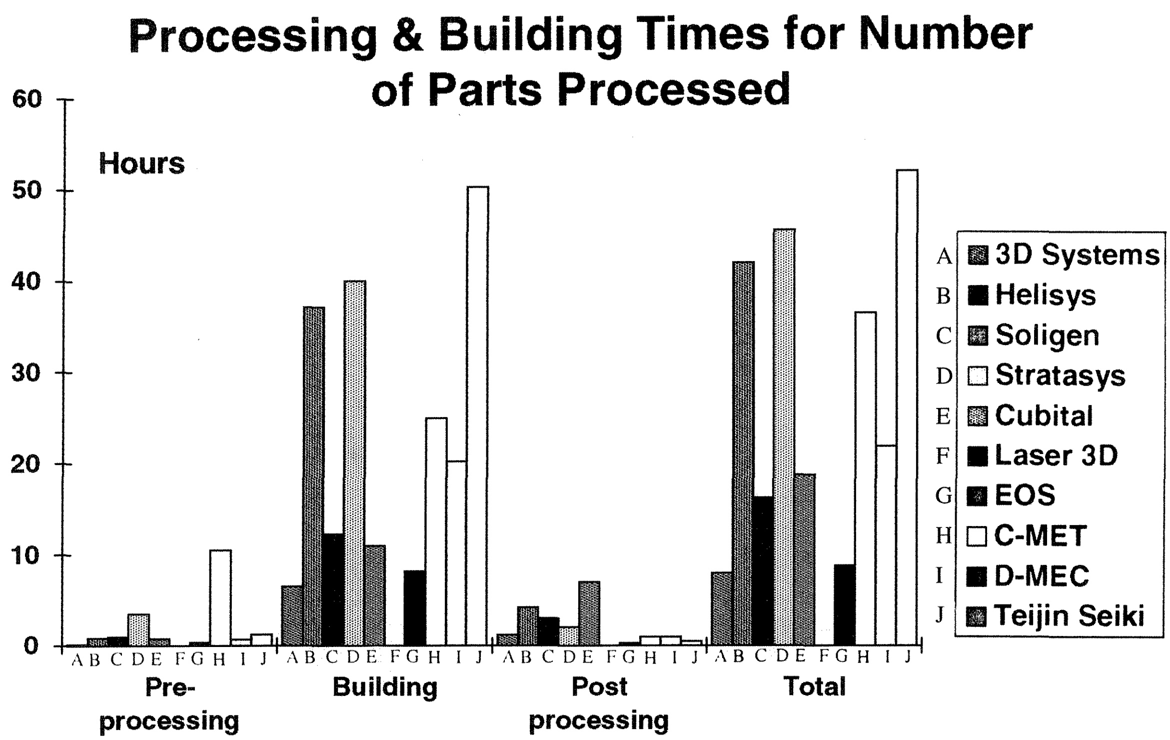

Figure 13. -- Actual pre-processing, building, post processing and total times for the IMS-T2 test parts.

Materials for Rapid Prototyping Systems:

The development of a variety of improved materials for rapid prototyping systems is one of the most significant issues to impact the applications of prototype parts and tooling. The improvements have led to increased accuracy and surface finish, which in turn can be applied to tooling applications in the form of molds and fixtures, or for conversion to make metal castings. Because some rapid prototyping systems can use a variety of materials, the opportunity to build parts that meet the end product material requirements is getting closer to being a reality. Table 5 shows the variety of materials currently available with their respective unit costs.

Company	Material Description	Cost per unit
3D Systems Inc.	XB 5081-1 Photopolymer resins XB 5139 XB 5143 XB 5149 XB 5131 XB 5154 XB 5170 (epoxy)	$145 per kg $150 per kg $160 per kg $165 per kg $140 per kg $145 per kg $170 per kg
Helisys Inc.	Paper coated with Polyethylene	$2-3 per pound
Soligen Inc.	Ceramic Powder Liquid Binder	$10 per Pound $100 per Gallon
Stratasys Inc.	Machinable wax (MW01) Investment casting wax (ICW04) Polyolefin (P200) Polyamide (P300)	$175 per spool $175 per spool $260 per spool $260 per spool
Cubital Ltd.	General purpose resin (G5601)	$65 per kg
Laser 3D	Dupont 5100 Photopolymer	$138 per kg
EOS GmbH	Dupont SOMOS 2100/3100/5100	$125 per kg
C-MET	Hard photopolymer HS 660 Semi rubber HS 661 Rubber HS 662	- cost not provided - -
D-MEC Ltd.	SCR-100 Urethane acrylate SCR-200 SCR-300 SCR-400 SCR-500	$150 per kg $150 per kg $150 per kg $150 per kg $250 per kg - SCS-1000 only
Teijin Seiki Co.	SOMOS 2100 SOMOS 3100	$190 per kg $190 per kg

Table 5.-- Listing of materials currently available for rapid prototyping.

University-led Rapid Prototyping Developments:

There are three prominent university-led programs in the area of rapid prototyping: Carnegie Mellon University, Massachusetts Institute of Technology (MIT) and the University of Texas. Each of these universities were charged with the challenge to fabricate copies of the IMS test parts using their technologies. The final 3 photographs in Appendix A show the IMS parts that were produced by these university developed technologies. .

