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Appendix C: MODIL Publications

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C2, Recent Results from the Spacecraft Fabrication and Test MODIL, Theodore T. Saito, April 12-16, 1993

Appendix D: Proprietary ASAP Information from Lockheed and Rockwell (separate document, not attached)

MASTER

SPACECRAFT FABRICATION AND TEST MODIL

MODIL Report 93-1

EXECUTIVE SUMMARY

The Lawrence Livermore National Laboratory (LLNL) served as the integrator for the Spacecraft Fabrication and Test MODIL. This report covers the period from October 1992 through the close of the project. FY 92 closed out with the successful briefing to industry and with many potential and important initiatives in the spacecraft arena. We prepared to initiate these initiatives once FY 93 funding became certain. Due to the funding uncertainties, we were directed to proceed as if our funding would be approximately the same as FY 92 (\$2M), but not to make any major new commitments. However, the MODIL's FY 93 funding was reduced to \$810K and we were directed to concentrate on the cryocooler area because a significant amount of the FY 93 funds were required to complete the FY 92 contractual obligations. The cryocooler effort completed its demonstration project. The final meetings with the cryocooler fabricators were very encouraging as we witnessed the enthusiastic reception of technology to help them reduce fabrication uncertainties. Support of the USAF Phillips Laboratory cryocooler program was continued including kick-off meetings for the Prototype Spacecraft Cryocooler (PSC). Under Phillips laboratory support, Gill Cruz visited British Aerospace and Lucas Aerospace in the United Kingdom to assess their manufacturing capabilities. In the Automated Spacecraft & Assembly Project (ASAP), contracts were pursued for the analysis by four Brilliant Eyes prime contractors to provide a proprietary snap shot of their current status of Integrated Product Development. In the materials and structure thrust the final analysis was completed of the samples made under the contract ("Partial Automation of Matched Metal Net Shape Molding of Continuous Fiber Composites") to SPARTA. Support was also received from The Aerospace Corporation in providing an evaluation of a BMDO structure requirement for a space vehicle and for inputs

regarding a material data base. The Precision Technologies thrust funded the Jet Propulsion Laboratory to prepare a plan to develop a Computer Aided Alignment capability to significantly reduce the time for alignment and even possibly provide real time and remote alignment capability of systems in flight. The promising plan was proposed to BMDO but adequate funds were unavailable. In addition the Precision Technologies Thrust identified and proposed a method to make quick micro-thrust measurements needed for precise propulsion of small and quick space vehicles . The Test and Assembly Thrust identified a very promising on-going effort, the Aerospace Corporation's development of Vehicles/Satellite Environmental Test Simulation System (V/SETSS). V/SETSS is evaluating large quantities of historical test/failure data. We had found a leader for the Test and Assembly Thrust.

The PTWG activity was much diminished during this period, and included our responding to a request from the Materials and Structures PTWG for a summary of PTWG needs.

I. CRYOCOOLER THRUST

The objective of the Cryocooler Thrust was to provide the means to develop and transfer to industry emerging production and manufacturing technologies. The cryocooler MODIL effort facilitated identification and implementation of high-payoff producibility thrusts that will mitigate production risks and costs through the use of concurrent engineering techniques.

The MODIL utilized the cryocooler Producible Technology Working Group (PTWG) to establish cooperative working relationships with the appropriate working-level engineers and technical specialists at each contractor and their suppliers. The PTWG was the primary technical support and focal point for the producibility effort.

A producibility demonstration project, involving the two Standard Spacecraft Cryocooler (SSC) contractors and their

manufacturing suppliers, and an error budget model project, involving one of the contractor cryocooler designs, were successfully completed.

The following sections of this report present detailed explanations of the demonstration project, error budget project, PTWG activities and activities performed in support of Phillips Laboratory.

CRYOCOOLER PRODUCIBILITY DEMONSTRATION PROJECT

OBJECTIVE

The Cryocooler Producibility Demonstration Project was established to demonstrate the need for cryocooler designers and manufacturers to concurrently interact with one another in the initial stages of the design process. The project was designed to demonstrate the cost and effect of producing components that were initially designed with minimal producibility issues taken into account.

Since we could not address building a complete cryocooler, we focused on a generic component geometry producibility issue that was common to all cryocoolers. The geometry was a thin-to-thick wall transition that necessitated precision tolerances. With this geometry, our objective was to develop a production process that would be developed, in real time, with the selected cryocooler manufacturer's suppliers. Our objective was accomplished at both LLNL and Modern Industries (with Hughes Aircraft) in Phoenix, AZ, and at both LLNL and Westfield Gage (with Creare) in Westfield, MA.

The process developed at Livermore was taken to Westfield Gage, and the first part produced by Westfield machinists with the new process complied with the specification. We also suggested inspection techniques to Westfield Gage that were implemented into their operation.

We influenced Westfield Gage to approach their work assignments in a manner that would generate the most efficient and

productive effort from their people. They were considering giving a project to the shop manager who in turn discussed it with the machinist who would then determine the most efficient process to use to manufacture the component, rather than using the method of giving a project to the machinist and telling him/her what process to use, which was their current method. Crafts person interaction with management and engineers is the important issue, because everyone involved now is part of the problem/solution. What optimized their approach was our introducing the Wire Electro Discharge Machining (EDM) process to Westfield to solve a producibility problem, one of which the EDM process would never have been considered.

The process development and technology transfer with Modern Industries were equally successful. We were instrumental with building a higher level of confidence within the Modern organization between the quality assurance staff and the production staff. We validated the producibility and inspection techniques utilized at Modern at LLNL by working issues in real time with Modern crafts people.

The results of the first phase of the demonstration project show that LLNL is now being considered as a resource for manufacturer suppliers, and that LLNL has developed, and can develop, a high level of trust in which to work closely with private industry. One example of this trust and confidence in LLNL is that Hughes has modified one of their cryocooler component designs based on our recommendations. Reference *MODIL Cryocooler Producibility Demonstration Project Results*, in Appendix A.

CRYOCOOLER ERROR BUDGET MODEL PROJECT

A design error budget is a necessary step in the design process, because it allows the designer to approach the design as a system instead of a combination of individual entities. Error budgets provide an understanding of the design requirements dictated by the system's function, and they allow the designer to examine and

budget error sources at the conceptual design phase of a project. The primary benefit of an error budget is that any change to a design can be accurately analyzed to determine the effect of the change at any level in the design. In effect, this tool allows the designer to design for function, manufacturability, and assembly. It also optimizes production costs, because most of the tolerance issues are addressed in the design phase.

The project entailed generating a cryocooler expander assembly computer model using nominal dimensions without tolerances. An existing Standard Spacecraft Cryocooler (SSC) design was used. The SSC component relationships to one another in the assembly were analyzed for inconsistencies and interferences. Parametric modeling techniques, with Unigraphics CAD software, were used to relate individual part features and related features in the cryocooler assembly.

The error budget model delineates individual parts that show mathematical expressions and dimensions which illustrate geometric relationships that control critical features on assembly components and on critical features between those components. The effect of dimensional changes between related components within an assembly are exhibited in the model.

The project results showed that the SSC design has errors with the nominal dimension application and the method in which the parts relate. Had tolerances been applied to the model, more errors would have become evident. Producibility, based on this design, will be a problem.

The project results were presented to the Thermal Management Branch of Phillips Laboratory in September 1993. Reference Appendix B for the viewgraphs of this presentation.

**BRILLIANT EYES (BE)/AEROSPACE/PHILLIPS LABORATORY
SUPPORT**

MODIL activity involved reviewing BE contractor cryocooler designs through contract kick-off meetings, preliminary design reviews, specific in-house design reviews, and design drawing evaluations.

As a member and co-chair of the cryocooler PTWG, Gill Cruz visited on numerous occasions Aerospace Corporation, TRW, Hughes Aircraft, Rockwell International, USAF Phillips Laboratory, TASC, TATI, and Lockheed Missile and Space for the purpose of reviewing and evaluating producibility issues pertaining to space qualified cryocoolers. This effort was an on-going effort throughout the project duration.

As a result of the PTWG meetings, kick-off reviews, and the fact that two contractors affiliated themselves with British Aerospace cryocooler suppliers (British Aerospace and Lucas Aerospace), Gill Cruz visited the British cryocooler suppliers to assess the status of cryocooler producibility in the U.K. Additional companies and agencies were visited for the same reason.

In support of Phillips Laboratory, Gill was an advisor for cryocooler RFP contractor selection.

SPIE PUBLICATION

The paper *MODIL Cryocooler Producibility Demonstration Project Results*, was presented at the April 1993 SPIE Small Satellite Technology and Applications Conference and is in Appendix C. This paper details the producibility demonstration project from planning through the project completion.

POSSIBLE FUTURE PROJECTS

Two proposals have been submitted to Phillips Laboratory and Hughes Aircraft that address error budget tools and cryocooler producibility respectively. The Phillips proposal is comprised of these scenarios that would address generating an error budget tool

for their cryocooler projects and an actual error budget for an existing cryocooler design.

The Hughes proposal is comprised of producing an error budget and a cryocooler drawing package for a new cryocooler design. In addition, a manufacturing effort for the new cryocooler was proposed. This proposal is in response to a Broad Agency Announcement from ARPA of which LLNL is a member of the proposal consortium headed by Hughes Aircraft.

II. Automated Spacecraft and Assembly Project

Anticipating the initiation of a pilot study in FY 93, the MODIL issued contracts to TRW, Martin Marietta, Lockheed, and Rockwell. These four were chosen because they were participants in the down select process for the Brilliant Eyes project (BE) as well as two of them already were down selected for Brilliant Pebbles. These four were not only major contractors involved in DOD spacecraft fabrication, but also leading candidates for (then) near term SDIO production.

In order to research the spacecraft manufacturing processes and generate recommendations regarding the implementation of an automated spacecraft assembly system each contractor was asked to provide information on:

- 1) the prime contractors' needs, current status, and future directions for soft technologies,
- 2) soft technology development efforts by OSD and the commercial sector,
- 3) SDIO and System Program Office (SPO) directions.

It was anticipated that the report would provide information on:

- 1) a model of how the prime contractor, their sub-contractors and suppliers function together to manufacture weapons systems,

- 2) description of their existing Integrated Product Development (IPD) use,
- 3) description of inter-networking with their sub-contractors and suppliers, and
- 4) future plans for the preceding items.

The above requirements were created in light of the generic requirements anticipated for a pilot project. It was felt that a pilot study would have the following characteristics:

- 1) Transferability
- 2) Multiple Weapons Systems Applicability
- 3) Standards Based
- 4) Near Term Focus
- 5) Scalability
- 6) Measurability

TRW¹

TRW formed an integrated product development team consisting of members from the Data Management, Manufacturing, Systems Engineering, Design, and Integration and Test disciplines to document the current "As-Is" processes and to look at existing automated tools in use at TRW.

The TRW team defined an architecture to integrate the various aspects of spacecraft manufacturing electronically. The proposed system would integrate all of the various functions of the spacecraft program and have the following benefits:

- Reductions in production and support costs associated with manufacturing cycle time, engineering change orders, scrap, rework and repair costs
- Inventory reduction through implementing electronic just-in time material and parts ordering
- Facilitation of paperless documentation implementation.
- Improved costs models from better program wide actual-costs data.

Electronic document review offered the potential of up to 40% time savings of the many individual sequential steps in the review of a CDRL (Contract Deliverable Requirements List) document. Developing electronic tools to support the concurrent process would address functions such as automated routing, status monitoring, and configuration management functions to support administrative tasks. Time sharing of data over a geographically large area would be made possible.

In addition an electronic document library would make specifications, drawings, and interim reports available in a "desktop" environment. Proper data formatting would allow text search capabilities to be exercised. Electronic storage of programmatic data enhanced retention of corporate knowledge so often lost when key persons leave a company.

A Product Data Management System has the goal to provide tool sets to control all aspects of engineering data. It would have a capability to electronically distribute drawings for reviews and establish a multi-tier, iterative review environment utilizing a desktop platforms.

TRW saw the requirement to implement a concurrent engineering automated environment to remain competitive as a spacecraft manufacturer. Funding and development of this environment offered a major challenge.

Martin Marietta²

Martin too recognized the value and need for integrated product development in the spacecraft area. Some on-going activities included:

- Computer-Aided Acquisition and Logistics Support (CALS)
- Shared Program Information Network (SPINE): a government developed electronically integrated information system for use by the Brilliant Eyes System Program Office

- Product Data Exchange using the Standard for the Exchange of Product Model Data (PDES/STEP): an international effort to advance the Initial Graphics Exchange Standard (IGES) to move data from one CAE/CAD/CAM application to another
- USAF Manufacturing Technology Directorate's Integration Technology section

Martin described the enterprise models for Brilliant Eyes and Brilliant Pebbles. The large number of estimated transaction per day between the SPO and sub-contractors, literally from coast to coast vividly illustrated the benefit of an automated information exchange and monitoring system. Martin has addressed requirement and advantages of establishing strategic partnerships with their major suppliers and listed key requirements for improvements as:

1. A prime contract significant dollar size
2. A stable prime contract
3. Multi-year funding
4. Revisions to the Competition in Contracting Act.

Martin observed that (the then) current SDIO development activities were at a disadvantage in providing the funding and contractual environment which would support and facilitate the development of robust and effective partnerships.

Martin uses a three level network architecture:

- Level I - Wide Area Network
- Level II - Metropolitan Area Networks
- Level III - Local Area/Organizational Networks

Their approach manages information with each team member able to share information in areas including: analysis, finance, metrics, schedules, office automation, drawings, documentation, specifications, operations concepts, and briefings. Careful attention has been given to insure that adequate security is present to control access to the networked information. The current system with transmission speeds of ~10 MB/sec easily handles textual files but other requirements such as multi-media would be difficult.

