Quarterly Status Report No. 11
Report Period: February 1, 1997, through April 30, 1997
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# CT-ASSISTED SOLID FREEFORM FABRICATION

**Prepared by:**

James H. Stanley
Principal Investigator



**Prepared for:**

Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5660
Attention: Dr. Steven G. Fishman



**Reference:**

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**ADVANCED RESEARCH AND APPLICATIONS CORPORATION**
*425 Lakeside Drive • Sunnyvale, California 94086-4701 • (408) 733-7780 • FAX (408) 732-1996*

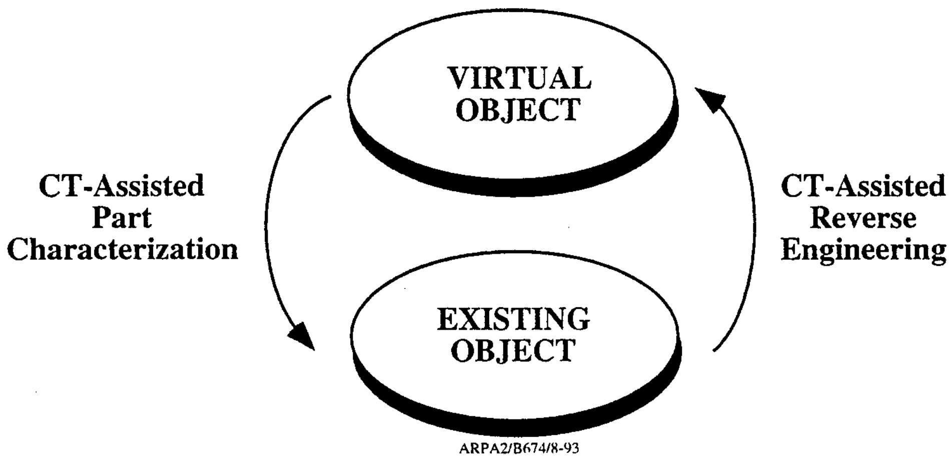
## 1.0 INTRODUCTION

Computed Tomography (CT) is a radiographic inspection method that uses a computer to reconstruct a cross-sectional image of an object from a set of in-line X-ray transmission measurements. CT was introduced in the early 1970's as a neurological examination technique and later extended to industrial applications by Advanced Research and Applications Corporation (ARACOR) and others. The original medical acronym, CAT, is still widely used and is likely to be familiar to the reader. The technology provides an ideal examination technique whenever the primary goal is to locate and size planar or volumetric detail in three dimensions. Because of the relatively good penetrability of X rays, as well as the sensitivity of absorption cross sections to the density and atomic number of matter, CT permits the nondestructive physical and, to a limited extent, chemical characterization of the internal nature of objects. And since the method is X-ray based, it applies equally well to metallic and non-metallic specimens, solid and fibrous materials, smooth and irregularly surfaced parts.

A key advantage of CT is that it can nondestructively obtain images of both exterior and interior surfaces and regions of an object. Because CT images are densitometrically accurate, complete morphological and part characterization information can be obtained without need for physical sectioning. With CT, complete 100% examinations can be obtained in a few hours, independent of part complexity. The data can be processed to create CAD representations of the part, to extract dimensional measurements, or to detect, size and locate defects. Current industrial CT systems have progressed to the point where they can provide dimensional measurements of a part with accuracies competitive with coordinate measuring machines (CMMs). However, unlike CMMs, CT systems can obtain thousands of measurements simultaneously, without special pre-programming, of internal as well as external surfaces, while also detecting flaws and defects. And because CT images are digital, they can be enhanced, analyzed, compressed, archived, retrieved, input to engineering calculations, and transmitted intramurally via local area network (LAN) or extramurally via the information super-highway.

As a result of these advantages, CT has emerged in the last few years as the leading modality for reverse engineering and part characterization applications. In 1988, the Air Force Wright Laboratory (WL) sponsored a Boeing-ARACOR team to investigate potential industrial applications of CT. Of the dozen or so generic areas studied, the use of CT for reverse engineering and part characterization was ranked as the most important industrial application of CT. The WL technical report, "X-Ray Computed Tomography for Casting Development" (WL-TR-92-4032), concluded that "areas which would benefit [from the use of CT] include internal dimensional measurements (eliminating destructive sectioning), specific region inspections, flaw characterization in critical regions (to allow passing or informed repair of castings), and geometric acquisition for CAD/CAM."