Carnegie Mellon University - Shape Deposition

CMU is developing a "Shape Deposition" layered manufacturing process/system which combines the benefits of solid freeform fabrication, CNC milling, and thermal deposition. The strategy is to first slice the CAD model of the shape to be fabricated into layers and then deposit it as a near-net shape using thermal spray and/or molten droplet deposition. The layer is then shaped with a 5-axis CNC milling machine to net shape before proceeding with the next layer. In addition, each layer is shot-peened to control internal stress buildup.

An automated testbed facility has been implemented and a CAD-based process planner/controller has been developed for investigating the Shape Deposition manufacturing paradigm. This testbed configuration consists of four processing stations; CNC milling, thermal deposition, grit blasting/shot peening, and cleaning. The parts are built on pallets which are transferred from station-to-station using a robotic palletizing system. Each station has a pallet receiver mechanism. The part transfer robot places the pallet on the receiver which locates and clamps the pallet in place.

Carnegie Mellon University used their Shape Deposition process to make a Zinc alloy copy of IMS-T1. The part produced demonstrates that the technology is capable of fabricating metal parts directly; however, there is evidence of delamination. See Appendix A.

MIT - 3D Printing
The 3D Printing process under development at MIT creates parts in layers by spreading powder materials on a build platform and selectively joining the powder in the layer by inkjet printing a binder material. The platform lowers and the process is repeated. The process is being applied to the fabrication of expendable molds such as ceramic molds for castings, re-usable dies such as dies for injection molding and end-use parts such as structural metal and ceramic parts.

MIT made several copies of the IMS-T2 test parts in a ceramic material using their 3D Printing process, and also made several ceramic molds of the IMS-T1 test part. These molds were then used at Cercast to mold molten aluminum, thus producing aluminum test parts via a conversion process. The initial trials in making aluminum castings resulted in some "unfilled" areas that can be attributed to air pockets and/or mold temperatures being too cold causing the metal to freeze prematurely.

University of Texas - Selective Laser Sintering:
The University of Texas used their selective laser sintering process to fabricate copper-polymer copies of IMS-T1 test parts. These parts were then baked and infiltrated with an epoxy material for improved density. Although the sintered test parts show signs of warping and "curl," they also demonstrate that the technology has great potential to fabricate metal parts directly.

The results from these university led efforts provide an excellent opportunity to assess the leading-edge capabilities of these emerging technologies. Although further development is indicated, they have all demonstrated that metal parts-making directly from a computer model in a layer-by-layer process is going to be one of the leading approaches of advanced manufacturing.

Discussion:
The rapid prototyping market had evolved from one system availability in 1988, to over 30 systems today. These systems provide part building capabilities in a variety of sizes and materials. At first glance, the casual observer is easily overcome by the confusion of claims that these rapid prototyping developers make in marketing their systems. To date, there are primarily two types of enterprises that have invested in acquiring these rapid prototyping devices: medium to large corporations and service bureaus.

The medium to large corporations have maintained a lead in applying these rapid prototyping technologies to their product development processes. During the initial stages of using these new technologies, a fair amount of experimentation has occurred to find the *best fit* for these technologies. The service bureaus on the other hand have facilitated and promoted these technologies to meet the needs of a wide variety of industries from aerospace and automotive to bio-medical, healthcare and architectural. Further, there has been a growing propensity to apply these technologies to manufacturing and tooling applications.

During the past few years, a differentiation of these rapid prototyping technologies has evolved. In much the same way a typical home owner has a variety of tools for the various seasons, e.g., gardening and lawncare tools for the spring and summer, rakes for the cleanup of leaves in the fall, and snow removal tools during the winter months, today's industries are discovering where rapid prototyping technologies have niche applications. The rapid prototyping devices that are less expensive are also typically less accurate, perhaps not as fast (lower through-put) and build smaller parts. The more expensive equipment is typically more accurate, is faster and has greater through-put, and has larger part building capacities. The leading commercial enterprises that have successfully applied these rapid prototyping technologies can categorize the utility of rapid prototyping technologies in the following applications:

1. **Design verification**: The process of using rapid prototyping to fabricate the first physical object in order to verify the designer's intent. Design flaws often go undetected until the first article is produced. Using traditional approaches to prototyping means that part drawings, fixtures and tools were designed and the parts were then manufactured, days, weeks or months after the design was completed only to discover a design flaw when the first article was produced. With rapid prototyping, these design flaws can be detected very early in the design process without the investment of time and costs in drawings, fixtures and tools. This application simply requires a mock-up of the part with minimal concern for accuracy.

2. **Manufacturing producibility and supplier quoting**: Competition is driving the manufacturing of parts to be faster, have higher quality, and be lower in cost. When manufacturing can have a "say" early in the design cycle, they can provide their input to making the parts easier and at less cost. This insight can lead to significant advantages in the product development life cycle in reducing time to market and lowering costs. Further, when suppliers must quote time and cost to fabricate complex parts from drawings, they typically provide additional "padding" to cushion their quotes for unforeseen problems. However, when a physical article is provided along with the drawings for a quote, the supplier can get the "right" mix of people resources to review the part and drawing to derive a better, more time and cost effective quote. This application also simply requires a mock-up of the part with minimal concern for accuracy.