Martin described their near-term future network architecture as well as future IPD plans. The transition strategies were responsive to some key dependent variables including, the pace and direction of standards and technology development, the congruence between developing standards and technology, and funding constraints. Potential information sharing examples of the future were: Ad Hoc Information Sharing; Electronic Team Meetings; On-line Trade Studies; Collaborative Analysis Activities; Electronic Design Review Boards, Electronic Schedule Management, and On-line Interactive Cost Management.

Martin outlined the steps they recommended for an expeditious transition to an effective IPD environment. These steps were broken into three major categories:

1. Adopt a single set of standards and technologies
2. Change their processes and work culture to incorporate the optimal use of information system standards and technologies.
3. Apply standards and technologies and process and cultural change to the way they do business.

In addition they outlined some specific steps to address requirements such as a CAD Neutral Formal Processable File Exchange and Text and Graphic Scanning and File Compression.

Lockheed Missiles & Space Company (LMSC), Inc³

Lockheed Missiles and Space Company (LMSC), Inc, (hereafter referred to as Lockheed) defined IPD as the use of cross-disciplinary teams empowered to develop quality products that meet physical, functional, cost, and schedule requirements for all phases of the products life-cycle. Their definition gave insight to the ensuing paradigm shift in manufacturing.

Past efforts at Lockheed reflect a true commitment as well as progress in IPD. It was impressive that Lockheed recognized the significant inertia that any large organization would experience when they said:

Companies demonstrating the most success at IPD are those where the drive was impending bankruptcy. ... Clearly, implementation means addressing cultural, procedural and technological issues. Just as clearly, upper management must aggressively promote IPD, not just permit it.

Furthermore Lockheed has taken steps to actively promote IPD by securing and developing in-house software creation capability to facilitate IPD, identifying and improving their quality programs, reorganizing to facilitate IPD implementation (including forming key project offices) and actively and formally educating their engineers.

Lockheed demonstrated excellent insights into the resistance to change stimulated by IPD. We have noticed these resistances in various MODIL interactions with most contractors, and Lockheed has done an excellent job of describing these changes and ways to overcome them. Re-organization and a vibrant training program with three thrusts were just two of their keys.

Lockheed recognized that a successful implementation of IPD requires integration of culture, process and technology.

Appendix D of the report contains proprietary information and is forwarded separately.

ROCKWELL⁴

Rockwell described the IPD team which it proposed for their proposed and on-going work. Rockwell created Integrated Product Teams (IPTs) in an organization to ensure "ownership" of specific products and to provide in-depth integration and risk management to deliver a system that meets all requirements, on cost, and on

schedule. However, they seemed to rely on co-location of teams more than an electronically created IPD environment.

The Program Management IPTs was in charge of the planning process and had five primary tasks:

1. Establishing a traceable numbering system that aligns specification, contract work breakdown structure and SOW
2. Defining the IPT structure
3. Defining top-level events, accomplishments, and criteria
4. Defining and allocating resources
5. Assigning product responsibility, authority, and accountability (RAA) to individual IPTs.

The IPTs were tiered analogously to the work break down structure. Each IPT started from the customers requirements and used its respective allocated requirements and resources to plan, manage and control the production of its specific product. Proper attention was given to cost, schedule, technical performance, risk and configuration management. The IPT leader was accountable for all costs associated with his team's product. Representation on the IPTs included appropriate sub-contractors and appropriate functions from all engineering and design activities through-out the life of the program, from design definition through production and support.

Risk avoidance was accomplished by a management planning process to accomplish:

1. Clear and definitive statement of work, specifications, and tailored data requirements.
2. Team participation in the subcontractor tasks.
3. Constant oral and electronic information exchange
4. Formal program review and action status
5. Built in schedule margins.

Rockwell also strove to have team member representatives in residence at each others facilities.

The existing networks described by Rockwell included several interesting systems. The Aerospace Information Management System (AIMS) included an enterprise process data manager, an automated logistics system, and a material requirements planning system. Other systems discussed included: a computer aided system engineering tools system (CASETS) supporting BMDO, the NASA orbiter project management information system (OMIS), and the group tele-communications system (GTCS) (software providing electronic presentation and distribution of a presentation), Further discussion is included in the appendix which contains proprietary information.

In implementing IPD, Rockwell recognized that significant personnel development is required. Some of the areas involved are: design for competitiveness training, concurrent design training, systems engineering organization, systems engineering training, empowerment training, principle based leadership training, organization excellence, and continuous improvement culture. Furthermore they saw that existing systems must be adapted to IPD needs to help change the way of doing business in the former matrix organization.

Appendix D of the report contains proprietary information and is forwarded separately.

III. Materials and Structures

The evaluation of parts from the "Demonstration of Partial Automation of Matched Metal Net Molding of Continuous Fiber Resin Matrix Composites" was completed in this period. The \$250 K contract to SPARTA, Inc., was completed in FY 92, but the final evaluation of parts by LLNL and SPARTA's final report was received during this period. Most of this information is extracted from SPARTA's final report⁵, Demonstration of Partial Automation of

Matched Metal Net Molding of Continuous Fiber Resin Matrix Composites, K. Cook, K. Cheverton, and G. Wonacott, SPARTA Report No LJ 93-53-TR.

The objectives of this project were to:

- Demonstrate automated closure and opening of the Matched Metal New Molding external tooling without disturbing the prepreg wrapped on the inner mandrel.
- Demonstrate reproducibility of the automated process by measuring and verifying repeatability from compression and bending ultimate load testing at LLNL.

The objectives were successfully met.

The contract was managed by Gordon Spellman of LLNL. From the outset efforts were made to introduce concurrent engineering and computer technology to reap the maximum benefits for the process. Furthermore, this work capitalized on earlier work by the Strategic Defense Initiative Office such as SPARTA's funding by the Army Research Laboratory - Materials Directorate (US Army ARL-MD Contract DAAL04-86-C-0045 and DAAL04-92-C-0031). The advantages of precision net shaped composite compression molding were evident from these and other developments, and the Fabrication and Test MODIL saw the benefit from automating the process for future SDIO system requirements. For example, SPARTA estimated a cost savings of \$30.5 M (33%) for four components for a 11 year production of the US. Army's JAVELIN shoulder-launched anti-tank weapon. There were numerous other potential projects already being considered by the Army. Furthermore SPARTA anticipated that a single molding machine could accommodate a wide family of components simply by changing the internal and external tooling. This project focused on automated closure of the mold. However, there were many manual operations in the process, with potential automation payoff:

1. Automated tool design given the part design on CAD

2. Automated/autonomous control of the cure process
3. Automated placement of the prepreg on the mandrel
4. Automated closure/cure/and opening of the external tooling
5. Automated punching of penetrations in prepreg prior to cure
6. Automated tool cleaning
7. In situ dimensional verification

The contract called for components which were 10 inches tall cylinders of 9 inches diameter with a wall thickness of 0.8 inches. The cylinder design consisted of four layers of cloth and 10 layers of tape.

The mold was made with NAK 55 tool steel because of its hardness (R_c 45) uniform and consistent grain structure, machinability and dimensional stability. SPARTA used its internally developed hydraulically operated mold closing machine which has full two dimensional motion with limited displacement in the vertical direction. Cartridge heaters, with a heating capacity greater than the $50^\circ - 100^\circ$ F per miniature ramp rate requirement, were used to heat the mold to a uniform temperature. Attention was given to the location and wiring of the heaters to achieve a balanced load on all circuits and establish separate heating zones.

The process development initially varied the dwell temperature while keeping other parameters constant. Four cylinders were made during this phase of the contract. It was found that after 10 minutes at a temperature of 195° F, the mold closed using a nominal constant pressure of 2200 PSI. Four tool modifications were made as a result of the first tests. Three of these modifications were made to accommodate the resin escape path and one was adding heaters to compensate for the loss of heat through the base plate into the machine structure. In addition the mold closing machine was modified to improve the fabricated part.

Twenty demonstration parts were produced. The parts are of high quality both visually and dimensionally. Some test results, discussed below, indicate that the production run is producing parts with performance virtually identical to predictions and with exceptional repeatability.

Visual inspection of the parts was very encouraging indicating high quality. Initial indications are that dimensions are all within the specification of the Statement of Work with the exception of the diameter. The diameter is small by 0.008" due to errors in tool design. This is the type of error which should be minimized by thorough process knowledge and control. Variations in wall thickness are about 1.5 mils, and the radius varies about +/- 4 mils on a 4.5" radius.

Parts were tested to failure in tension and in compression. The modulus in tension were 15.5, 15.5 and 16.2 MSI, and in compression they were 12.9 and 13.2 MSI. Two of the tensile specimens failed in the fixture at a point about 75% of ultimate, and the one component failed at an ultimate stress of 140,000 PSI which is essentially the same as the predicted value. The compressive failure stresses were 39 and 44 KSI and the mode was buckling. The main results to date are predictability and repeatability which are very high for these components. The MODIL believes this is a key feature of this type of automated process.

Some of the major conclusions from this project include that partial automation of matched metal net molding of continuous fiber resin matrix composites was successfully achieved. A partially automated mold produced parts that were of equal or superior quality to those produced using the current state of practice with manual tool closure. More reproducible part properties may be achieved through an automated process. Resin viscosity was an extremely critical parameter. (However complete evaluation and *optimization* of viscosity was not within the scope of this contract.) Since resin viscosity is a function of time and temperature, varying

the ramp rates, dwell times, and temperatures could improve the process. Gaps at the point of initial high pressure closing and the eventual equilibrium point were noticed. Two facts influence these: machine design not optimized for a 10 inch tall part and the tool locating design and method used for initial loading and positioning of the tool on the machine.

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MODIL Cryocooler Producibility Demonstration Project Results

**Gilbert E. Cruz
R. Mark Franks**

June 24, 1993

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the Laboratory.
Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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*MODIL Cryocooler Producibility
Demonstration Project Results*

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June 24, 1993

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MODIL Cryocooler Producibility Demonstration Project Results*

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ABSTRACT

Cryocoolers are essential components for many spacecraft. We summarize some spacecraft cryocooler requirements and discuss our observations regarding Industry's current production capabilities of cryocoolers. The results of the Lawrence Livermore National Laboratory (LLNL) Spacecraft Fabrication and Test (SF&T) MODIL's Phase I producibility demonstration project is presented. The current project that involves LLNL and industrial participants is discussed.

ACKNOWLEDGMENTS

The authors wish to acknowledge the participation and cooperation of many involved people in the LLNL MODIL Demonstration Project. In particular, we wish to thank the following individuals:

Messrs. Jack Daniel and Dan Yahraus of Modern Industries.

Messrs. Bill Baschnagel, Dodd Stacy, and Bob Stearns of Creare, Inc.

Messrs. Lou Filios, Ted Macutkiewicz, and Dick Patterson of Westfield Gage.

Messrs. Larry Gresko and Steve Neville of Hughes Aircraft.

The following Lawrence Livermore National Laboratory Staff: John Benedict, Terry Benton, Jeff Groth, Dewayne Harkov, Jay Jacobs, Skip Peters, Mike Prokosch, Dick Rose, Kim Shelly, and Don Yordy.

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I. INTRODUCTION

The production of large quantities of spacecraft needed by SDIO will require a cultural change in design and production practices. Low rates production and the need for exceedingly high reliability has driven the industry to custom designed, hand crafted, and exhaustively tested satellites. These factors have mitigated against employing design and manufacturing cost reduction methods commonly used in tactical missile production.

Additional challenges to achieving production efficiencies are presented by the SDI spacecraft mission requirement. IR sensor systems, for example, are comprised of subassemblies and components that require the design, manufacture, and maintenance of ultra precision tolerances over challenging operational lifetimes. These IR sensors demand the use of reliable, closed loop, cryogenic refrigerators or active cryocoolers to meet stringent system acquisition and pointing requirements. Although a stable production base exists for small tactical IR coolers, a domestic base for cryocoolers of the capacity and durability required by SDI satellites does not currently exist. MODILs were established by USAF Lieutenant General Abrahamson in response to his initiatives to mitigate risk and cost escalation of SDIO systems. He wanted to apply proven accelerated approaches such as concurrent engineering to reduce production risks and costs for SDIO. MODILs have grown from a concept to an essential part of the SDIO Producibility and Manufacturing Program, and are a coalition of government, industry, and university participants working together to develop and demonstrate new production and automation processes for current, emerging, and leapfrog product technologies in SDI enabling technology areas¹. Through the integration of production R&D efforts in non-proprietary locations, advanced processing and production technologies can be demonstrated and transferred to industry more expediently and cost effectively than by current industrial practices.

MODILs have two salient objectives:

- Identify and implement high payoff producibility thrusts to reduce production risks and costs.
- Develop and transfer to industry emerging production and manufacturing technologies to achieve "pre-planned" product improvements.

This report describes the results of the LLNL MODIL Producibility Demonstration Project.

II. REQUIREMENTS, ISSUES, AND PROJECT PLAN

2.1 Spacecraft Requirements

Cryocoolers are key components on which spacecraft depend. Simply stated, a cryocooler is a refrigerating engine that uses a working fluid, helium, for a recuperative generator or for a Stirling engine, to cool the spacecraft components. A cryocooler uses a displacer to push compressed gas isochorically from the warm region, where it is compressed, through the regenerator into the cold region where the compressed gas is expanded isothermally, does work on the piston, and produces refrigeration. Although several different concepts and designs exist, the current spacecraft cooler is based on a Split Stirling design.

Cryocoolers provide essential cooling capability for sensors/seekers, cryogen storage, system thermal management, superconducting devices, cold electronics, and super computers. In order to provide adequate cooling capability, unresolved technical issues need to be addressed and resolved.

Several DoD and NASA cryocooler candidates are at development or prototype demonstration stages. Both NASA and DoD have mission needs for cryocoolers of equal or higher capacity.

Operational experience with satellite cryocoolers has been limited and no appreciable life has been accumulated on most coolers.