Like casting production, solid freeform fabrication (SFF) is also a near-net-shape technology. Thus, the above conclusions are as applicable to SFF practices as to castings. A model of the relationship between CT and SFF is presented in the figure. As illustrated, CT can be used to create "virtual objects" from existing objects. The process of scanning a part, extracting part contours from a CT image, and converting the data to a CAD-compatible format is commonly referred to as CT-assisted reverse engineering. Conversely, when a part is fabricated from a CAD model, CT can be used to nondestructively examine (NDE) the end product. The process of CT scanning a part, extracting defect and dimensional data from an image, and generating a variance report is commonly referred to as CT-assisted part characterization. Together, CT-assisted reverse engineering and part characterization form a complementary pair. Both are essential elements of a powerful dynamic with the ability to drive and accelerate the development of SFF equipment, methods and processes.




**CT-Assisted Solid Freeform Fabrication.**

## 2.0 PROGRAM OBJECTIVES

In response to the Advanced Research Projects Agency (ARPA) Broad Area Announcement (BAA) 93-24, "Solid Freeform Manufacturing," ARACOR successfully proposed the development and demonstration of CT-assisted solid-freeform fabrication practices. The project will provide critical reverse engineering and part characterization functions common to all ARPA-sponsored SFF activities. The goal is to facilitate the timely transition of CT-assisted reverse-engineering, dimensional verification and defect detection practices to the SFF community. To meet this goal, the following major technical objectives have been established:

- *Develop application software to make CT-assisted manufacturing practices available to the SFF community.* The application will run on a variety of common workstation platforms, accept data from different CT scanners, and output results in various formats to facilitate reverse engineering, dimensional verification and report generation. The SFF software tools will be derived from existing capabilities previously developed for the investment casting industry and from capabilities defined during interactions with other BAA participants.
- *Provide the SFF community access to CT-assisted reverse engineering, dimensional verification, and defect detection services.* Through ARPA, BAA participants will be able to request access to CT scan and analysis services. Access to high-resolution (< 25μ) CT scans will be provided for structural ceramics and other composites needing high-definition nondestructive evaluation (NDE) imaging, and access to high-energy (~9 MV) CT scans will be provided for metallic and other components needing large-structure NDE imaging. CAD, dimensional and defect information will be extracted from image data by ARACOR and provided to other BAA participants.
- *Transfer CT-assisted manufacturing practices to the SFF industry by beta siting application software and training users in its operation.* The SFF application software will be installed at beta-site locations designated by ARPA and recipients instructed in its use. As directed by ARPA, ARACOR staff will travel to BAA participant sites to demonstrate the extraction and analysis of CT-derived data with the proposed SFF application software.

## 3.0 WORK PLAN

The Work Breakdown Structure (WBS) for the above activities comprises the following three technical and one management tasks:

<u>Task 1. Develop CT-Assisted SFF Software Application.</u> ARACOR shall develop a software package to make CT-assisted SFF manufacturing practices universally accessible to system-level designers. First, ARACOR shall integrate existing ARACOR reverse engineering and dimensional verification tools into a pre-commercial version of a software application that can run on a variety of common workstations (WBS 1.1). At a minimum, versions which run on Silicon Graphics, Sun and IBM workstations will be developed. Following that, ARACOR shall develop and integrate advanced analysis tools specially for composites produced by SFF techniques into the application (WBS 1.2). The application will allow users to input CT data from a variety of CT systems and output results in formats suitable for reverse engineering, dimensional verification and report generation purposes. The application will feature an intuitive graphical user interface and

networking capabilities for transferring data between workstations. Task 1 will run through years 1 and 2 and will be complete when the beta-site version of the application is ready for release.

Task 2. Provide Access to CT-Assisted Manufacturing Services. ARACOR shall provide CT-assisted reverse engineering (WBS 2.1), dimensional verification (WBS 2.2) and defect detection (WBS 2.3) services to the SFF community. Access to high-resolution and high-energy CT scan services are included. The work plan proposes that all requests for services will be directed to and approved by ARPA. The work plan assumes that the demand for analysis services will concentrate in the first two years while the SFF application software is being developed and will decrease during the third year once other BAA participants are provided beta-site versions of the necessary CT software tools (see Task 3). The work plan also assumes that scan services will be provided throughout the three-year SFF program to support third-year technology insertion efforts. Task 2 will be complete when the level of effort budgeted for these services has been expended.