3. **Conversion technologies**: When a physical article is required that has the same physical and mechanical properties as the final part, a variety of conversion technologies can be employed to convert the rapid prototype article into a "final" article. Typically a rapid prototype model is processes and hand finished to be used as a "master" in a cloning operation such as RTV or silicone tooling, epoxy tooling, etc., where either the final plastic material is injected into the tool, or a wax is injected into the tools and used in the "lost wax" or investment casting process to produce a metal part in a variety of ferrous and non-ferrous metals. This

application requires a part that is more dimensionally accurate and has better surface finish characteristics than the previous applications.

4. **Tooling**: A growing application of rapid prototyping is to use the prototype article as a tool or fixture for the fabrication of a the final parts, e.g., making a rapid prototype mold, or a holding fixture for the machining or inspection of the final part. This application also requires a part that is more dimensionally accurate and has better surface finish characteristics than the previous applications.

Clearly, the most valuable outcome of this assessment is to actually see the IMS T2 test parts that were produced in this effort. The display of these parts provides the viewer with an appreciation for the variety of materials and surface characteristics that each of these different rapid prototyping technologies possess. See Appendix A for photos of these IMS test parts.

Conclusions:

The rapid prototyping industry has been evolving at a fast pace since 1987 when the first Stereolithography SLA-1 System from 3D Systems was introduced. During these past 5 years, significant improvements have been realized in stereolithography and other rapid prototyping systems in accuracy, surface finish and in application development. This proliferation of emerging rapid prototyping systems has, to some degree, created some confusion in the market place. With so many different systems available, it is difficult for potential customers and users to differentiate among the variety of systems. However, with time and users' experience, the analysis of this assessment clearly points to several conclusions:

- The less expensive rapid prototyping systems are an excellent choice for design verification applications that require parts of minimal dimensional accuracy or scaled sizes. These include parts that may be sub scale or oversize that are used to verify the designers intent.
- These less expensive systems can also be used for manufacturing producibility studies to get a "reality check" on the design from a manufacturing point of view.
- The systems that provide greater accuracy are the choice for fabricating "masters" and or "patterns" for conversion technologies such as investment casting and injection molding tooling.
- Tooling applications require "parts" that meet physical property and accuracy needs beyond the capabilities of design verification parts. These applications require stiffness and other characteristics to maintain utility for typical manufacturing applications. Examples include holding fixtures for manufacturing and inspection, and dies and mold halves for both direct and indirect conversion to metal.
- A host of yet-to-be discovered applications in a variety of industries surely exist. The users that are willing to take the "road less traveled" stand to gain much from using and deploying these technologies within their enterprises.

In summary, the tables, figures, charts and the actual IMS test parts provide a wide array of information that can be used to draw a number of conclusions. It is interesting to note that all of these different rapid prototyping developers are continually improving their capabilities. Some of these improvements in accuracy and surface finish are providing a dramatic impact in reducing product development cycle times and costs. Future enhancements to these systems will lead to even more savings by expanding the use and application of the parts produced by these systems Clearly, the industries that can effectively use and deploy these rapid prototyping technologies for their product lines will have the competitive advantage. The industries that are currently using these rapid prototyping technologies fully appreciate the benefits of "prototyping early and prototyping often."

Acknowledgment:

A special thank you is given to the officers of the participating companies that signed the questionnaires and provided the necessary resources to fabricate the IMS test parts; without their cooperation, this assessment would not have been possible.