2.2 Producibility Issues

The salient cryocooler producibility issues are as follows:

- Develop and demonstrate space qualifiable cryocoolers. (This is the generic issue addressed by the MODIL.)
- Build a cryocooler that generates extremely low vibration. (This is a precision alignment and component fabrication issue.)
- Achieve low weight, input power and volume. (These are critical design and performance parameters.)
- Attain low component and assembly contamination, which must be mitigated early in the system assembly phase. (These are process procedure issues.)
- Achieve high quantity component and assembly producibility. (These are end-products of the MODIL thrust area effort.)
- Obtain a high system reliability during operation. (This is an issue dependent on those preceding.)
- Readily and reliably integrate the cryocooler system with the spacecraft systems.

2.3 Demonstration Project

Establishing and implementing a producibility plan, such as for cryocoolers, require a series of events to take place in order to be successful, refer to the plan specifics on page 7. Each aspect of the process demands close interaction and cooperative effort from industry. A flow chart depicting this process is shown in figure 1.

The primary contractors were visited with the intent of reviewing and identifying the salient cryocooler producibility issues that are inhibiting cryocooler production. Since the Standard Spacecraft Cryocooler (SSC) contracts were well underway, and the Air Force and Phillips Laboratory needed to understand what they were receiving from the two contractors, the project focused on producibility issues for the two SSC designs.

Figure 1 Interaction with Industry

The producibility demonstration project was designed to demonstrate the necessity for implementing concurrent engineering techniques in the design and production of cryocoolers. Concurrently working production problems with the suppliers, provide the catalyst that facilitates the technology transfer needed to enhance their production capability. By focusing the effort on both the cryocooler developer's design and the supplier's manufacturing approaches, manufacturability can be achieved in real time and disseminated throughout more of industry, through these suppliers who make components for many other companies. The manufacturing supplier effort generates a more far-reaching effect within industry than a single contractor.

2.3.1 Producibility Demonstration Plan Specifics

- Agree on project component to produce (LLNL, prime contractor, supplier). The purpose is to solve a common problem.
- LLNL Manufacturing Support Group forms a producibility team.
- Evaluate manufacturing supplier capabilities (LLNL Producibility Team) with contractor and supplier personnel.
- Put contracts in place with contractors to enable effort to continue at LLNL, the contractors, and at contractor's manufacturing suppliers.
- Establish a production sequence (@ LLNL).
- Establish a process plan (@ LLNL).
- Implement the process plan (@ LLNL).
- Develop inspection techniques (@ LLNL).
(Implemented before establishing the production sequence)
- Validate the process (includes: inspection techniques, data acquisitions, etc.)
- Establish production machine tool and inspection set ups.
- Implement a production run (includes: in-process inspection, data acquisition).
- Finish part production - 100% inspection (@ LLNL).
- Maintain the producibility team (for continuity) when moving to supplier facility.
- Supplier personnel acquire hands-on lead with LLNL personnel as consultants to them (@ supplier's).
- Work with suppliers to enhance their machines where applicable (@ supplier's).
- Develop and implement the producibility process (@ supplier's).
- Produce the end product:
 - Process detail planning
 - Process summary documentation
 - Parts delivery
 - Supplier capable of utilizing new technology
- Hold project close-out meetings with contractors and suppliers.

Two components were selected for this demonstration project, (figure 2), both of which have the thin to thick wall interface and close tolerance features, to assess producibility and develop a manufacturing plan to be transferred to the participants. Titanium and Inconel were the materials to be used for these items. Stainless steel was substituted for the Inconel when thorough process development attempts did not result in the desired geometries from Inconel. Findings on the three materials, Titanium, Inconel, and Stainless Steel are reported in section V of this report.

Figure 2 Titanium (L) and Inconel (R) Demonstration Project Components

III. PROJECT SUMMARY

3.1 Selection of Resources

The exacting natures of the demonstration components require that skilled crafts people be used throughout the entire operation. The importance of this "soft technology," the people involved, must not be underestimated. The team concept was shown to be very effective in the development of processes and the manufacturing of these components. The precision and accuracy of these components rely on the thorough planning and deliberate execution of processes by these skilled individuals.

Machinery and tooling resources representative of those possessed by, or commercially available to, the participating vendors were chosen in an attempt to develop processes that will be readily assimilated by the private sector. The issue continues to be the utilization of appropriate resources to assure accuracy and precision in production.

3.2 Machinery

Common CNC lathes and conventional lathes were used in the roughing operations of all components.

Hardinge HLV-H 10 inch Toolmaker's Lathes (figure 3) were used in roughing and finishing operations.

Agietron Agiecut 200 (figure 4) and Charmille Robofill 600 (figure 5) wire EDM machines were used to finish the inner features.

Trim-Sol, the coolant used by LLNL personnel for this project, contains chlorine; it is one of several substances restricted in the manufacture of aerospace hardware. The aggressive project schedule and the generic non-flight natures of the demonstration components were primary factors in this decision. New-Lube is one acceptable alternative.

Figure 3 Hardinge HLV-H 10 inch Toolmaker's Lathes were used in the development of turning operations.

Figure 4 LLNL's Agietron Agiecut 200, similar to the participating vendor's Agiecut 100, was used to finalize processes for finishing the bore of the titanium component. Minor part program modifications were needed to duplicate our results in the vendor's shop. This result demonstrated that continuity in tooling contributes to productivity.

Figure 5 The application of EDM technology to the titanium component bore was developed on this Charmille Robofil 600. An electrified wire travels continuously from the head of the machine, through the work piece and into the lower guide (not visible). The electric discharge from the wire erodes the work piece material as it passes.

3.3

Tooling

Tooling consists of "off-the-shelf" resources; the exception being the after market grinding of high back rake on the VC-29 carbide inserts used for finishing the outer profiles of the Inconel and Stainless steel components (detailed in section 5.2). This high back rake produces better chip flow characteristics resulting in less tool pressure on the part. Stresses induced in the part are minimized with this type of tool configuration, therefore, providing a more geometrically stable component.

The nomenclature identifying carbide insert lathe tooling generally contains three segments, one alpha, one numeric and the third, generally, alphanumeric. The alpha portion pertains to the insert's geometry. The numeric segment identifies the size, thickness, and tool nose radius of the insert, while the alphanumeric portion defines the grade of carbide used in the cutting tool. This designation varies by manufacturer.

3.4

Measuring Tools

Measuring tools available at LLNL were used to verify part sizes and geometric features. The function of the primary inspection tool, the Bendix Indi-Ron roundness gage (figure 6) can be duplicated by commercially available tools. The Federal Formscan Circular Geometry Gage and Rank Taylor Hobson's Talyrond 250 are commercially available for approximately \$100K. The precision and accuracy requirements of the demonstration components dictated the use of this type of inspection equipment.

Sheffield gaging (figure 7) was purchased and evaluated to determine the effect of the air pressure on the thin wall components during inspection. Test results revealed air gaging as a viable option for the determination of internal size. Air gaging exhibited no appreciable distortion of the part geometry when employed during inspection.

A LaserMike (figure 8) brand micrometer was purchased for \$6K. This inspection equipment provides a non-contact method of measuring outer diameters in a precise manner. Potential human influence and variation are negated with this tool, because the tool uses a laser light transmitter and receiver to establish size.

A Federal Surfanalyzer was adapted to determine straightness of some inner features for the tight tolerances specified (figure 9).

An OGP brand optical comparator was used to provide non-contact linear verification of outer features (figure 10).

Figure 6 The Bendix Indi-Ron roundness gage was used to measure and document roundness, a total runout factor, of the demonstration components. Note the four inch probe in position to take the first inner diameter trace on the Titanium component. A similar process was used on the Inconel and Stainless Steel components.

Figure 7 The Sheffield Air Cage was used to determine inner diameter sizes. This process of measurement assures minimal impact to the thin wall portion of the demonstration components.

Figure 8 The LaserMike uses light to provide a non-contact measuring tool for outer features.

Figure 9 A Federal Surfanalyzer was adapted to provide the straightness check on the EDM's bore of the titanium component. Two full length traces, taken orthogonally, were used to link the roundness measurements obtained in a prior operation.

Figure 10 OGP Optical Comparator—The magnified shadow of a part is projected to the screen of an optical comparator. Outer features and impression moldings of inner features were verified in this manner. Measurements were recorded manually, automation of this operation is recommended in a production environment

IV. DRAWINGS AND PHOTOS

The drawings (figures 11 and 12) presented in this section were used to produce the two parts for which the manufacturing processes were developed. Both drawings are modifications of actual component drawings provided by the two participating contractors.

The photographs (figures 13 and 14) show the two components at successive stages of process development.

Figure 11 Titanium demonstration component drawing. Note the thin wall section, the generic issued addressed in this MODIL demonstration project and the close geometric and size tolerances. The numbering of the drawing dimensions aid in referencing inspection documentation to the drawing.

Figure 12 Inconel/Stainless Steel demonstration component drawing. Note the thin wall section, the generic issued addressed in this MODIL demonstration project and the close geometric and size tolerances. The numbering of the drawing dimensions aid in referencing inspection documentation to the drawing.

Figure 13 The Titanium demonstration component shown through various steps of the manufacturing process; Lot R The blank following the process described in 5.1.1.1; through the first portion of 5.1.2.1; prior to the datum machining detailed in segment 5.1.2.1; the completed demonstration component.

Figure 14 The Inconel/Stainless Steel demonstration component at successive stages of process completion; L to R The blank following segment 5.2.2; the blank shown through 5.2.3.1, with the outer skin removed; semi-finished outer and inner features following 5.2.5; foreground, the completed Inconel/Stainless Steel demonstration component.

V. MANUFACTURING DATA

5.1 Titanium 6A14V

5.1.1 Blank Preparation

5.1.1.1 Process

Due to a compressed project schedule, we obtained one and one-half-inch diameter bar stock in four foot lengths for the demonstration project. The blanks were sawed to length, leaving approximately one-eighth inch for face machining, bringing the initial facing operation blank length to .03 inch over the finish dimension. A one-inch diameter hole was then drilled through the center of the blank, creating a tube. These processes, though carried out on standard machine tools, are not optimum for a production environment; however, this method was employed for expediency.

5.1.1.2 Recommendation

Blanks should be purchased in a tubular configuration to optimize the manufacture and reduce the cost of these components.

5.1.1.3 Parameters

SFM Work Speed	IPR Feed Rate	Depth of Cut (inch)	Tool Designation
200	.010	.025	KNGP-K313

Table 1: Parameters used for the Blank Facing Operations

RPM Work Speed	IPR Feed Rate	IPT	Tool Designation
330	.010	.005	Cobalt Steel

Table 2: Parameters used for the Blank Drilling Operation

5.1.2 Rough Machining

5.1.2.1 Process

The "as received" blank is machined to a semi-finished configuration to remove stock before annealing and finishing. Most numerically controlled lathes can be used to perform this operation. The blank was chucked with 4 inches protruding from the chuck jaw faces. A multi pass roughing operation was performed to leave .025 inch diametrical stock for finishing. The blank was then reversed in the chuck and supported on the 1.160 inch diameter section. A second roughing operation, using the same parameters, was performed. The over all length was left .02 inch longer than the finished component, leaving material for subsequent finishing operations.

Finish allowances are symmetrical, with equal amounts of stock removed from each end during the finishing operation.

5.1.2.2 Parameters

SFM Work Speed	IPR Feed Rate	Depth of Cut	Tool Designation
200	.010	.025	KNGP-K313

Table 3: Parameters for the Rough Machining Process

5.1.3 Heat Treat Cycle

5.1.3.1 Metallographic Investigation

An abbreviated metallographic study of the annealing and stabilization processes was conducted. Sample coupons were subjected to the various processes, sectioned and examined with a 500X microscope. The resulting micrographs (figures 15-18) reveal no appreciable differences in grain structure or hardness of the sample pieces. The annealing processes are detailed in the following sections of this report. An alternate vacuum annealing process (5.1.3.5) was requested by the contractor after this study was concluded. This alternate process was not included in the study.

Sample Identification	Process
A1	Vacuum anneal only (5.1.3.2)
B1	Cryogenic stabilization only (5.1.3.3)
C1	Vacuum anneal and cryogenic stabilization (5.1.3.2 and 5.1.3.3)
D1	Stock material—no thermal processing (5.1)

Table 4: Samples Identified to Corresponding Processes

Additional information regarding the EDM processing of these coupons is reported in section 5.1.5.4 of this report.

PART #A-1

330.5 VICKERS/200gm

500X

Figure 15 Part A-1—Vacuum Anneal Only

PART #B-1

332.5 VICKERS/200gm

500X

Figure 16 Part B-1—Cryogenic Stabilization Only

PART #C-1

320.8 VICKERS/200gm

500X

Figure 17 Part C-1—Vacuum Anneal and Cryogenic Stabilization

PART #D-1

356.5 VICKERS/200gm

500X

Figure 18 Part D-1—Stock Material

5.1.3.2 Vacuum Anneal

The blanks were annealed at 1300 degrees F and held at temperature for two hours in an Abar BM-772 vacuum furnace. A temperature ramp speed of 60 degrees per minute was used with the furnace vacuum at 10^{-5} TORR. The blanks were allowed to return to room temperature by furnace cooling. This cooling takes approximately eight hours of the 12 1/2 hour process (figure 19).

Figure 19 Titanium Component Vacuum Anneal Process

5.1.3.3 Alternate Process Investigation—Cryogenic Stabilization

The technology of cryogenic treatment of materials is not fully understood. We have used this process successfully on aluminum parts to provide greater material stability. Cryogenic cooling helps to maintain geometric tolerances such as flatness, parallelism and surface profile by minimizing stresses in the material. Cryogenic processing allows the material to retain mechanical properties that would otherwise be lost with the application of conventional heat treating processes.

Industry has used the cryogenic process for approximately ten years to extend the cutting life of steel and carbide cutting tools².

Subsequent to the vacuum anneal process, a control sample of titanium blanks was processed following the cryogenic sequences shown in figure 20. The applicability of this process and any resulting manufacturing benefits for this component were determined to be nil.