Task 3. Transition CT-Assisted Practices to Industry. ARACOR shall install the software application at beta sites specified by ARPA and train participants in the use of CT-assisted SFF practices (WBS 3.0). Up to three beta-site locations for the application may be selected. The work plan proposes that CT scan data be provided as part of Task 2 and that ARACOR travel to participant sites to provide on-site training and assistance in the application of CT-assisted flaw detection, dimensional verification and reverse engineering practices. At ARPA's direction, ARACOR will provide up to twelve trips for staff specialists to BAA participant sites to assist with the analysis of the scan data and to train designers in the use of the software. This will have the added benefit of providing ARACOR direct pre-commercial-release feedback from the SFF industry about the performance of the product. Task 3 will run during the third year and will be complete when the level of effort budgeted for these activities has been expended.

Task 4. Manage Program and Prepare Reports. ARACOR shall provide program management (WBS 4.1) for the duration of the contract and shall satisfy the contract data requirements list (CDRL) associated with the program. In particular, ARACOR will submit Quarterly Progress reports (WBS 4.2) and a Final Report (WBS 4.3) in the company's standard format. The sole deliverables associated with this program are beta versions of the software application, the quarterly Progress Reports, and the Final Report.

## 4.0 EXECUTIVE SUMMARY FOR REPORT PERIOD

- The development of ARCHIMEDES v2.0 continued (WBS 1.2).
- The tenth quarterly report was submitted (WBS 4.2).

# 5.0 TECHNICAL DISCUSSION

Task 1.2. ARCHIMEDES v2.0

Task 1.2.1, Constituent Module, has been rescheduled to begin in June 1997. Morphological filters will be developed to help segment low-contrast features.

Task 1.2.2, Metrology Module, is complete. A variety of measurement tools were added to ARCHIMEDES. Over a hundred classes for calculating parameters associated with lines, circles, and boxes were created. A text window component has also been created so that results can be reported to a text window.

Task 1.2.3, Porosity Module, is complete. Statistical tools for characterizing low-contrast features have been added. Segmented low-contrast features can be viewed in a new 3-dimensional viewer, the Multi-Material Viewer.

Task 1.2.4, Reinforcement Module, is 30% complete and is expected to be completed in July 1997. This task is adding second-order statistical tools to aid in the detection of textures and patterns associated with the distribution of reinforcements, like fibers and whiskers. New classes for integrating existing ARACOR libraries containing some of these tools are being designed.

Task 1.2.5, Convert DXF to NURBS, is complete. Under this task, we implemented the capability to convert point representations of contours to continuous curves in NURBS (Non-Uniform Rational B Splines) format. A stack of 2D contour points can be displayed in 3D in the Model Viewer. The C++ classes for reading and writing IGES files have been implemented and tested.

Task 1.2.14, Add Medical Format, has begun. We have investigated the nature and scope of the DICOM standard from the American College of Radiology and have found it to be very comprehensive and elaborate. It is relevant here, because this international standard for communicating digital images in medicine is being promoted for industrial applications as well. However, we do not have enough remaining resources to learn how to program this standard. We are investigating the availability of external consultants and/or software libraries to provide us with a basic capability to read DICOM files.

Task 1.2.15, Testing and Release, is approximately 75% complete. This task began in October 1996 and is expected to be completed in July. It originally included adding progress bars, data preprocessing and scaling, and other tasks deemed essential to the use of ARCHIMEDES 2.0 in an engineering environment. Many of these tasks have been completed; one in particular is worth noting. During testing, we found that the image display was slow; so we optimized the code to obtain a 63% speedup. Substantial speedups have also been realized in reading and displaying large STL files ($\approx$ 4 million triangles).

Task 2. Manufacturing Services

Under Subtask 2.1, Reverse Engineering, the level of effort set aside for this task has been expended. This subtask is now complete.