Company	Name
3D Systems 26081 Avenue Hall Valencia, CA 91355	Mr. Chuck Hull - President Phone 805-295-5600 Fax 805-257-1200
Helisys, Inc. 2750 Oregon Court Bldg. M-10 Torrance, CA 90503	Mr. Michael Feygin Phone 310-782-1949 Fax 310-782-8280
Soligen, Inc. 19408 Londelius Street Northridge, CA 91324	Mr. Yehoram Uziel - CEO Phone 818-718-1221 Fax 818-718-0760
Stratasys Inc. 14950 Martin Drive Eden Prairie, MN 55344-2019	Mr. Scott Crump Phone 612-937-3000 Fax 612-937-0070
Cubital, Ltd. 13 Hasadna Street, Industrial Zone North Raanana 43650 Israel	Mr. Itzchak Pomerantz - Founder Phone 972-52-906888 Fax 972-52-919937
Laser 3D 6, Allee Pelletier-Doisy 54603 Villers-Les-Nancy CEDEX France	Mr. Claude Medard - Managing Director Phone 83-61-44-76 Fax 83-44-04-82
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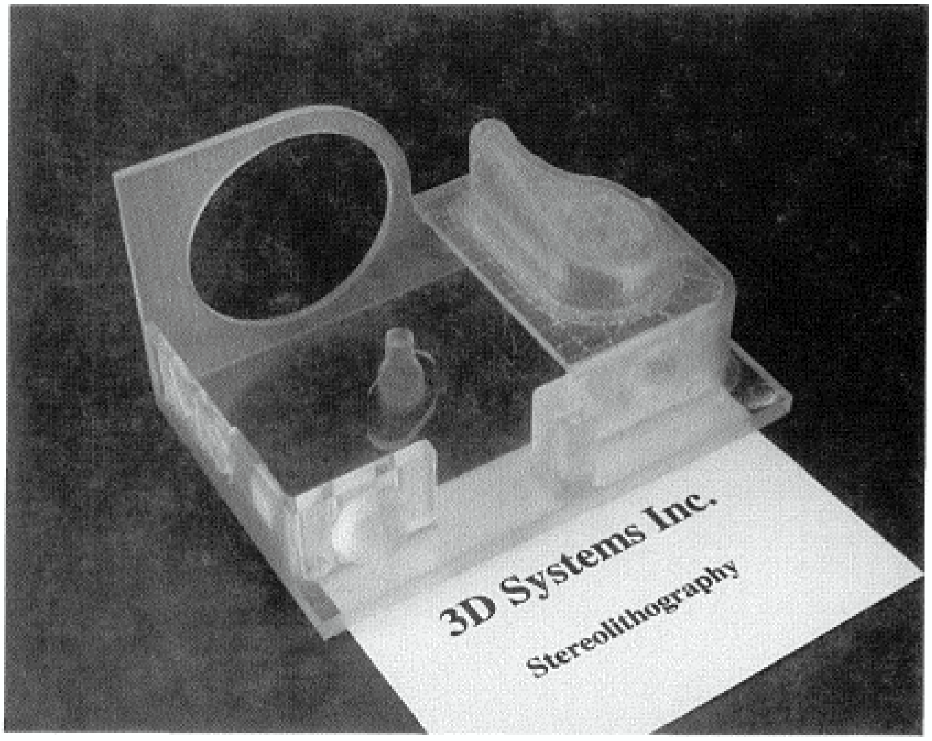
Tegin Seiki Co. Kanagawa Science Park 4Df, 2-1 3-Chome, Sakada Takatsu-Ku, Kawasaki-City 213, Japan	Mr. Kazuo Nakanishi - Office of Corp. Tech. Phone 03-3348-2185 Fax 03-3348-1050

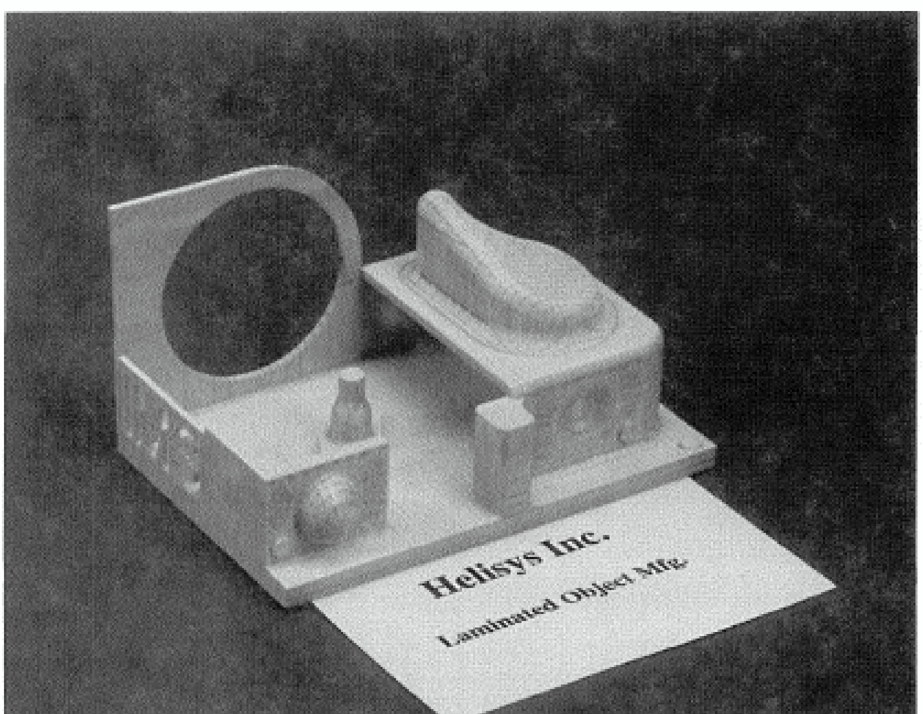
Appendix A - Photographs of IMS Test Parts