Figure 20 Titanium Component Cryogenic Stabilization Cycle

5.1.3.4 Recommendation

This process did not result in a more stable work piece than blanks subjected to the lone vacuum anneal process. Benefit or detriment was not detected in the control batch; therefore, the cryogenic process is not necessary.

5.1.3.5 Alternate Vacuum Anneal Process (Contractor supplied)

The blank was vacuum annealed at 1350 degrees F and held at temperature for four hours. A ramp speed of fifteen degrees per minute was used. Appreciable differences in geometric stability were not noted in the blanks subjected to this alternate process; however, a complete study may conclude differently (figure 21).

Figure 21 Titanium Component Alternate Vacuum Anneal Process

5.1.4 Datum Machining

This operation establishes diameters -A- and -B-, from which most subsequent features are referenced. Precise alignment of the blank is not critical at this point; however, stresses should be minimized in the clamping of the blank.

5.1.4.1 Fixture

The aluminum mandrel's outer diameter is about .010 inch smaller than the bore of the blank. A 3/8-24 threaded hole is machined into the end of the mandrel. This will accept the screw and washer unit used to hold the part on the mandrel.

The 3/8-24 screw was modified to accept a 60 degree live center from the tailstock for support and vibration dampening.

5.1.4.2 Process

The blank was placed on the mandrel, lightly secured with the screw, and indicated to within .002 inch maximum runout. The tailstock was then engaged to provide support and vibration dampening. Datum diameters -A- and -B- were then cut to .02 inch oversize. This .005 inch skim cut establishes the concentricity of these two diameters following the annealing process. Size will be attained in a subsequent operation.

The weld prep grooves in both faces were initially machined at this stage. The groove designated by dimensions 9, 21, and 23 (figure 11) proved to have a negative effect on the flushing action in the wire EDM operation that finished the inner feature. The small groove defined by dimensions 5 and 30 (figure 11) should be completed at this stage of the process by using standard manufacturing practices.

5.1.4.3 Recommendation

It is suggested that the weld prep groove designated by dimensions 9, 21, and 23 (figure 12) be produced in the outer profile finishing sequence following the finishing of the inner feature.

5.1.4.4 Parameters

SFM Work Speed	IPR Feed Rate	Depth of Cut	Tool Designation
200	.010	.005	VC-29

Table 5: Datum Machining Parameters

5.1.5 Electrical Discharge Machining (EDM) of Inner Feature

5.1.5.1 Process

A wire EDM process was used to finish the inner feature. The part was mounted in the fixture with about .001 inch clearance between the clamping mechanism and the part. A stop was clamped to the bottom fixture plate to assist in vertical alignment. Eastman 910 adhesive was used to secure the blank in the fixture. A ground strap of aluminum tape was attached to the blank and to the machine ground. This assured conductivity requirements were met.

An Agietron Agiecut 200 (figure 4) and a Charmille Robofil 600 (figure 5), both capable of submerged cutting, were used in the development of this process. A series of four cuts was made to achieve size, finish and geometric feature. This "skim cutting" technology is commercially available and currently used in the EDM industry.

5.1.5.2 Recommendation

Most variables can have a major impact in a positive or negative manner on the close tolerances of size and geometry of these components. A primary variable, water conductivity, determines the consistency of the spark gap and should not exceed 20 micro-siemens for precision EDM operations.

The EDM machine tool should be operated in the mode presenting the finest resolution of machine table movement. The metric mode generally provides the finest resolution available on machine tools today. The metric mode was used on the EDM machine tools at LLNL during the development of this process.

A reduction in the environmental influences of the machine tool will result in greater accuracy and repeatability during the manufacturing process.

Isolation from ground vibration will enable the machine tool to produce a more consistent feature. Vibration dampening pads, supplied with the machine tool, should be used as a minimum precaution. Additional isolation can be achieved by anchoring the machine tool to a stable foundation.

Thermal variations can cause the physical features of the machine tool to drift. Three such thermal influences are; an air conditioner or heater blowing on the tool, and opening an outside door near the machine tool. The machine tool can be protected from these sudden thermal shocks

by physically shielding it from these direct sources of temperature change. Protection can be in the form of an enclosure that can be designed to provide temperature, particulate, and humidity controls.

5.1.5.3 Parameters

A 0.25 mm diameter Gisco brand, Bronco Cut X wire was used in the development of cutting parameters.

Power and Wire Settings

	Main Cut	First Trim	Second Trim	Third Trim
M	5	5	5	2
t	12	8	8	20
I	10	10	4	5
PR	10	1	1	1
P	10	32	32	32
td	25	35	40	32.5
HC	10	1	1	0
Cw	2	2	2	2
FW	20	20	20	20
VW	180	160	140	140

Table 6: Power and Wire Settings for the Agietron 200

M: Establishes the "mode" that the machine works in
t: Preselection for the pulse duration, varies according to M
I: Selection of maximum pulse current amplitude
PR: Power range, adapted to a selected power level
P: Selector switch for maximum power erosion
td: Discharge delay preselection
HC: Height compensation for workpiece dependent bowing-back of wire in full thickness cut
Cw: Class of wire (two is for wires above .1 mm diameter)
Fw: Tension of wire in the work zone in Newtons
Vw: Rate of unwinding for the wire electrode

Flushing Settings

	Main Cut	First Trim	Second Trim	Third Trim
B	1	1	1	1
K	10	10	10	10
Q	3	1	1	1
Qo	12	12	12	12
Qu	12	12	12	12
Qou	.4	.4	.4	.4

Table 7: Flushing Parameters for the Agietron 200

B: Selection parameters for eroding in a bath (submerged work piece)
K: Water conductivity in micro-siemens/centimeter
Q: Selection of programmed flushing parameters
Qo: Full thickness cut in plane/parallel parts
Qu: Full thickness cuts in parts with recesses
Qou: First full thickness cut, follow up cut

Geometric Setting

D	Main Cut	First Trim	Second Trim	Third Trim
	.257	.191	.174	.169

Table 8: Geometric Parameter Setting for the Agietron 200

D: The offset distance, expressed in millimeters, for determining the size of the feature. This value is a function of the finished dimension, power, flushing, and wire size parameters.

5.1.5.4 Metallographic Investigation

Cursory studies were conducted to quantify the heat affected zone and to determine the integrity of the EDM surface. The heat affected zone was determined to be .0005 inch, measuring from the largest "nodule" to the base of the modified grain structure of the material (figure 22-25).

An attempt to determine the adhesion characteristics of the "nodules" was conducted by applying a .75 inch² tape to the EDM surface. Removal of this tape was followed by a 150X microscopic video examination for particulate. A "soot" was found on the tape in several places, but no distinguishable particulate was discovered.

PART #A-2

304.5 VICKERS/200gm

500X

PART #A-2

EDM CUT SURFACE

500X

Figure 22 Part A-2—Vacuum Anneal and Wire EDM. Top: A 500 times magnification of the grain structure of 6 Al 4 V Titanium (ELI variety) after undergoing the vacuum anneal process followed by EDM processing. Material hardness, based on the Vickers scale is shown. Bottom: A sectional view of the EDM surface, note the nodules that have attached themselves to the surface and the compressed grain structure near the surface. Determination of the .0005 inch heat affected zone was made from this photomicrograph.

PART #B-2

332.5 VICKERS/200gm

500X

PART #B-2

EDM CUT SURFACE

500X

Figure 23 Part B-2—Cryogenic Stabilization and Wire EDM. Top: A 500 times magnification of the grain structure of 6 Al 4 V Titanium (ELI variety) after undergoing the cryogenic stabilization process followed by EDM processing. Material hardness, based on the Vickers scale is shown. Bottom: A sectional view of the EDM surface, note the nodules that have attached themselves to the surface and the compressed grain structure near the surface. This is the heat effected zone generated by the EDM process.

PART #C-2

299.3 VICKERS/200gm

500X

PART #C-2

EDM CUT SURFACE

500X

Figure 24 Part C-2—Vacuum Anneal followed by Cryogenic Stabilization and Wire EDM. Top: A 500 times magnification of the grain structure of 6 Al 4 V Titanium ELI after undergoing the vacuum anneal process and cryogenic stabilization, followed by EDM processing. Material hardness, based on the Vickers scale is shown. Bottom: A sectional view of the EDM surface, note the nodules that have attached themselves to the surface and the compressed grain structure near the surface. This is the heat effected zone generated by the EDM process.

PART #D-2

324.6 VICKERS/200gm

500X

PART #D-2

EDM CUT SURFACE

500X

Figure 25 Part D-2—Stock Material and Wire EDM. Top: A 500 times magnification of the grain structure of 6 Al 4 V Titanium (ELI variety) stock. Thermal processing was not done prior to EDM processing. Material hardness, based on the Vickers scale is shown. Bottom: A sectional view of the EDM surface, note the nodules that have attached themselves to the surface and the compressed grain structure near the surface. This is the heat effected zone generated by the EDM process.

5.1.5.5 Recommendation

Wire brushing of the EDM surface will remove most of the "soot". An acceptable material for the brush will need to be determined by the cryocooler supplier, and an acceptable cleaning procedure must be identified.

A complete metallurgical study of the effects of the EDM process should be undertaken to establish the process viability for cryocooler components.

5.1.6 Finishing of Outer Features

5.1.6.1 Process

The blank is mounted on a non-influencing mandrel. The mandrel diameter is cut .005 under the inner diameter of the blank to assure a free-state condition. Tail stock force is applied through the part to drive the blank. This driving method and mandrel configuration assure roundness and straightness within machine tool capability. Wall thickness and the related concentricity are compromised with this method.

5.1.6.2 Alternate Process (Contractor supplied)

This process will provide for a constant component wall thickness. It has a negative impact on the free state geometric requirements specified on the print. The mandrel, .0002 to .0003 inch over the nominal blank inner diameter, is placed in a deep freeze at -120 degrees F for 12 hours. The blank and mandrel are assembled, allowed to return to room temperature and are then ready for the finish machining operation. This "shrink" fit provides for a constant wall thickness. Inner diameter irregularities will be transferred to the outer profile, resulting in a compromise of the free state geometric requirements.

5.1.6.3 Recommendation

Modification of drawing specifications to reflect the functional preference of a constant wall versus the free state geometric definition currently specified (figure 11).

5.1.6.4 Parameters

SFM Work Speed	IPR Feed Rate	Depth of Cut	Tool Designation
200	.010	.005	VC-29

Table 9: Parameters for Finishing of the Outer Profile

5.1.7 Inspection

5.1.7.1 Diametrical Size

A laser micrometer was used to characterize external features. Air gaging was shown as a viable option for internal size determination. Conventional micrometers can be used to measure the more robust features.

5.1.7.2 Runout Measurement Process

Portions of the following sequence can be visualized by referring to figure 6.

The Indi-Ron roundness gage was used to check the runout condition of the component. A small diameter, .001 inch, stylus probe tip is recommended to minimize the effects of airborne contaminants.

Polar charts (figure 26) were generated for all diameters with a runout tolerance. All total runout requirements will need polar charts generated at one-half inch increments. When the cylinder is less than one half inch long, a chart at the top and bottom of the cylinder is required.

The component was placed, -A- datum end down, on the table of the Indi-Ron Gage and centered, it was then bonded in position with a cyanoacrylate adhesive.

The EDM "blue line" was oriented to zero on the polar chart. This "blue line" results from the initial EDM cut and provides a permanent index mark for future rotational reference to the documentation.

Align datums -A- and -B-; generate a polar chart to document concentricity.

A polar chart of the upper most face (datum B end) was generated to document the face runout.

The interior diameter was probed for runout using a four inch long probe. Runout measurements at one-half inch increments, were taken off of the inner surface and plotted on polar charts.

Datums -A- and -B- were reinspected to verify that their positioning had remained constant through this process. A polar chart was generated to document their position.

Straightness checks were made to tie the polar chart data together. This was done on a Federal Surfanalyzer (figure 9).

All charts must be clearly and completely marked with information relating to part serial number, location of measurement and feature being measured.

CHART #7
P/N WG #2
PART HELD WITH GLUE

IS .000128
CHECKED IN CENTER
AREA OF DIAMETER

Figure 26 Polar Chart

5.1.7.3 Linear Features

All external linear, angular, and radii features were measured and recorded with an optical comparator.

Internal radii and angles were transferred to an optical comparator and was then used to check these features.

Depth dimensions can be checked with a conventional depth micrometer.

Widths of grooves can be verified with gage pins or vernier calipers.

5.2 718 Inconel and 321 Stainless Steel

Initial considerations led to the specification of 718 Inconel for this demonstration component. After a thorough attempt (see section 6), efforts were redirected to a vendor accepted alternative, 321 Stainless Steel. Manufacturing processes were similar for the two materials and are reported in this manner where possible. Alternative process investigations are also documented.

The understanding that all decisions, from process steps and machining parameters to equipment and personnel selection, have a major impact on the successful production of these components is one of the primary findings of this project. Maximizing speeds, feeds and depths of cut, standard practice in conventional manufacturing plans, is false economy when components of this nature are to be produced. Seemingly inconsequential operations, such as rough drilling the bore, are thought to have been a root cause of geometric instability encountered in our first attempts to produce this component.

5.2.1 Recommendation

Skilled crafts' people must be involved in the manufacture of these challenging parts. The team concept, bringing together manufacturing and inspection, proved valuable during the development of the following processes. We believe that this type of involvement would have been most beneficial beginning with the initial design phase, resulting in a more producible product. The development of a manufacturing plan, the "fine tuning" of it and strict adherence to it, will contribute greatly in the successful production of difficult components.

Most CNC lathes are capable of performing these operations, and are indeed encouraged, as they can provide the consistent cutting conditions that help maintain the process control.

5.2.2 Blank Preparation

We obtained 5/8 inch diameter 718 Inconel and 321 Stainless Steel bar stock, in four foot lengths, for these demonstration parts. The blanks were sawed to length, leaving approximately 1/8 inch for the initial face machining, which leaves the blank length .02 inch over the finish dimension.