Under Subtask 2.2, Dimensional Verification, a study of the dimensional accuracy of ARCHIMEDES continued with minimal progress due to the lack of available staff. To date, the basic methodology for analyzing dimensional accuracy has been set up and largely automated. Scan data has been obtained on several systems and the analysis of the data started. This task will be completed this quarter.

Subtask 2.3, Defect Detection, is complete. A way to capture defect data in digital format and link it to standard FEA software was developed.

Task 3. Technology Transfer

The level of effort set aside for this task has been expended. Except for providing beta-site copies of ARCHIMEDES to interested parties, this task is complete.

Task 4. Management and Reporting

Program management continued; the tenth progress report was submitted.

## 6.0 ANTICIPATED ACTIVITIES FOR NEXT REPORT PERIOD

- Development of ARCHIMEDES v2.0 will be completed.
- Dimensional verification will be completed.
- The Draft Final report will be prepared and submitted.

## 7.0 COST AND PERFORMANCE STATUS

The program will finish ahead of schedule and within budget. Quarterly and cumulative man-hours and funds expenditure data, along with outstanding commitments, through the current reporting period are shown by task in Table A. The Program Schedule is shown in Figure A. The Funds Expenditure Graph, showing the planned-versus-actual total-dollar expenditures, is presented in Figure B. The Work Completed Graph, showing planned-versus-actual earned-value milestones completed, is presented in Figure C. Following that is the Cost/Schedule Status Report (C/SSR). The percentage of total contract dollars that the expenditure to date represents and the percentage of total work that the technical completion represents are given in the C/SSR. Along with the C/SSR, variance analysis reports have been prepared for variances greater than 10% of the cumulative work scheduled. The Latest Revised Estimates (LREs) are generated as needed from a bottoms-up re-costing.

**Table A. Current and Cumulative Expenditures.**

Prime Contract: N00014-94-C-0120

Contract Award: $1,263,853

Authorized Funding: $770,803

Period of Performance: February 1, 1997, through April 30, 1997

Submission Date: May 30, 1997

| WBS | Billings | | Hours | | Open |
|---|---|---|---|---|---|
| | Per. | Cum. | Per. | Cum. | Commitments |
| 1. Software Development | $74,929 | $860,542 | 500.5 | 5,937.0 | $0 |
| 2. Manufacturing Services | 9,980 | 99,236 | 65.5 | 799.5 | $0 |
| 3. Technology Transition | 0 | 94,945 | 0.0 | 492.0 | $0 |
| 4. Program Management | 8,931 | 120,075 | 53.0 | 715.0 | $0 |
| Total | $93,840 | $1,174,798 | 619.0 | 7,944.0 | $0 |
| Contract Amount | | $1,263,853 | | 7,312.0 | |
| Percent Complete | | 93% | | 108% | |