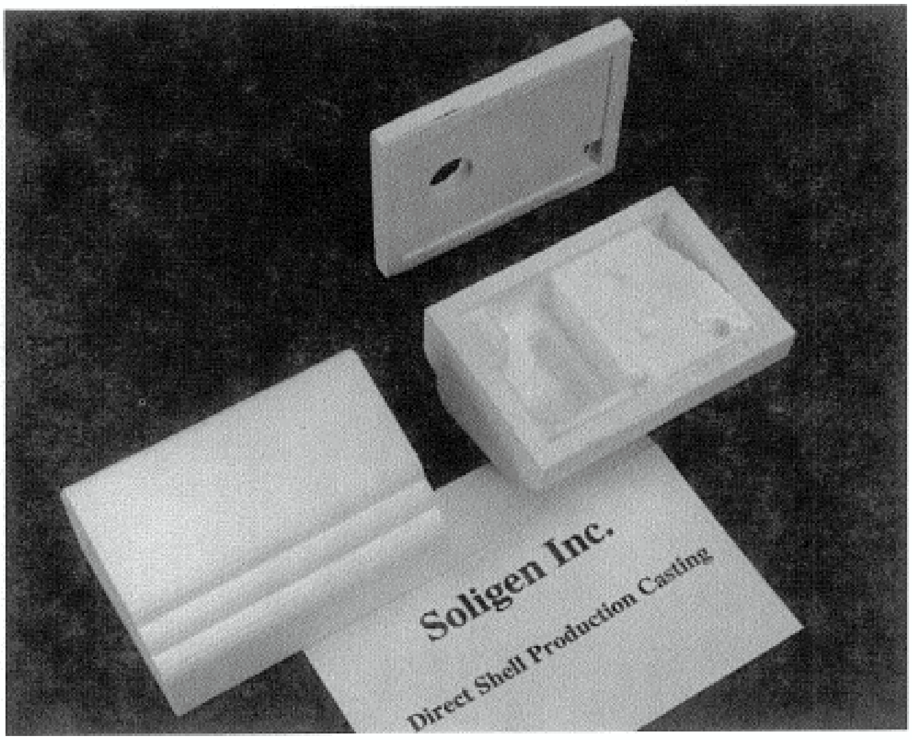
The photos on the following pages show the parts produced by the companies and universities that participated in the IMS Rapid Product Development test case:

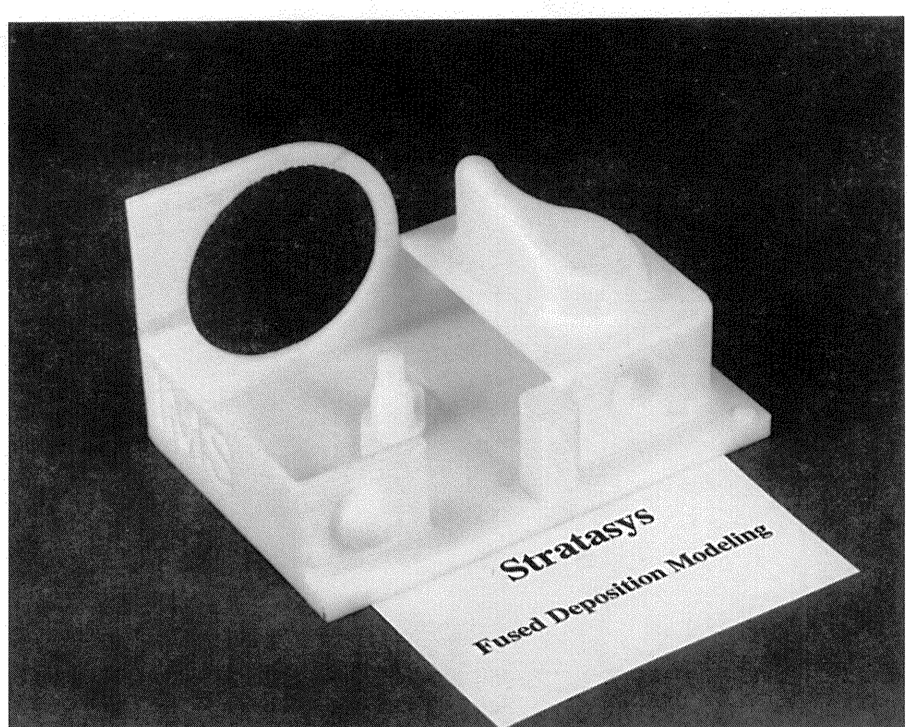
Company	Material & Description
3D Systems	Photopolymer IMS-T2 test part measuring 6" by 4"
Helisys Inc.	Paper " "
Soligen Inc.	Ceramic mold for half-scale IMS-T1 test part
Stratasys, Inc.	Polyolefin P200 IMS-T2 test part measuring 6" by 4"
Cubital Ltd.	Photopolymer " "
EOS GmbH	Photopolymer " "
C-MET	Photopolymer " "
D-MEC	Photopolymer " "
Teijin Seiki	Photopolymer " "