5.2.3 First Roughing Operation (Inconel/Stainless Steel)

5.2.3.1 Process

The first operation removed the bulk of the inner material by drilling. The removal of the "skin" from one end of the blank's outer diameter was also done at this time. The removal of this skin relieves the stresses inherent in raw stock. These stresses are the result of the proper bar sizing and surface cooling contractions during manufacture.

The blank was gripped in a collet with three inches of material protruding for this operation. The blank was center drilled, then drilled with a .453 inch diameter cobalt drill to a depth to 2.5 inches. The outer diameter was turned to .578 inches with .01 inch depth of cuts. The light cuts were taken to minimize the introduction of stress into the blank. A Cool-Mist atomizer was used to apply a Trim-Sol mist to help keep the cutting tool and blank cool. Refer to Section 3.2 for clarification on the use of Trim-Sol.

5.2.3.2 Parameters

SFM Work Speed	IPR Feed Rate	Depth of Cut (inch)	Tool Designation
120	.01	.01	VNMS 331 K-68

Table 10: Parameters for the First Roughing Operation-718 Inconel

RPM Work Speed	IPR Feed Rate	IPT (drill)	Tool Designation
280	.010	.005	.453" Cobalt Steel

Table 11: Drilling Parameters for 718 Inconel Roughing Operation

SFM Work Speed	IPR Feed Rate	Depth of Cut (inch)	Tool Designation
160	.005	.01	VC-29 Hi-Rake*

Table 12: Parameters for the First Roughing Operation-321 Stainless Steel

* VC-29 grade carbide in 35 degree configuration with a .01 inch nose radius. An after market, 30 degree positive back rake was ground onto this insert to reduce cutting pressure.

RPM Work Speed	IPR Feed Rate	IPT (drill)	Tool Designation
370	.010	.005	.453" Cobalt Steel

Table 13: Drilling Parameters for the 321 Stainless Steel Roughing Operation

5.2.4 Second Roughing Operation (Inconel/Stainless Steel)

5.2.4.1 Process

The blank was reversed and held in a 37/64 inch collet, with a minimum of material protruding, for the roughing of the remaining diametric features and the spherical radius. Multiple passes were taken to remove stock and leave .02 inch on the .250 and .185 inch diameters, spherical radius and length. A flood coolant of Trim-Sol was used during this process to help remove heat from the cutting zone.

5.2.4.2 Parameters

SFM Work Speed	IPR Feed Rate	Depth of Cut	Tool Designation
120	.01	.02	VNMS 331 K-68

Table 14: Second Roughing Operation Parameters on the 718 Inconel Component

SFM Work Speed	IPR Feed Rate	Depth of Cut	Tool Designation
160	.01	.02	VC-29 Hi-Rake*

Table 15: Second Roughing Operation Parameters on the 321 Stainless Steel

* VC-29 grade carbide in 35 degree configuration with a .01 inch nose radius. An after market, 30 degree positive back rake was ground onto this insert to reduce cutting pressure.

5.2.5 Heat Treat Cycle

Conventional annealing processes and cryogenic stabilization processes were employed on the demonstration project components following the second roughing operation.

The technology of cryogenic treatment of materials is not fully understood. We have used this process successfully on aluminum parts to provide greater material stability. Cryogenic cooling helps to maintain geometric tolerances such as flatness, parallelism and surface profile by minimizing stresses in the material. Cryogenic processing allows the material to retain mechanical properties that would otherwise be lost with the application of conventional heat treating processes.

Industry has used the cryogenic process for approximately ten years to extend the cutting life of steel and carbide cutting tools².

5.2.5.1 Stainless Steel - Vacuum Anneal

Conventional annealing (figure 27) was performed on the Stainless Steel components following the second roughing operation. The resulting condition of the blanks was consistent with the expectations of this process.

Figure 27 321 Stainless Steel Vacuum Anneal Cycle

5.2.5.2 Inconel - Cryogenic Stabilization

The Inconel parts blanks were subjected to the cryogenic sequence described by figure 28. Appreciable benefit could not be determined within the scope of this project.

Figure 28 718 Inconel Cryogenic Stabilization Cycle

5.2.6 Finishing Operation (Inconel)

Cylindrical grinding was identified as a suitable method of finishing the outer features of this component. Findings of this process investigation are presented in the following sections of this document.

The annealed blank was held in a collet on the solid portion of the .578 inch diameter, with three inches extending. Alignment of the blank, though not crucial at this time, was assured by indicating and adjusting any discrepancy at both ends of the exposed blank. This effort at alignment was intended to alleviate potential difficulties in the following operations.

The inner bore was finished using a 3/8 inch diameter solid carbide boring bar with a triangular shaped K-313 insert. The insert had a .005 inch radius on the cutting tip and a 30 degree back rake which was ground onto the insert to enhance the chip flow characteristics of the insert.

SFM Work Speed	IPR Feed Rate	Depth of Cut (inch)	Tool Designation
100	.001	.005	K-313

Table 16: Finish Machining Parameters for the .4774 inch diameter bore of the Inconel Component

A Weldon CNC cylindrical grinder was used initially to attempt finishing the tightly tolerated outer features. A tooling mandrel was ground, and the Inconel blank mounted on the mandrel. Driving force and support was achieved by using the tail stock of the grinder.

Finish grinding of all external features, diameters, tapers and the spherical radius was attempted during the first operation. The initial results showed good surface finish on the diameters, however the taper and radius did not finish to an acceptable level.

A second grinding theory, grinding each feature independently of the others, proved unacceptable. Break out of the inner bore occurred during this process causing a rethinking of the process. Examination of our second part revealed evidence of two suspected problems. The inner diameter was getting larger as material was ground from the outer surface, residual stresses from the roughing operation were thought to cause of this situation. The other area of suspicion was

the grinding relief put into the blank in the roughing operation. The tail stock pressure was great enough to cause the blank to flex at the relief, allowing the part to continuously pull into the grinding wheel, causing a greater depth of cut. This constant flexing is also thought to be a source of stress build up in the blank during the finishing operation.

SFM Work Speed	IPR Feed Rate	Depth of Cut	Wheel Designation
150 RPM	5 IPM	.0001	Norton 60

Table 17: Parameters for the CNC Weldon grinder process

Lack of ideal tooling and configuration of the CNC grinder led to the consideration of a conventional cylindrical grinder. A Brown and Sharpe Number two grinder was considered our best available machine to continue this process investigation.

Attempting to machine the blanks between centers was chosen as the suitable method of part fixturing for this operation. Hardened support pins were made to fit the inner diameter of the blanks, a tooling center was dressed in a center grinder after the pins were hardened. The tailstock center was redressed in the machine to provide optimum alignment between the support pin and blank configuration and the tailstock.

A wall thickness of .007 inch was attained prior to the inner bore increasing in size. Considerable effort was made to provide mandrel support in pursuit of the specified .005 inch wall thickness. Successively larger support pins were required as the inner bore continued to enlarge when work was done on the outer features. The resulting parts were not within the prescribed tolerances, resulting in the decision to pursue Stainless Steel as the subsequent material of choice for this component.

SFM Work Speed	IPR Feed Rate	Depth of Cut	Wheel Designation
150 RPM	5 IPM	.0002	Norton 32A 46J*

Table 18: Parameters for the Brown and Sharpe conventional process

* Dressed to .600 inch wide, suggested to relieve to .25 inch

5.2.6.1 Recommendation

Results of these investigations preclude grinding as available process in the precision production of this cryocooler component. We acknowledge differing results may be attained with a more thorough study done in conjunction with persons possessing a more applicable experience base.

Processes developed for the Stainless Steel components (detailed in section 5.2.7) are very promising. We recommend the application of these processes in an attempt to produce an acceptable component from Inconel.

5.2.7 Finishing Operation (Stainless Steel)

5.2.7.1 Method 1

The annealed blank was held in a collet on the solid portion of the .578 inch diameter, with three inches extending. Alignment of the blank, though not crucial at this time, was assured by indicating and adjusting any discrepancy at both ends of the exposed blank. This effort at alignment was intended to alleviate potential difficulties in the following operations.

The inner bore was finished using a 3/8 inch diameter solid carbide boring bar with a triangular shaped K-313 insert. The insert had a .005 inch radius on the cutting tip and a 30 degree back rake which was ground onto the insert to enhance the chip flow characteristics of the insert. Lead

tape was fixed to the outer diameter to dampen the machining vibrations generated in finishing the inner diameter.

SFM Work Speed 160	IPR Feed Rate .001	Depth of Cut (in.) .005	Tool Designation K-313
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Table 19: Finish Machining Parameters for the .4774 inch diameter bore of the Stainless Steel Component (Method 1)

The .4843 outer diameter was finished following the completion of the bore. A mandrel was placed in the bore and supported by the tail stock of the lathe. This provides the backing necessary to machine to thin walled configurations. Light cuts with continuous feed of the tool are required to minimize the amount of stress introduced into the component.

SFM Work Speed 160	IPR Feed Rate .002	Depth of Cut (in.) .005	Tool Designation VC-29*
-----------------------	-----------------------	----------------------------	----------------------------

Table 20: Finish machining parameters for the .4843 outer diameter

* VC-29 grade carbide in 55 degree configuration with a .01 inch nose radius. An after market, 30 degree positive back rake was ground onto this insert to reduce cutting pressure.

The blank was then held in a V-block registering on the finished .4843 diameter, the blank's tooling center was redressed in a center grinder to assure coincident centerlines of these two features prior to finishing the remaining outer features. A CNC lathe was used for the finishing operation.

A support pin was placed in the finished bore prior to gripping the solid portion of the .4843 diameter lightly in a collet. A floating center (figure 29) was used to apply driving pressure to the part during this turning operation. The floating center method reduces the affects of misalignment factors found in the blank or machine, resulting in the optimum conditions for achieving the close tolerances specified for this component. The finish machining of the remaining diameters, 30.25 degree conic section and the spherical radius was done during this operation. Alignment was verified using an electronic indicator.

SFM Work Speed 160	IPR Feed Rate .002	Depth of Cut (inch) .005	Tool Designation VC-29*
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Table 21: Parameters for Finishing Outer Features of the Stainless Steel Component

* VC-29 grade carbide in 55 degree configuration with a .01 inch nose radius. An after market, 30 degree positive back rake was ground onto this insert to reduce cutting pressure.

The .068 inch diameter holes were machined using conventional LLNL manufacturing practices. The hole drilling operation has the potential for raising material at the hole and spherical radius interface, causing a violation of the true position tolerance of the .250 radius. An awareness of this possibility, as stated earlier, is crucial in producing a quality component.

Figure 29 Floating Center

5.2.7.2 Method 2

The annealed blank was held in a V-block, registering on the skimmed .578 diameter, to redress the tooling center in a center grinder to assure alignment of these two features prior to the first finishing operation step.

The blank was then held in a .578 inch (37/64) collet with 3 1/8 inches of the smaller diameter end protruding. The floating center (figure 29) was employed to apply noninfluential driving force to the part during this turning operation. The floating center method reduces the affects of misalignment factors found in the blank or machine, resulting in the optimum conditions for achieving the close tolerances specified for this component. Alignment was verified using an electronic indicator.

The .2500 and .185 diameters, spherical radius and conic section were finished at this time. Prior to the final .01 inch being removed, the tooling center redressing process was repeated, assuring minimal impact of misalignment issues. The minimization of additional stresses in the blank was achieved by using sharp tools, small depths of cut (.005 inch) and light but continual feed rates. The .4843 diameter was finished to within approximately .100 inch of the depth of the .4744 diameter bore. This process was used to avoid stressing the thin wall section of the blank during this phase of the finishing operation.

A split fixture (figure 30) was built to support the .250 and .4843 diameters during the remaining turning operations. Clamping forces of the fixture were limited to the .4843 diameter. The inner bore was semi-finished using a 3/8 inch diameter solid carbide boring bar with a triangular shaped K-313 insert. The insert had a .005 inch radius on the cutting tip and a 30 degree back rake which was ground onto the insert to enhance the chip flow characteristics of the insert. The finishing passes were taken with a K-68 grade insert. Lead tape was fixed to the outer diameter to dampen the machining vibrations generated in finishing the inner diameter.

SFM Work Speed	IPR Feed Rate	Depth of Cut (inch)	Tool Designation
160	.002	.005	K-68*

Table 22: Bore Finishing Parameters for 321 Stainless Steel (Method 2)

* K-68 grade carbide in a triangular configuration with a .007 inch nose radius and 30 degree positive back rake to reduce cutting pressure through improved chip flow characteristics.

The outer finishing process was aided by placing a support pin, .0002 inch smaller than the finished inner bore, to provide support during the finishing of the outer diameter. The pin was designed to provide a driving force to the 10 degree angled base of the inner bore. A tooling center in the support pin provided for the tailstock engagement to provide this force. The .4844 diameter, finished in this configuration, was turned with a minimum disruption of existing features by employing sharp tools, small depths of cut (.005) and light but continual feed rates.

SFM Work Speed	IPR Feed Rate	Depth of Cut (inch)	Tool Designation
100	.001	.005	VC-29*

Table 23: Outer Feature Finishing Parameters (Method 2)

* VC-29 grade carbide in 55 degree configuration with a .01 inch nose radius. An after market, 30 degree positive back rake was ground onto this insert to reduce cutting pressure.

MOUNTING ADAPTER

CRYOCOOLER COMPONENT

RETAINING CAP

Figure 30 Split Fixture

5.2.8 Inspection

5.2.8.1 Diametrical Size Determination

The thin wall section necessitated the use of the non-contact LaserMike, which may be used to inspect the other outer diameters. Most outer diametrical dimensions can also be determined with a conventional micrometer.

Air gaging was used to measure the thin wall section inner diameter. The smaller diameters, being less fragile, were inspected with gage pins.

5.2.8.2 Runout Measurement Process

LLNL's Bendix Indi-Ron roundness gage was used to inspect the runout condition of the component. A small diameter, .001 inch stylus probe tip is recommended because it minimizes the effects of airborne contaminants.