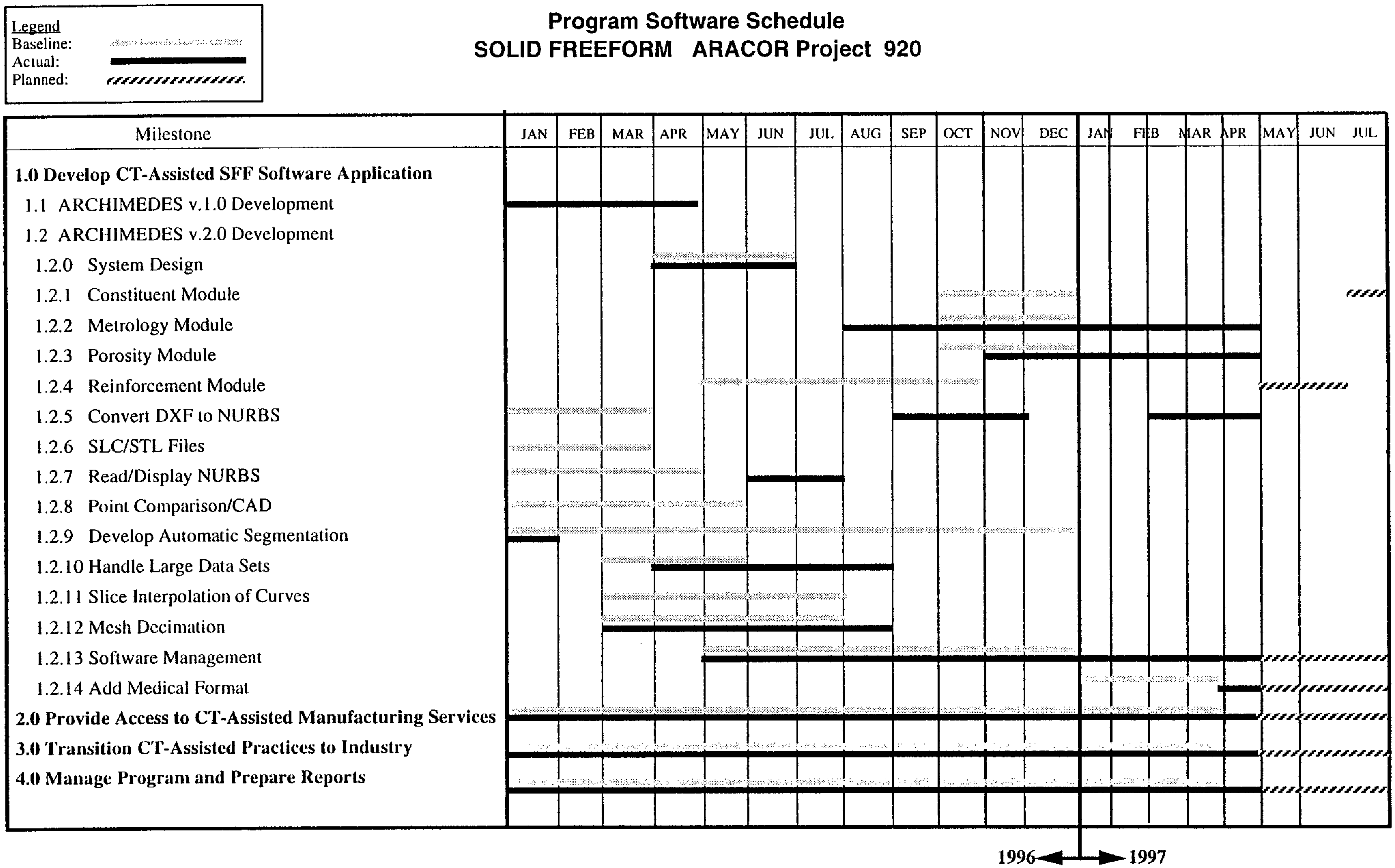



**Figure A. Program Schedule.**

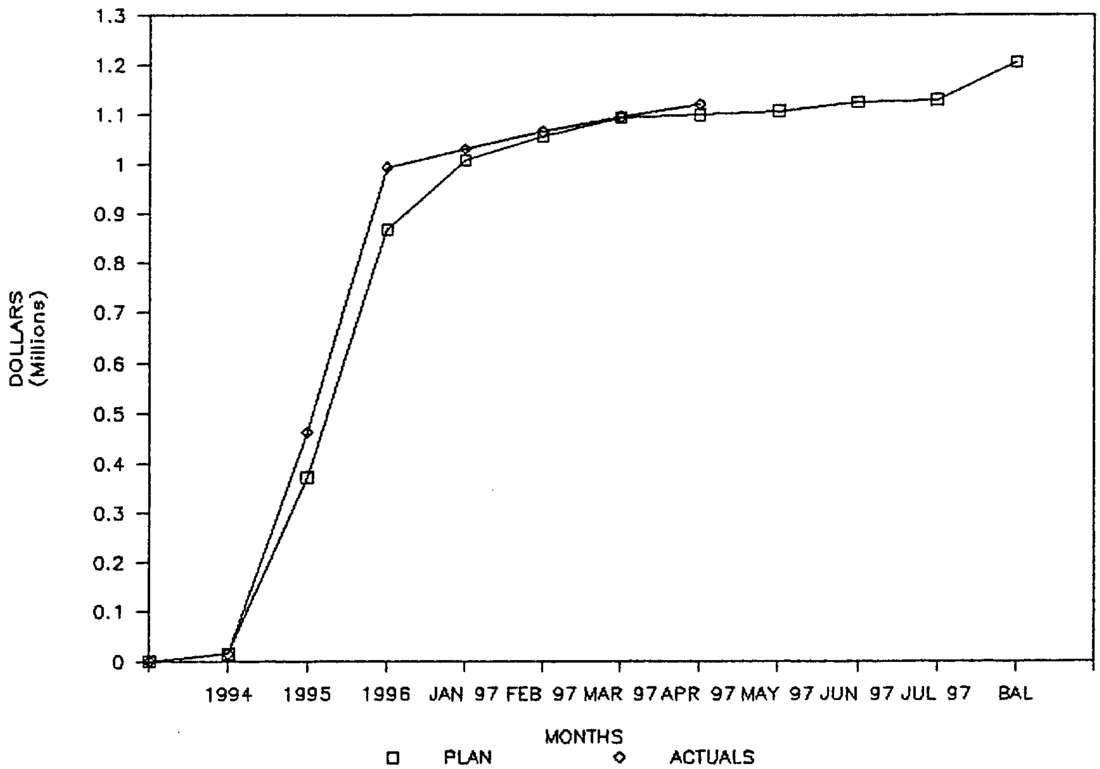



**Figure B. Funds Expenditure Graph.**

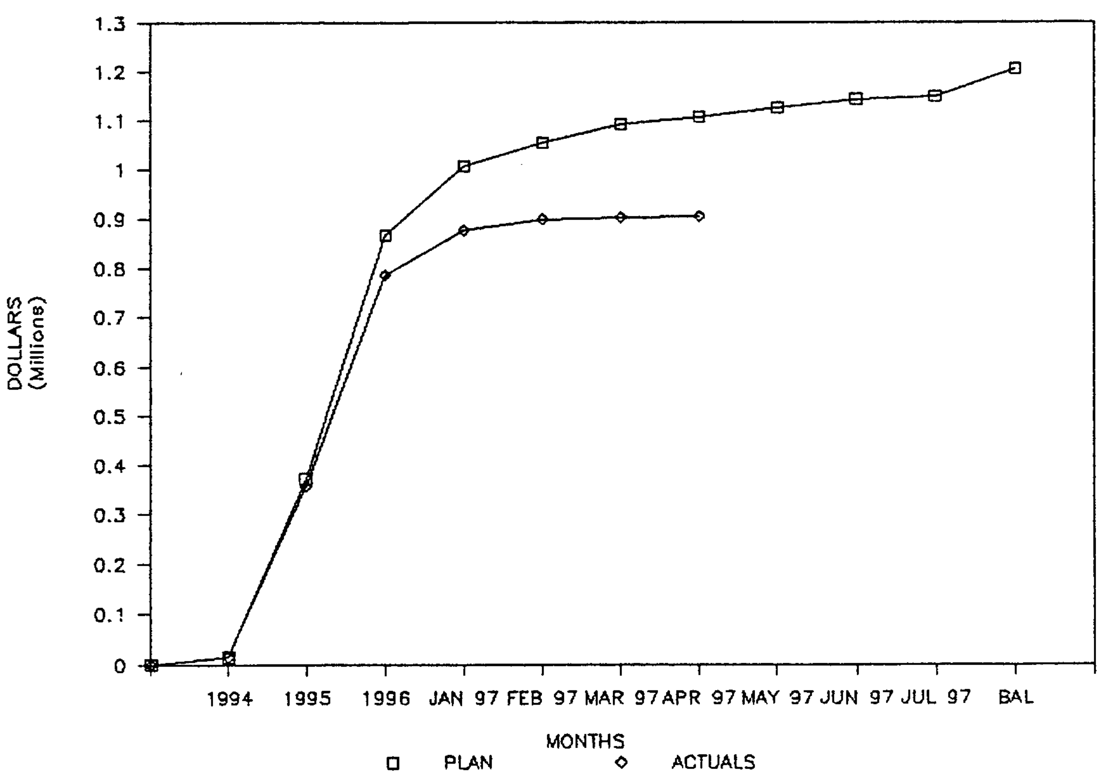



**Figure C. Work Completed Graph.**

# COST/SCHEDULE STATUS REPORT

MONTH ENDING: APRIL 1997
06/02/97

CT-ASSISTED SOLID FREEFORM MANUFACTURING
COST/SCHEDULE STATUS REPORT (C/SSR)