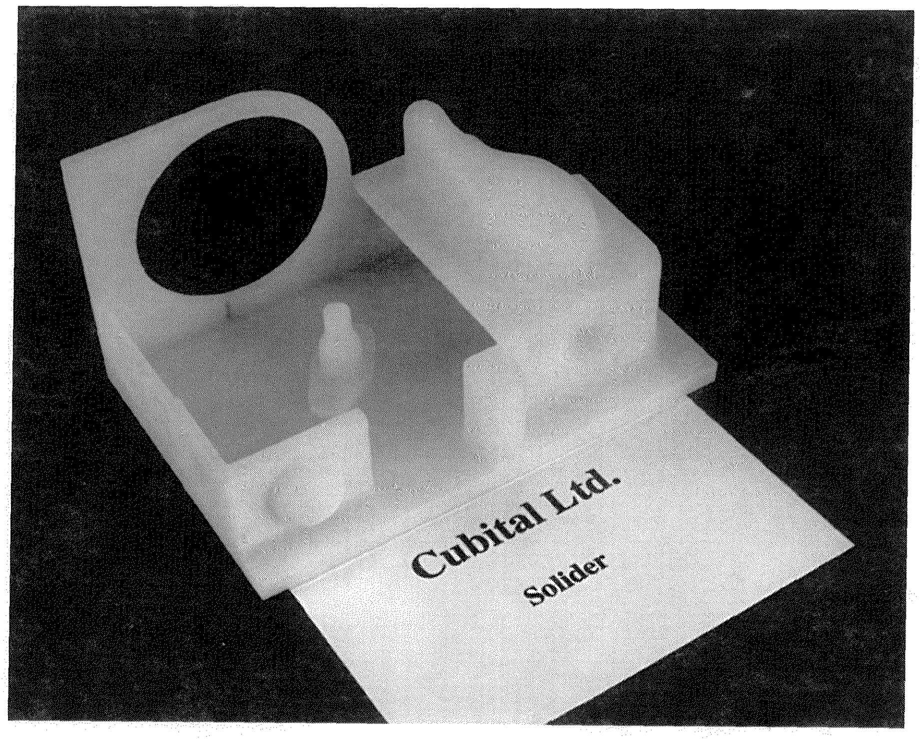
University	Material & Description
Carnegie Mellon University	Zinc alloy half-scale IMS-T1 test part
MIT	Ceramic 3/4-scale of IMS-T2 test part
MIT	Ceramic mold and Aluminum casting of half-scale IMS-T1
University of Texas	Copper-polymer half-scale IMS-T1 test part