Polar charts (figure 26) were generated for all diameters with a runout tolerance. All total runout measurements will need polar charts generated at one-half inch increments. When the cylinder is less than one half inch long, a chart at the top and bottom of the cylinder is required.

The polar chart was oriented to the zero degree position. Using a flow ball pen, a mark was placed on the part. This index mark provided the necessary correlation of chart data to the location of the measurement.

The part was held in a V-Block on the Indi-Ron table. Datums -A- and -B- were aligned and a polar chart was generated to document the concentricity of the two diameters.

The exterior and interior diameters were probed for at this time. Polar charts, at one-half inch increments, were taken of all diametrical features with associated runout tolerances.

Three radial traces, at varying heights on the .25 inch spherical radius, were made to determine its runout to the datums.

Datums -A- and -B- were reinspected to verify their positioning had remained constant through this process. A polar chart was generated to document their position.

Straightness checks were made to correlate the polar chart data. This was done on a Federal Surfanalyzer.

All charts must be marked clearly and completely with information relating to part serial number, location of measurement, and feature being measured.

5.2.8.3 Linear Feature Verification

All external linear, angular, and radii features were measured and recorded with an optical comparator.

Internal radii and angles were transferred to a dental impression material. An optical comparator was then used to check these features.

Depth dimensions were checked with a conventional depth micrometer.

VI. COSTS

MODIL Demonstration Project costs are presented in a man-hours format that separates costs for the development, production and demonstration phases of the project (figure 31).

The Inconel component machining development process did not reach the production phases. This is illustrated with only one bar on the graph. Information detailing this development process is in section 5.2.6.1 of this report.

The stainless steel component process development was achieved in major part by capitalizing the information derived from the Inconel component process development effort.

Figure 31 Hours/Component/Phase Comparison

6.1 First Briefing to Industry

On September 23-24, 1993, an industry-wide briefing was hosted by SDIO's Spacecraft Fabrication and Test MODIL at LLNL. The over 100 attendees represented a broad spectrum of aerospace industry involved in producing SDIO systems, as well as many key representatives from SDIO programs (BE, GBI, BP, etc.). The briefing included numerous presentations, working sub-sessions, and tours of MODIL applicable, potentially applicable, and showcase facilities.

The briefing had two major objectives:

- To explain the objectives and progress of the SF&T MODIL and
- To present LLNL technology applied to current MODIL thrusts, as well as, key technology of potential benefit to SDIO programs.

The cryocooler thrust area subsession consisted of four presentations which are as follows:

- Cryocooler MODIL Thrust Area Subsession
- Producibility for Cryocoolers FY93
- MODIL Demonstration, Material Fabrication Division Phase
- Partnership with the California Community Colleges, Centers for Applied Technologies

Details of the briefing are published in the proceedings³.

VII. CONCLUSIONS AND RECOMMENDATIONS

Through the contractor, supplier, and LLNL project summary meetings, many issues were raised that offered solutions to producibility problems encountered within the design/manufacturing environment. The results of the producibility demonstration project illustrated the need to consider and to implement changes in the current method of operation in the production community.

Following are recommendations that surfaced in our working interaction and meetings with the participating contractors, their suppliers, and the LLNL producibility teams:

- Make sure all parties involved know what the project goals are and what's expected of them.
- Involve all participants in the whole project (from beginning to end), solicit their ideas from the beginning (engineering, manufacturing, QA, purchasing, etc.). Brainstorming is a must.
- Engineering staff should share floor time with machinist to understand what it takes to make parts.
- Ideas have to be readily accepted for consideration without personal bias.
- Teams assigned to the project are most efficient and cost effective when maintained as an entity throughout the project.
- Evaluate every manufacturing option to optimize project end-product.
- LLNL is a resource for manufacturing technology available to US industry.
- Minimize inspection by building robustness into parts and controlling the manufacturing process. Spend the time needed in the design phase.
- Design reviews must include all parties to ensure the drawings are as correct as possible before parts are manufactured. Pre-production design changes have a lesser financial impact than making changes during manufacturing.

The results of this demonstration project demonstrated that precision production issues can and should be addressed early in the design phase of any project. Concurrent engineering practices do work!

VIII. PROJECT CLOSE-OUT MEETING SUMMARIES

1. Gilbert E. Cruz, "Creare/Westfield Gage/LLNL Demo Project Close-Out Meeting", Dec 1992, 92-249, LLNL.
2. Gilbert E. Cruz, "Hughes Aircraft/Modern Industries/LLNL Demo Project Close-Out Meeting", Dec 1992, 92-250, LLNL.

MATERIALS FABRICATION DIVISION

Mail Station L - 332

Ext: 2-4849

December 1, 1992
92-249

To: Distribution
From: G. E. Cruz
Subject: Creare/Westfield Gage/LLNL Demo Project Close-Out Meeting

The guidelines for the meeting were that it was to be an open, candid and issue oriented meeting with the purpose of summarizing the LLNL Producibility Demonstration Project results with LLNL, Creare and Westfield Gage. Issues raised are to be used to help improve the production capabilities of Westfield Gage in addition to other U.S. companies that can use the information. Creare will continue to be a contract R&D company and not work production issues.

The key issue of the demo project was to demonstrate the vital need for companies to employ concurrent engineering techniques within their respective companies. The salient point of the interactions is the early-on and continuous communication between all the parties involved in the production of a product through to the end of the project.

The demo project began slowly because of a number of issues. A key issue being that everyone did not know each other and a working relationship had to be established between all of the involved parties.

Other impediments were: a lack of a full understanding about the project goals, what each company would get out of the project, and what the boundary conditions of the project were.

Once the project settled into a working entity, the communication between all of the parties was very good and candid. Each party communicated openly with one another and at the time this began, progress was achieved. Ideas and problem solutions transferred back and forth rapidly, both LLNL and Westfield Gage learned things from one another. By working in close proximity, information was shared first hand, therefore, facilitating better comprehension of the problems and their solutions. It was learned that to better transfer technology it is optimal to be in close proximity where issues and questions can be addressed in real time. Another fact that was learned was that mutual trust amongst the involved parties is necessary to succeed. This takes personal contact. Westfield Gage demonstrated this with LLNL and Creare during this project and because of this

University of California

Lawrence Livermore
National Laboratory

attitude, the project was a success. What is being shown is that any company has to work closely and openly with their suppliers if they are to be successful.

The project demonstrated that the complete goals of the project need to be presented to the project participants at the beginning of the project and that the designers, machinists, technicians, etc. need to have access to the engineering and scientific staff throughout the project in order to mitigate risk, cost, schedule and production problems.

Project teams must be maintained throughout the project for continuity. Rotating participants in and out of the project creates confusion, schedule delays and extensive learning curve effects.

Tabulated inspection data needs to be documented to efficiently track the results of in-process work and to produce the highest quality end product.

The inspection work between LLNL and Westfield Gage validated the inspection techniques at Westfield Gage.

The Laboratory did not utilize the full extent of MFD capability because processes were to be developed utilizing only the machines comparable to what industry has. Developing a process on state-of-the-art equipment would not help industry, who in most cases does not possess this type of equipment.

A key technical issue learned by all was the importance of using non-contact inspection techniques (i.e., air gauging, laser micrometer) on thin wall, precision toleranced parts. The results are more accurate and repeatable. In addition, using EDM techniques to machine internal diameters was presented. Westfield had not considered using EDM for this application. Westfield Gage learned, through the close interaction with the LLNL people, the importance of controlling the EDM machine operating parameters (water conductivity, etc.) in order to be able to produce continually high quality parts. Westfield is considering how they work projects and what changes could be made to optimize their operation (e.g., involving shop floor people in early-on project planning).

The LLNL machinists learned the benefit of using machines with adjustable tail stocks.

One institutional problem arose that caused problems. The procurement and contracts procedure caused delays with the project start-up. The major issue is that if LLNL wants to effectively work with outside companies the in-house process has to be optimized.

These issues were the primary subject brought up at the meeting. There were others, however, they were variations of communications and techniques learned, which was previously mentioned.

In summary, time and money constraints dictated certain requirements of this project, therefore, the project scope was limited to a goal that could readily be achieved. That goal was to focus on the process of concurrent engineering in a manufacturing environment.

The success of the program was dependent upon demonstrating a tangible result that could be readily understood. Our results demonstrated this. Creare and Westfield Gage were very instrumental in the success of this project. They are helping to prevent the Laboratory from being the nation's best secret; they realize that LLNL is a resource to industry and are looking for ways to work with the Laboratory.

G. E. Cruz
Operations Manager

GEC:jsc

Distribution: Benedict, John
Franks, Mark
Locke, Susan
Patterson, Dick (Westfield Gage)
Prokosch, Mike
Stearns, Bob (Creare)
Yordy, Don

MATERIALS FABRICATION DIVISION

Mail Station L - 332

Ext: 2-4849

**December 1, 1992
92-250**

To: Distribution
From: G. E. Cruz
Subject: Hughes Aircraft/Modern Industries/LLNL Demo Project Close-Out Meeting

The guidelines for the meeting were that it was to be an open, candid and issue oriented meeting with the purpose of summarizing the LLNL Producibility Demonstration Project results with LLNL, Hughes Aircraft and Modern Industries. Issues raised are to be used to help improve the production capabilities of each company in addition to other U.S. companies that can use the information.

The key issue of the demo project was to demonstrate the vital need for companies to employ concurrent engineering techniques within their respective companies. The salient point of the interactions is the early-on and continuous communication between all the parties involved in the production of a product through to the end of the project.

The demo project began slowly because of a number of issues. A key issue being that everyone did not know each other and a working relationship had to be established between all of the involved parties.

Other impediments were: a lack of a full understanding about the project goals, what each company would get out of the project, and what the boundary conditions of the project were.

Once the project settled into a working entity, the communication between all of the parties was very good and candid. Each party communicated openly with one another and at the time this began, progress was achieved. Ideas and problem solutions transferred back and forth rapidly, both LLNL and Modern Industries learned things from one another. By working in close proximity, information was shared first hand, therefore, facilitating better comprehension of the problems and their solutions. It was learned that to better transfer technology it is optimal to be in close proximity where issues and questions can be addressed in real time. Another fact that was learned was that mutual trust amongst the involved parties is necessary to succeed. This takes personal contact. Modern Industries demonstrated this with LLNL and Hughes during this project and because of this attitude, the project was a success. What is being shown is that any company has to work closely and openly with their suppliers if they are to be successful.

The project demonstrated that the complete goals of the project need to be presented to the project participants at the beginning of the project and that the designers, machinists, technicians, etc. need to have access to the engineering and scientific staff throughout the project in order to mitigate risk, cost, schedule and production problems.

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Project teams must be maintained throughout the project for continuity. Rotating participants in and out of the project creates confusion, schedule delays and extensive learning curve effects.

Tabulated inspection data needs to be documented to efficiently track the results of in-process work and to produce the highest quality end product.

The inspection work between LLNL and Modern Industries validated the inspection techniques at Modern Industries.

The Laboratory did not utilize the full extent of MFD capability because processes were to be developed utilizing only the machines comparable to what industry has. Developing a process on state-of-the-art equipment would not help industry, who in most cases does not possess this type of equipment.

A key technical issue learned by all was the importance of using non-contact inspection techniques on thin wall, precision toleranced parts. The results are more accurate and repeatable.

These issues were the primary subject brought up at the meeting. There were others, however, they were variations of communications and techniques learned, which ~~was~~ previously mentioned.

WHL

In summary, time and money constraints dictated certain requirements of this project, therefore, the project scope was limited to a goal that could readily be achieved. That goal was to focus on the process of concurrent engineering in a manufacturing environment.

The success of the program was dependent upon demonstrating a tangible result that could be readily understood. Our results demonstrated this. Hughes and Modern Industries were very instrumental in the success of this project. They are helping to prevent the Laboratory from being the Nation's best secret; they realize that LLNL is a resource to industry.

G. E. Cruz
Operations Manager

GEC:jsc

Distribution: Benton, Terry
Daniel, Jack (Modern Industries)
Fasholz, Dick
Franks, Mark
Gresko, Laurence (Hughes Aircraft)
Harkov, Dewayne
Neville, Steve (Hughes Aircraft)
Peters, Charles
Prokosch, Michael
Rose, Kevin (Modern Industries)
Saito, Ted
Yahraus, Dan (Modern Industries)

IX. REFERENCE MATERIAL

Glossary

- EDM:** Electrical Discharge Machining, a process involving the charging of an electrode and its subsequent discharge to the work piece. Variation of the charge determines the amount of cutting action at the electrode/work piece interface. Plunge or sinker EDM machines duplicate the electrode shape in the part. The electrode may be completely through the part or stop at any level into the part (blind hole). Traveling wire EDM allows a computer to direct the work piece under the wire to cut intricate shapes. The nature of wire EDM requires that the wire is allowed to pass through the part in a straight line.
- IPR:** Inches per Revolution, a common measure of the speed which a cutting tool moves across a work piece. Typically used in lathe operations.
- IPT:** Inches per Tooth, a common measure of cutting efficiency for drills or milling cutters.
- MODIL:** Manufacturing Operation Development and Integration Laboratory
- SFM:** Surface Feet per Minute, a measure of the amount of surface passing a cutting tool.
- Siemens:** The electrical conductance of a conductor in which a current of one ampere is produced by an electric potential difference of one volt. One siemens is the reciprocal of one ohm.

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1. Gilbert E. Cruz, Theodore T. Saito, Larry Fehrenbacher, TATI, "Cryocooler Producibility within a MODIL Concept", Apr 1992, UCRL-JC-110272, LLNL.
2. Pete Paulin, "Mechanisms and Applicability of Heat Treating at Cryogenic Temperatures", *Industrial Heating*, Aug 1992, pp. 24-27, 300 Below Inc., Decatur, IL.
3. Theodore T. Saito, "Proceedings, Spacecraft Fabrication and Test MODIL, First Briefing to Industry", September 23-24, 1993, Vol. 1, Oct, 1992.