| | | CUMULATIVE TO DATE | | | | | AT COMPLETION | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | BUDGETED COST | | ACTUAL COST OF | VARIANCE | | | | | |
| TASK | TECH COMP. % | WORK SCHEDULED | WORK PERFORMED | WORK PERFORMED | SCHEDULE | COST | BUDGETED | LATEST REVISED ESTIMATE | VARIANCE | FUNDS REMAINING |
| 1.0 SOFTWARE DEVELOPMENT | 70% | $615,727 | $532,115 | $819,564 | ($83,612) | ($287,449) | $764,685 | $871,082 | ($106,397) | $51,518 |
| 2.0 MANUFACTURING SERVICES | 87% | $154,346 | $171,348 | $94,511 | $17,002 | $76,837 | $196,000 | $102,957 | $93,043 | $8,446 |
| 3.0 TECHNOLOGY TRANSFER | 100% | $64,451 | $89,320 | $90,424 | $24,869 | ($1,104) | $89,320 | $90,424 | ($1,104) | $0 |
| 4.0 MANAGEMENT/REPORTING | 69% | $106,338 | $106,338 | $114,357 | $0 | ($8,019) | $153,665 | $139,207 | $14,458 | $24,850 |
| TOTAL COST | 75% | $940,862 | $899,121 | $1,118,856 | ($41,741) | ($219,734) | $1,203,670 | $1,203,670 | $0 | $84,814 |
| FEE | | | | $55,942 | | | $60,183 | $60,183 | | |
| PRICE | | | | $1,174,798 | | | $1,263,853 | $1,263,853 | | |

CURRENT PERIOD COST AND PERFORMANCE

| TASK NO. | CURRENT BCWS | CURRENT BCWP | CURRENT ACWP | SCHEDULE VARIANCE | COST VARIANCE |
|---|---|---|---|---|---|
| 1.0 | 4,843 | 0 | 24,577 | (4,843) | (24,577) |
| 2.0 | 2,544 | 0 | 0 | (2,544) | 0 |
| 3.0 | 3,552 | 0 | 0 | (3,552) | 0 |
| 4.0 | 1,952 | 1,952 | 1,124 | 0 | 828 |
| TOTAL | 12,891 | 1,952 | 25,700 | (10,939) | (23,748) |

## VARIANCE ANALYSIS REPORTS

TASK: Software Development WBS: 1.0

| Budgeted Cost of Work Scheduled | Budgeted Cost of Work Performed | Actual Cost of Work Performed | Cumulative Schedule Variance | Cumulative Cost Variance | Originally Budgeted Cost | Latest Revised Estimate |
|---|---|---|---|---|---|---|
| $615,727 | $532,115 | $819,564 | ($83,612) | ($287,449) | $764,685 | $871,082 |

CAUSE OF SCHEDULE VARIANCE: Additional tasks have been added, delaying completion of originally scheduled work.

ANTICIPATED IMPACT OF SCHEDULE VARIANCE ON TASK: None.

PROPOSED CORRECTIVE ACTION: None.

LATEST REVISED SCHEDULE ESTIMATE: The completion date of Task 1 has been extended.

ANTICIPATED IMPACT OF SCHEDULE VARIANCE ON PROGRAM: None. Program will finish ahead of schedule.

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CAUSE OF COST VARIANCE: Task 1.1 overran its budget by $209,869.

ANTICIPATED IMPACT OF COST VARIANCE ON TASK: This task will overrun.

PROPOSED CORRECTIVE ACTION: Some non-critical functionality remaining to be implemented under Task 1.2 has been eliminated; other to-be-developed functionality has been scaled back. In addition, some efficiencies have also been achieved. Altogether, Task 1.2 is now expected to be completed for $103,472 less than originally expected. This savings, coupled with additional funds from Task 2 and 4, will allow Task 1 to be successfully completed.

LATEST REVISED COST ESTIMATE: The LRE now stands at $871,082, an increase of $437 from last time. Task 1.1 was completed at a cost of $486,056, an increase of $209,869 relative to the amount originally budgeted for this subtask. Task 1.2 is forecasting an LRE of $385,036, a decrease of $103,472 relative to the amount originally budgeted for it.

ANTICIPATED IMPACT OF COST VARIANCE ON PROGRAM: Resources has been transferred from Task 2 and Task 4, reducing the level of effort on those tasks.