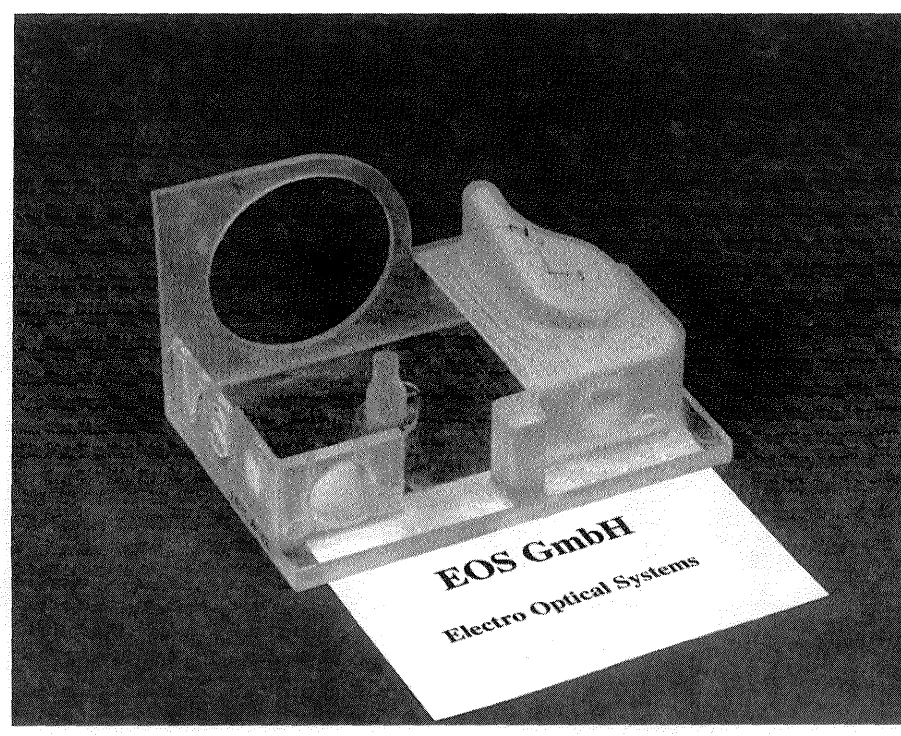

3D Systems Inc.
Stereolithography

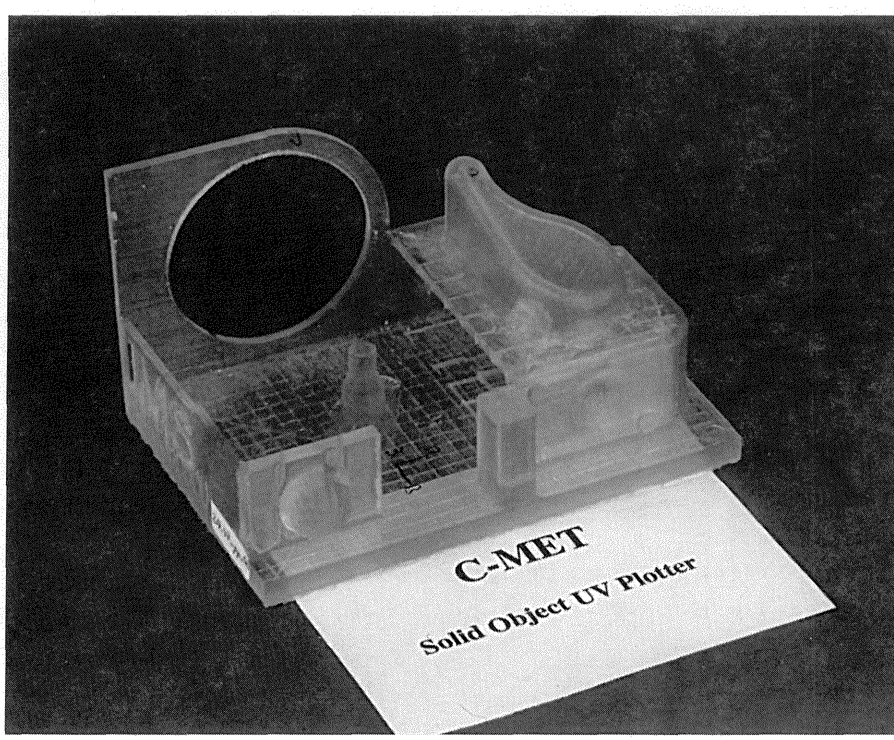

Helisys Inc.
Laminated Object Mfg.