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Error Budget Model

Stan Edson

**Lawrence Livermore National Laboratory
Livermore, California**

September 23, 1993

Error Budget Philosophy

- **Approach the design as a system.**
- **Understand the design requirements dictated by the system's function.**
- **Examine and budget error sources at the conceptual design phase.**
- **Design for function, manufacturability, and assembly.**

Project Approach

- **Mock-up Cryo Cooler Expander Assembly computer model using nominal sizes.**
- **Using an existing design (Hughes SSC), the component relationships to one another in the assembly were analyzed for inconsistencies and interferences.**
- **Utilized Parametric modeling techniques, with Unigraphics CAD software, to relate features on individual parts and related features in the Cryo Cooler Assembly.**
- **The end product illustrates that the Cryo Cooler design has errors with nominal dimensions and the method in which the parts relate to one another.**

Project Detail

- **A mock-up computer model of the Hughes SSC Cryo Cooler Expander Assembly will be shown.**
- **Individual parts showing expressions and dimensions illustrating geometric relationships controlling critical features on individual assembly components and on critical features between those components will be shown.**
- **This tool displays the effects of dimensional changes between related parts within an assembly.**

AIM

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Centimeter

Inches

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BY APPLIED IMAGE, INC.

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```

Conclusion

- **The error budget model was based on nominal dimensions; and, it was determined that the cryocooler expander design could not be assembled per the drawings.**
- **The model shows critical functional relationships.**
- **The product results show the need to apply an error budget analysis approach at the beginning of the design phase (Establish a robust design).**
- **A proper error budget analysis facilitates design for manufacturing and assembly.**
- **Applying the error budget after the design is complete generates higher costs and schedule delays.**

Summary

- **The error budget tool used does not provide all the answers; however, it demonstrates the benefit of a proper error budget analysis (By establishing the model on which to base the error budget).**
- **The next step is to look at the geometric dimensioning and tolerancing of the cryocooler features and their relationship to one another.**
- **Products (software) exist that analyze geometric dimensioning and tolerancing for complex assemblies.**

JC-112216

UCRL-
PREPRINT

MODIL Cryocooler Producibility Demonstration Project Results

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This Paper was Prepared for Submittal to
SPIE's Small Satellite Technology and Applications III Conference
12-16 April 1993, Orlando, FL

April 7, 1993

The logo of Lawrence Livermore National Laboratory is a large, stylized 'V' shape. The left vertical bar of the 'V' is composed of three horizontal bands: a white top band, a dark gray middle band, and a black bottom band. The right vertical bar of the 'V' is also composed of three horizontal bands: a white top band, a dark gray middle band, and a black bottom band. The text 'Lawrence Livermore National Laboratory' is written diagonally across the right side of the 'V' in a sans-serif font.

Lawrence
Livermore
National
Laboratory

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MODIL Cryocooler Producibility Demonstration Project Results

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**Lawrence Livermore National Laboratory
Materials Fabrication Division, Livermore, CA 94551**

ABSTRACT

Cryocoolers are essential components for many spacecraft. We summarize some spacecraft cryocooler requirements and discuss our observations regarding Industry's current production capabilities of cryocoolers. The results of the Lawrence Livermore National Laboratory (LLNL) Spacecraft Fabrication and Test (SF&T) MODIL's Phase I producibility demonstration project is presented.

1. INTRODUCTION

The production of large quantities of spacecraft needed by SDIO will require a cultural change in design and production practices. Low rates production and the need for exceedingly high reliability has driven the industry to custom designed, hand crafted, and exhaustively tested satellites. These factors have mitigated against employing design and manufacturing cost reduction methods commonly used in tactical missile production.

Additional challenges to achieving production efficiencies are presented by the SDI spacecraft mission requirement. IR sensor systems, for example, are comprised of subassemblies and components that require the design, manufacture, and maintenance of ultra precision tolerances over challenging operational lifetimes. These IR sensors demand the use of reliable, closed loop, cryogenic refrigerators or active cryocoolers to meet stringent system acquisition and pointing requirements. Although a stable production base exists for small tactical IR coolers, a domestic base for cryocoolers of the capacity and durability required by SDI satellites does not currently exist. MODILs were established by USAF Lieutenant General Abrahamson in response to his initiatives to mitigate risk and cost escalation of SDIO systems. He wanted to apply proven accelerated approaches such as concurrent engineering to reduce production risks and costs for SDIO. MODILs have grown from a concept to an essential part of the SDIO Producibility and Manufacturing Program, and are a coalition of government, industry, and university participants working together to develop and demonstrate new production and automation processes for current, emerging, and leapfrog product technologies in SDI enabling technology areas¹. Through the integration of production R&D efforts in non-proprietary locations, advanced processing and production technologies can be demonstrated and transferred to industry more expediently and cost effectively than by current industrial practices.

MODILs have two salient objectives:

- Identify and implement high payoff producibility thrusts to reduce production risks and costs.
- Develop and transfer to industry emerging production and manufacturing technologies to achieve "pre-planned" product improvements.

This paper describes the results of the LLNL MODIL Producibility Demonstration Project.

2. DEMONSTRATION PROJECT

2.1 Producibility Issues

The salient cryocooler producibility issues are as follows:

- Develop and demonstrate space qualifiable cryocoolers. (This is the generic issue addressed by the MODIL.)
- Build a cryocooler that generates extremely low vibration. (This is a precision alignment and component fabrication issue.)
- Achieve low weight, input power and volume. (These are critical design and performance parameters.)
- Attain low component and assembly contamination, which must be mitigated early in the system assembly phase. (These are process procedure issues.)
- Achieve high quantity component and assembly producibility. (These are end-products of the MODIL thrust area effort.)
- Obtain a high system reliability during operation. (This is an issue dependent on those preceding.)
- Readily and reliably integrate the cryocooler system with the spacecraft systems.

2.2 Demonstration project

Establishing and implementing a producibility plan, such as for cryocoolers, require a series of events to take place in order to be successful, refer to section 2.2.1. Each aspect of the process demands close interaction and cooperative effort from industry. A flow chart depicting this process is shown in figure 1.

The primary contractors were visited with the intent of reviewing and identifying the salient cryocooler producibility issues that are inhibiting cryocooler production. Since the Standard Spacecraft Cryocooler (SSC) contracts were well underway, and the Air Force and Phillips Laboratory needed to understand what they were receiving from the two contractors, the project focused on producibility issues for the two SSC designs.

Fig. 1 Interaction with Industry

The producibility demonstration project was designed to demonstrate the necessity for implementing concurrent engineering techniques in the design and production of cryocoolers. Concurrently working production problems with the suppliers, provide the catalyst that facilitates the technology transfer needed to enhance their production capability. By focusing the effort on both the cryocooler developer's design and the supplier's manufacturing approaches, manufacturability can be achieved in real time and disseminated throughout more of industry. The manufacturing supplier effort generates a more far-reaching effect within industry than a single contractor.

2.2.1 Specifics of the producibility demonstration plan

- Agree on project component to produce (LLNL, prime contractor, supplier). The purpose is to solve a common problem.
- LLNL Manufacturing Support Group forms a producibility team.
- Evaluate manufacturing supplier capabilities (LLNL Producibility Team) with contractor and supplier personnel.
- Put contracts in place with contractors to enable effort to continue at LLNL, the contractors, and at contractor's manufacturing suppliers.
- Establish a production sequence (@ LLNL).
- Establish a process plan (@ LLNL).
- Implement the process plan (@ LLNL).
- Develop inspection techniques (@ LLNL).
(Implemented before establishing the production sequence)
- Validate the process (includes: inspection techniques, data acquisitions, etc.)
- Establish production machine tool and inspection set ups.
- Implement a production run (includes: in-process inspection, data acquisition).
- Finish part production - 100% inspection (@ LLNL).
- Maintain the producibility team (for continuity) when moving to supplier facility.
- Supplier personnel acquire hands-on lead with LLNL personnel as consultants to them (@ supplier's).
- Work with suppliers to enhance their machines where applicable (@ supplier's).
- Develop and implement the producibility process (@ supplier's).
- Produce the end product:

- Process detail planning
- Process summary documentation
- Parts delivery
- Supplier capable of utilizing new technology
- Hold project close-out meetings with contractors and suppliers.

Two components were selected for this demonstration project, (figure 2), both of which have the thin-to-thick wall interface and close tolerance features, to assess producibility and develop a manufacturing plan to be transferred to the participants. Titanium and Inconel were the materials to be used for these items. Stainless steel was substituted for the Inconel when thorough process development attempts did not result in the desired geometries from Inconel. Findings on the three materials, Titanium, Inconel, and Stainless steel are reported².

Fig. 2 Titanium (L) and Inconel (R) Demonstration Project Components

3. PROJECT SUMMARY

3.1 Selection of resources

The exacting nature of the demonstration components requires that skilled crafts' people be used throughout the entire operation. The importance of this "soft technology," the people involved, must not be underestimated. The team concept was shown to be very effective in the development of processes and the manufacturing of the demonstration components. The precision and accuracy of these components rely on the thorough planning and deliberate execution of processes by skilled individuals.

Machinery and tooling resources representative of those possessed by, or commercially available to, the participating vendors were chosen in an attempt to develop processes that will be readily assimilated by the private sector. The issue continues to be the utilization of appropriate resources to assure accuracy and precision during production.

3.2 Machinery

Common CNC lathes and conventional lathes were used during the roughing operations of all components.

Hardinge HLV-H 10 inch Toolmaker's Lathes were used during roughing and finishing operations.

Agiatron Agiecut 200 and Charmille Robofill 600 wire EDM machines were used to finish the inner features.

Trim-Sol, the coolant used by LLNL personnel for this project, contains chlorine; it is one of several substances restricted in the manufacture of aerospace hardware. The aggressive project schedule and the generic non-flight natures of the demonstration components were primary factors in this decision. New-Lube, a registered trademark product, is one acceptable alternative.

3.3 Tooling

Tooling consists of "off-the-shelf" resources; the exception being the after market grinding of a high back rake on the VC29 carbide inserts used for finishing the outer profiles of the Inconel and Stainless steel components³. The high back rake produces a chip flow characteristics resulting in less tool pressure on the part. Stresses induced in the part are minimized with this type of tool configuration, therefore, providing a more geometrically stable component.

3.4 Measuring tools

Measuring tools available at LLNL were used to verify part sizes and geometric features. The function of the primary inspection tool, the Bendix Indi-Ron roundness gage can be duplicated by commercially available tools. The Federal Formscan Circular Geometry Gage and Rank Taylor Hobson's Talyrond 250 are commercially available for approximately \$100K. The precision and accuracy requirements of the demonstration components dictated the use of this type of inspection equipment.

Sheffield gaging was purchased and evaluated to determine the effect of the air pressure on the thin wall components during inspection. Test results revealed air gaging as a viable option for the determination of internal size. Air gaging exhibited no appreciable distortion of the part geometry when employed during inspection.

A LaserMike brand micrometer was purchased for \$6K. This inspection equipment provides a non-contact method of measuring outer diameters in a precise manner. Potential human influence and variation are negated with this tool, because the tool uses a laser light transmitter and receiver to establish size.

A Federal Surfanalyzer was adapted to determine straightness of some inner features for the tight tolerances specified.

An OGP brand optical comparator was used to provide non-contact linear verification of outer features

4. DRAWINGS

The drawings (figure 3) presented in this section were used to produce the two parts for which the manufacturing processes were developed. Both drawings are modifications of actual component drawings provided by the two participating contractors.

5. PROCESS

Technical details of the demonstration project are reported in the manufacturing data section of the MODIL Cryocooler Producibility Demonstration Project Results report².

6. COSTS

MODIL Demonstration Project costs are presented in a man-hours format that separates costs for the development, production and demonstration phases of the project (figure 4).

Fig. 4 Hours/Component/Phase Comparison

The Inconel component machining development process did not reach the production phases. This is illustrated with only one bar on the graph. Information detailing this development process³.

The Stainless Steel component process development was achieved in major part by capitalizing on the information derived from the Inconel component process development effort.

6.1 First Briefing to Industry

On September 23-24, 1993³, an industry-wide briefing was hosted by SDIO's Spacecraft Fabrication and Test MODIL at LLNL. The over 100 attendees represented a broad spectrum of aerospace industry involved in producing SDIO systems, as well as many key representatives from SDIO programs (BE, GBI, BP, etc.). The briefing included numerous presentations, working sub-sessions, and tours of MODIL applicable, potentially applicable, and showcase facilities.

The briefing had two major objectives: -

- To explain the objectives and progress of the SF&T MODIL and
- To present LLNL technology applied to current MODIL thrusts, as well as key technology of potential benefit to SDIO programs.

7. CONCLUSIONS AND RECOMMENDATIONS

Through the contractor, supplier, and LLNL project summary meetings, many issues were raised that offered solutions to producibility problems encountered within the design/manufacturing environment. The results of the producibility demonstration project illustrated the need to consider and to implement changes in the current method of operation in the production community.

Following are recommendations brought forth in our working interaction and meetings with the participating contractors, their suppliers, and the LLNL producibility team:

- Ensure all parties involved know what the project goals are and what is expected of the participants.
- Involve all participants in the whole project (from beginning to end), solicit their ideas from the beginning (engineering, manufacturing, QA, purchasing, etc.). Brainstorming is a must.
- Engineering staff should share floor time with machinist to better understand what is required to provide parts.
- Ideas have to be readily accepted for consideration without personal bias.
- Teams assigned to the project are most efficient and cost effective when maintained as an entity throughout the project.
- Evaluate every manufacturing option to optimize project end-product.
- LLNL is recommended as a resource for manufacturing technology available to U.S. industry.
- Minimize inspection by building robustness into parts and controlling the manufacturing process. Spend the time needed in the design phase.
- Design reviews must include all parties to ensure the drawings are as correct as possible before parts are manufactured. Pre-production design changes have a lesser financial impact.