## VARIANCE ANALYSIS REPORTS (CONTINUED)

TASK: Manufacturing Services WBS: 2.0

| Budgeted Cost of Work Scheduled | Budgeted Cost of Work Performed | Actual Cost of Work Performed | Cumulative Schedule Variance | Cumulative Cost Variance | Originally Budgeted Cost | Latest Revised Estimate |
|---|---|---|---|---|---|---|
| $154,346 | $171,348 | $94,511 | $17,002 | $76,837 | $196,000 | $102,957 |

CAUSE OF SCHEDULE VARIANCE: This task is running ahead of schedule.

ANTICIPATED IMPACT OF SCHEDULE VARIANCE ON TASK: None.

PROPOSED CORRECTIVE ACTION: None.

LATEST REVISED SCHEDULE ESTIMATE: This task will be completed during the coming report period.

ANTICIPATED IMPACT OF SCHEDULE VARIANCE ON PROGRAM: None.

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CAUSE OF COST VARIANCE: Level of effort has been less than originally anticipated.

ANTICIPATED IMPACT OF COST VARIANCE ON TASK: None.

PROPOSED CORRECTIVE ACTION: None.

LATEST REVISED COST ESTIMATE: The level of effort has been reduced to correspond to the reduced projections for this task.

ANTICIPATED IMPACT OF COST VARIANCE ON PROGRAM: The positive variance forecast for this task has been used to offset cost growth elsewhere in the program.

# VARIANCE ANALYSIS REPORTS (CONTINUED)

TASK: Technology Transition WBS: 3.0

| Budgeted Cost of Work Scheduled | Budgeted Cost of Work Performed | Actual Cost of Work Performed | Cumulative Schedule Variance | Cumulative Cost Variance | Originally Budgeted Cost | Latest Revised Estimate |
|---|---|---|---|---|---|---|
| $64,451 | $89,320 | $90,424 | $24,869 | ($1,104) | $89,320 | $90,424 |

CAUSE OF SCHEDULE VARIANCE: This task was completed ahead of schedule.

ANTICIPATED IMPACT OF SCHEDULE VARIANCE ON TASK: None.

PROPOSED CORRECTIVE ACTION: Not applicable.

LATEST REVISED SCHEDULE ESTIMATE: This task is complete.

ANTICIPATED IMPACT OF SCHEDULE VARIANCE ON PROGRAM: None.

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CAUSE OF COST VARIANCE: Not applicable (less than 10% of BCWP).

ANTICIPATED IMPACT OF COST VARIANCE ON TASK: None.

PROPOSED CORRECTIVE ACTION: None.

LATEST REVISED COST ESTIMATE: This task is complete.

ANTICIPATED IMPACT OF COST VARIANCE ON PROGRAM: None; not material.

## VARIANCE ANALYSIS REPORTS (CONTINUED)

TASK: Program Management WBS: 4.0

| Budgeted Cost of Work Scheduled | Budgeted Cost of Work Performed | Actual Cost of Work Performed | Cumulative Schedule Variance | Cumulative Cost Variance | Originally Budgeted Cost | Latest Revised Estimate |
|---|---|---|---|---|---|---|
| $106,338 | $106,338 | $114,357 | $0 | ($8,019) | $153,665 | $139,207 |

CAUSE OF SCHEDULE VARIANCE: Not applicable; level of effort.

ANTICIPATED IMPACT OF SCHEDULE VARIANCE ON TASK: Not applicable.

PROPOSED CORRECTIVE ACTION: Not applicable.

LATEST REVISED SCHEDULE ESTIMATE: Not applicable.

ANTICIPATED IMPACT OF SCHEDULE VARIANCE ON PROGRAM: Not applicable.

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CAUSE OF COST VARIANCE: Not applicable; less than 10% of BCWP.

ANTICIPATED IMPACT OF COST VARIANCE ON TASK: None.

PROPOSED CORRECTIVE ACTION: None.

LATEST REVISED COST ESTIMATE: The level of effort has been reduced to correspond to the reduced projections for this task.

ANTICIPATED IMPACT OF COST VARIANCE ON PROGRAM: The positive variance forecast for this task has been used to offset cost growth elsewhere in the program.