Soligen Inc.
Direct Shell Production Casting

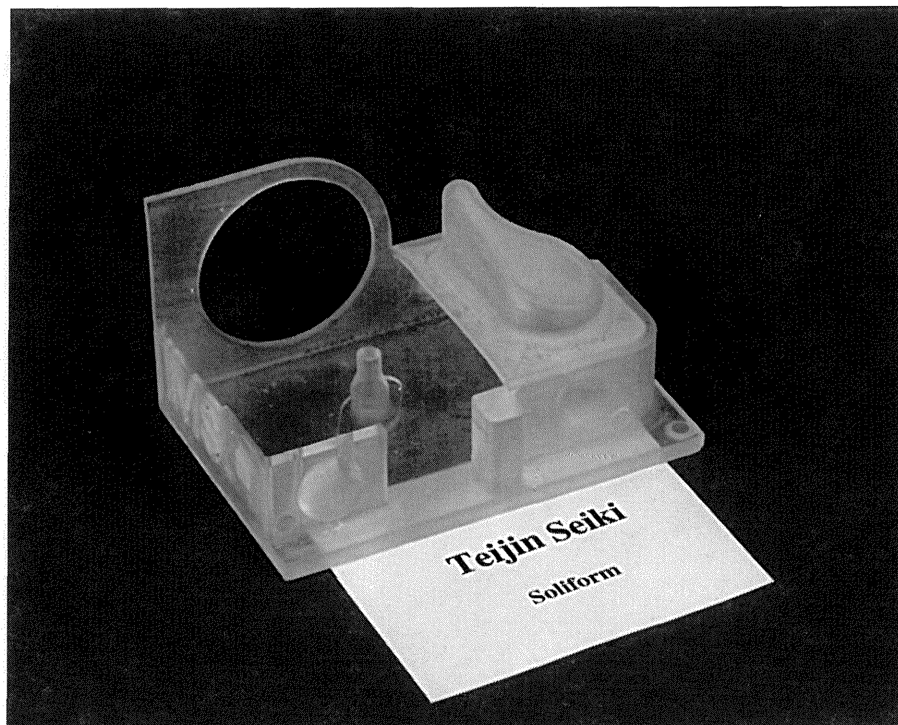

Stratasys
Fused Deposition Modeling


Cubital Ltd.
Solider

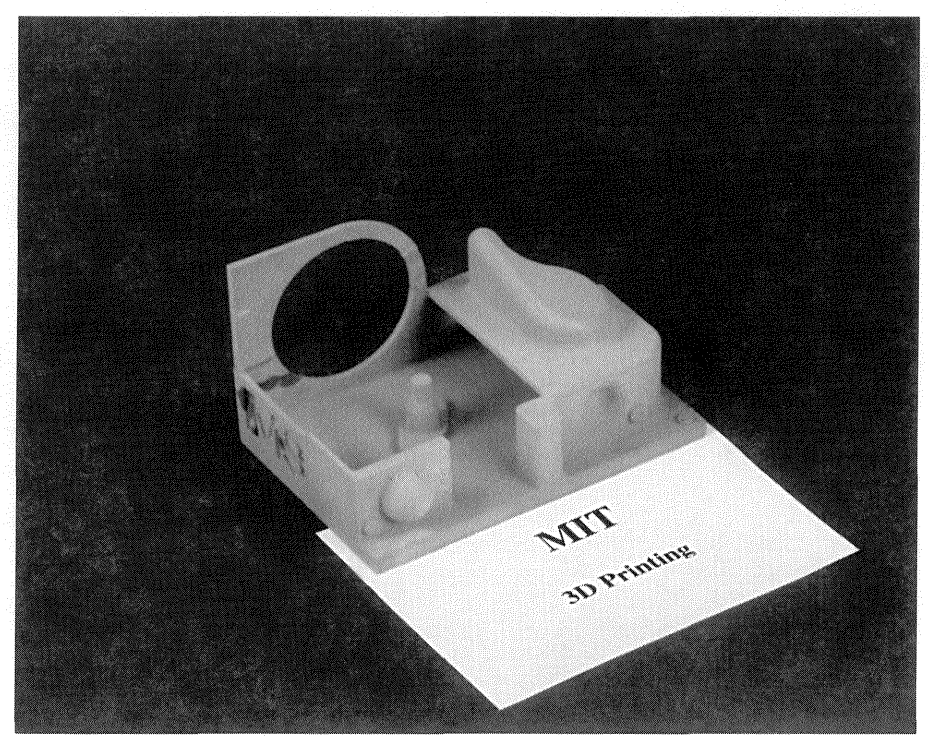

EOS GmbH
Electro Optical Systems

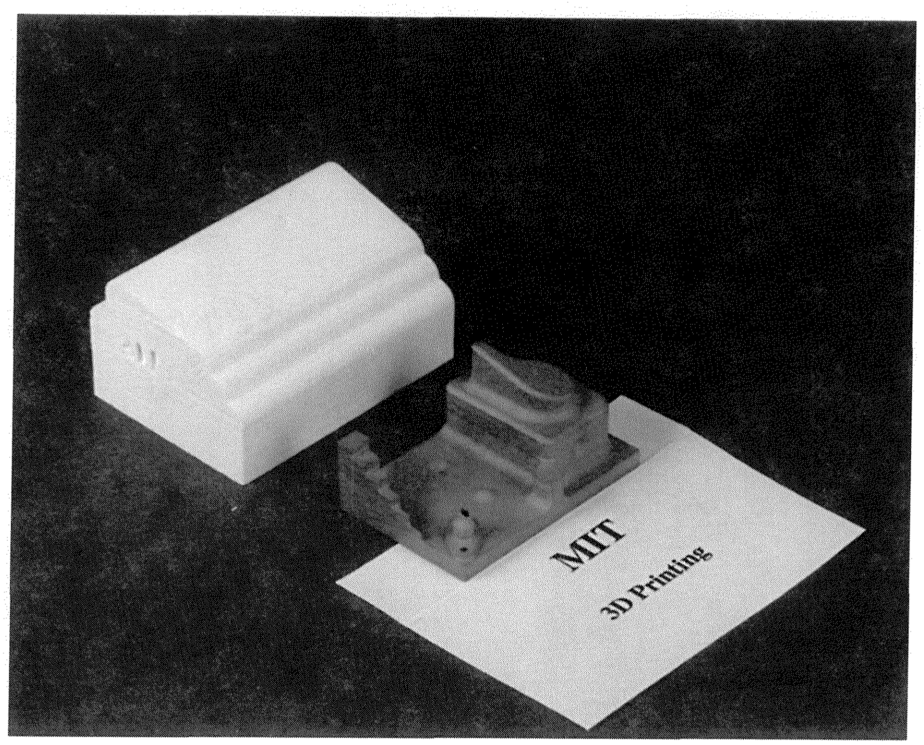

C-MET
Solid Object UV Plotter

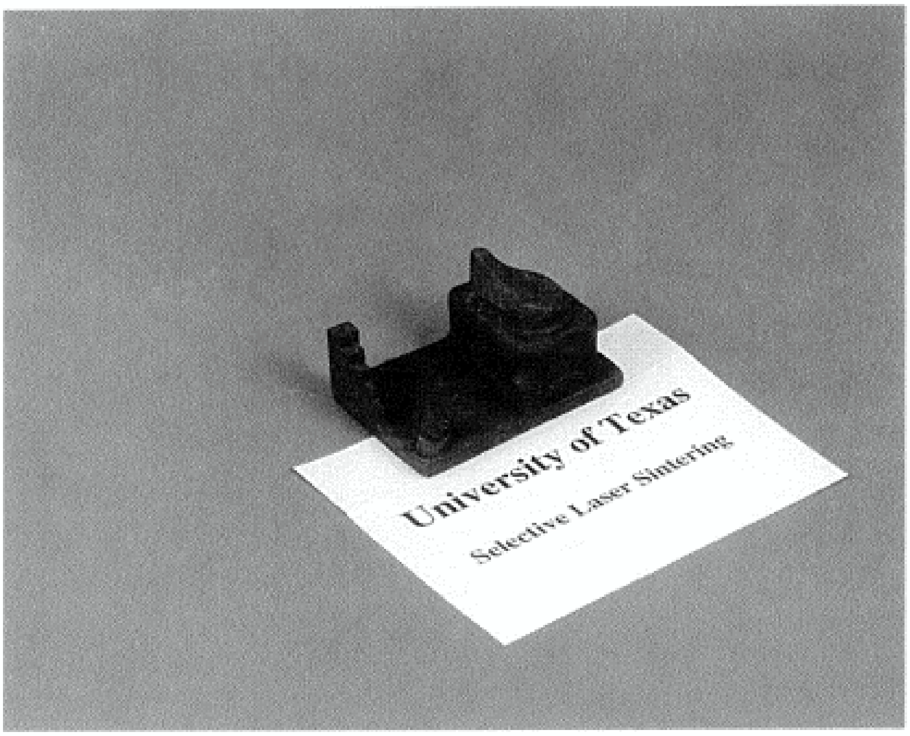

D-MEC Ltd.
Solid Creation System


Teijin Seiki
Soliform


Carnegie Mellon
Shape Deposition


MIT
3D Printing


MIT
3D Printing


University of Texas
Selective Laser Sintering