The results of this demonstration project demonstrated that precision production issues can and need to be addressed early in the design phase of any project; if they are, costs will be minimized and a better product will be produced. Concurrent engineering practices do work!

8. ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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**Recent Results from the Spacecraft Fabrication and Test
MODIL**

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Recent Results from the Spacecraft Fabrication and Test MODIL

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Abstract

The Spacecraft Fabrication and Test Manufacturing Operations Development and Integration Laboratory (SF&T MODIL) is working with SDIO program offices and contractors to reduce schedule and budget risks for SDIO systems as they go into production. The concurrent engineering thrust has identified potential high payoff areas. A materials and structures demonstration project has successfully completed a partial automated closing of matched metal molds for a continuous fiber composite. In addition to excellent accuracy, the parts demonstrated excellent predictability and repeatability of physical properties. The cryocooler thrust successfully demonstrated and inserted precision technologies into a generic cryocooler part. The precision technologies thrust outlined two potentially high payoff areas in precision alignment and miniature rocket thrust measurement. The Producible Technology Working Group (PTWG) efforts identified the need for a test and assembly thrust. Due to funding limitations, continuing efforts are limited to the cryocooler thrust.

1. Introduction

1.1 Background

The Spacecraft and Fabrication (SF&T) MODIL (Manufacturing Operations Development and Integration Laboratory) was initiated in December 1991 under funding from the Department of Defense.¹ There are now four MODILs as listed in Table 1 which are under the direction of Mr. Greg Stottlemyer of SDIO.

Table 1.
Current MODILs

MODIL Name	Integrator	Leader
Electronics and Sensors	Sandia National Laboratory	Peter Winokur
Optics	Oak Ridge National Laboratory	Brigham Thomas
Software	National Institute of Standards and Technology	Arnold Johnston
Spacecraft Fabrication & Test	Lawrence Livermore National Laboratory	Ted Saito

*This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract no. #W-7405-Eng-48.

The SF&T MODIL is off to a good start to achieve its objective of establishing a producibility culture in the spacecraft fabrication community. The SF&T MODIL has been organized into five thrust areas:

- Automated Spacecraft & Assembly Project (ASAP)²
- Materials and Structures³
- Cryocoolers⁴
- Precision Technologies
- Assembly & Test.

1.2 Demonstration Projects

An early goal was set to show potential payoff and if possible feasibility at small scale through a demonstration project. Demonstration projects were designed to cost less than a few \$100K and last about a half year or less. Close coordination with the potential producer (contractor) and program office was also desirable. These projects also helped fulfill the general SDIO guideline that approximately half the MODIL funding was to be expended outside of the integrator.

This paper will describe the progress of each thrust since the last paper¹, the Producible Technology Working Group (PTWG) process, and our successful first briefing to industry. Due to a funding cut in the first quarter of FY93, the current scope of activities are focused on the cryocooler efforts.

2.0 Automated Spacecraft & Assembly Project (ASAP)

The ASAP thrust is led by Dave Sanders. ASAP is studying the potential for leveraging "soft" (computer-based) technologies in spacecraft manufacturing, because above-the-shop-floor costs typically account for 40 to 70% of the total costs of manufacturing. Last year we reported that our preliminary survey of soft technologies of above-the-shop-floor operations identified the areas which show a significant potential benefit in cost and time savings for SDIO spacecraft fabrication and test.²

The ASAP demonstration projects were contracts with all contenders for the Brilliant Eyes Program. The contractors provided, on a proprietary basis, a snapshot of their current status of Integrated Product Development (IPD) or Concurrent Engineering (CE) in the prime contractor community. The participants in this effort are Lockheed, Martin Marietta, Rockwell, and TRW. The contracts also pay for time for contractor employees to be interviewed by the ASAP team, as well as the time necessary to prepare a final report.

Concurrent with the information gathering contracts, ASAP formed an Industrial Working Group with representatives from the previously mentioned contractors and appropriate government agencies. The response to this group was quite positive, especially at the SF&T MODIL industrial briefing.

The three areas which were being explored were a "Virtual Factory" for the manufacture of spacecraft, an "Interoperability Testing Laboratory" for design and manufacturing software, and "Infrastructure Enhancements" to facilitate the practice of IPD in SDI systems. The ASAP team made progress towards defining all three of these areas and establishing a basis to determine the cost/benefit ratio for each.

Although the specific results of the demonstration project are proprietary, several important observations resulted. There is significant interest in establishing a concurrent engineering atmosphere, both by the SDIO program offices and the contractors. The costs to establish the concurrent atmosphere hinder management decisions for investments to establish IPD, because of the major uncertainties of SDIO's future. Completion or termination of a program results in major shifts of personnel for a contractor. Departure of experienced personnel often means the loss of understanding and expertise which would have remained had an effective IPD been in place. This was another sincere reason why contractors wanted to expedite the establishment of IPD. The down sizing of the defense industries is therefore another reason to implement an IPD atmosphere, so as to minimize the loss of expertise.

After the funding cut, ASAP investigated the possibility of applying the lessons learned from the demonstration projects and earlier work to the cryocooler. It appears that notable contributions can be achieved by creating an IPD atmosphere for a cryocooler demonstration project. The IPD approach would be used for a cryocooler project in such a way as to create and demonstrate a methodology for producing moderate numbers of cryocoolers. This methodology could then be a model for other spacecraft subsystems and would serve as a building block in establishing a producibility culture in the spacecraft fabrication community.

3.0 Materials and Structures³

The Materials and Structures thrust is led by Gordon Spellman. The demonstration project was a six-month contract "Partial Automation of Matched Metal Net Shape Molding of Continuous Fiber Composites" with Sparta Corporation. This contract covered the design, construction, and demonstration of the partial automation of a novel composites fabrication process. The process allows for near net shape fabrication of complex structures from continuous fiber, organic matrix composites. The objective was to demonstrate the key element of the automation process which was the closure of the matched metal tooling to hard stops with a fully automatic process cycle. Since this process was partially developed by SDIO's Key Technology (now IS&T), this project also gave us the opportunity to leverage previous SDIO advances.

A part was selected which would be of generic interest to the SDIO community. It was a 9" diameter, 10" high thin-wall cylinder with a high quantity of unidirectional plies oriented along the cylinder axis.

Tooling was designed to lead to automated production. The tooling mated to a concurrently developed hydraulic closure machine which was funded through the contractors IRAD.

An iterative process was planned for the process development. The mechanical and thermal cycle times were determined from experience and experimentation. The development proceeded rapidly and, in fact, the first part produced was very successfully used in the program test phase. However, the process was not optimized for considerations beyond part performance; but even so, the production process from start to finish, including pre-consolidation, can be completed in one shift.

Twenty demonstration parts were produced. The parts are of high quality both visually and dimensionally. Some test results, discussed below, indicate that the production run is producing parts with performance virtually identical to predictions and with exceptional repeatability.

Visual inspection of the parts was very encouraging indicating high quality. Initial indications are that dimensions are all within the specification of the Statement of Work with the exception of the diameter. The diameter is small by 0.008" due to errors in tool design. This is the type of error which should be minimized by thorough process knowledge and control. Variations in wall thickness are about 1.5 mils, and the radius varies about +/- 4 mils on a 4.5" radius.

Parts were tested to failure in tension and in compression. The moduli in tension were 15.5, 15.5 and 16.2 MSI, and in compression they were 12.9 and 13.2 MSI. Two of the tensile specimens failed in the fixturing at a point about 75% of ultimate, and the one component failed at an ultimate stress of 140,000 PSI which is essentially the same as the predicted value. The compressive failure stresses were 39 and 44 KSI and the mode was buckling. The main results to date are predictability and repeatability which are very high for these components. The MODIL believes this is a key feature of this type of automated process.

The program has resulted in a proof of concept of the automation of a process with a high potential for production of quality composite components at a reasonable cost. The MODIL hopes to demonstrate this process on an actual limited production run.

4.0 Cryocooler Thrust⁴

The Cryocooler thrust results are given in detail in the accompanying paper co-authored by the thrust leader Gill Cruz.⁵ Therefore, it will only be summarized here.

The Cryocooler Producibility Demonstration Project was established to demonstrate the need for cryocooler designers and manufacturers to concurrently interact with one another in the initial stages of the design process. The project is

designed to demonstrate the cost and effect of producing components that were initially designed with minimal producibility issues taken into account.

The project focused on a generic component with a geometry which had a producibility issue common to all cryocoolers. The geometry was a thin-to-thick wall transition that required precision tolerances. The objective was to develop a production process that would be developed, in real time, with the selected cryocooler manufacturer's suppliers. Our objective was accomplished at both LLNL and Modern Industries (with Hughes Aircraft) in Phoenix, Arizona, and at Westfield Gage (with Creare) in Westfield, Massachusetts. Contracts were established with both to pay for their efforts to cooperate with the LLNL MODIL team to define and work out production problems. In order to avoid conflicts between potential competitors, work with each contractor was handled separately to insure any proprietary information was protected.

Processes were developed at Livermore and then transferred to the contractors. Significant benefits were gained from Livermore's experience in precision fabrication. The MODIL worked with the contractors in streamlining and improving processes as well as introducing new technology and techniques. For example the MODIL introduced the Wire Electro Discharge Machining (EDM) process. Close coordination, effecting more of a concurrent engineering atmosphere, was encouraged.

In addition to the demonstration project and PTWG activities, the Cryocooler thrust had a major interaction with the USAF Cryocooler program from the Phillips Laboratory, Albuquerque, New Mexico. In addition to consulting and advising regarding producibility, the MODIL also assisted in their cryocooler contract selection.

5.0 Precision Technologies

The Precision Technologies Thrust, led by Lee Griffith, is pursuing two projects that will greatly advance the state of the art in satellite manufacturing. One project is in sensor alignment, and the other is in precision miniature rocket thrust vector measurement.

5.1 Sensor Alignment

Sensor alignment is an enormously costly and time consuming aspect of spacecraft fabrication. A one-of-a-kind spacecraft will typically allocate eighteen months for sensor alignment. A copy of the same spacecraft will probably allocate twelve months for the same alignment task. The task can be even more involved as noted on the Hubble Space Telescope. To achieve the cost requirements for SDI elements, the sensor alignment time needs to be reduced drastically.

In conjunction with the Jet Propulsion Laboratory (JPL), the SF&T MODIL investigated ways to improve alignment. Inputs from PTWG visits were very helpful in indicating alignment issues and areas of potential improvement. JPL

and the SF&T MODIL outlined a four task approach to improving alignment. The first task was completing the fact-finding initiated by the PTWG visits to pin-point critical alignment needs. Furthermore, ideas regarding methods to reduce alignment time for both assembly and on-orbit were to be sought. Secondly, procedures and software tools were to be developed and tested to address the issues found in the first task. Precision techniques, such as the "snap-together" optics techniques developed by the Optics MODIL, would be considered. This includes designing and manufacturing components with adequate accuracy to achieve alignment upon assembly. Other potential techniques included computer-aided interferometric alignment and image-based alignment. The third task, computer-aided alignment (CAA), was the most important and most powerful. The final task would be a hardware demonstration of the basic feasibility of the CAA. Preferably the final task could be demonstrated on an actual SDIO pre-production system.

JPL has extensive experience with computer-aided alignment. Images of a well known scene, or a known star, are taken after changing alignment parameters (such as focus, spacing, or tilt). Computer analysis of the images then can give information on error sources of the optical train. This method was successfully used by JPL in analyzing the Hubble Space Telescopes spherical aberration problem. The analysis of the images predicted very well the error in the primary that was later deduced by the Allen Committee which reviewed the archival data and the test set up.

Another very exciting aspect of this approach is being able to align sensors in orbit. On orbit alignment offers significant design flexibility while reducing the alignment requirements during fabrication and test. Also the alignment requirements to be held during and after launch are reduced offering system advantages.

In addition to intrasensor alignment, one must be concerned with co-alignment of the many sensor packages on a satellite. Co-alignment is essential to communications, guidance, inertial management, and sensor-to-sensor image hand-off. Malcolm Shuster of Johns Hopkins Applied Physics Laboratory describes pre-launch alignment determination as costly and difficult. The SF&T MODIL had planned to build off Shuster's experience to reduce the difficulties of co-alignment. Plans were to integrate Shuster's work with JPL's to form a thorough on-orbit sensor calibration system.

5.2 Miniature Rocket Thrust Measurement

The SF&T MODIL's effort in miniature rocket thrust vector measurement emphasizes the MODIL's role as an integrator. In this case, the MODIL planned to bring together several smaller projects to accomplish valuable research at lower cost and in less time than would have been possible without MODIL coordination. The SF&T MODIL has heard concerns about rocket thrust vector measurement from a variety of sources which include from contractors during PTWG visits and other MODIL interactions. Some applications are very sensitive

to knowing both the magnitude and the direction of the thrust vector. Failure to apply the thrust through the center of mass can cause the spacecraft to roll and jeopardize the mission. The problems can range from excessive roll creating loss of orientation to misdirection requiring increased fuel consumption for compensation.

The SF&T MODIL planned work with existing SDIO contractors such as Martin Marietta, Aerojet, and LLNL's Brilliant Pebbles program to both have adequate sensitivity and accuracy of thrust measurement. The plan included a careful finite element analysis of the test stand to insure that it would have the stability and strength for the test. Then a redesign of ancillary elements of the test stand plus a change in the calibration procedure was conceived with hopes of achieving the necessary sensitivity and accuracy.

6.0 Assembly and Test Thrust

The Assembly & Test Thrust was initiated after the Brilliant Eyes PTWG visit in March of 1992. Based on direct feedback from the contractors and discussions with Greg Stottlemeyer, of SDIO, and Mohan Aswani, of the Aerospace Corporation, the decision was made to start the Assembly & Test Thrust. One suggestion was to consider a major re-visiting of the DOD spacecraft testing requirements. This study could consider the current state-of-the-art of spacecraft fabrication, review data from current satellites, and propose a test requirement suitable for quantity production of spacecraft.

There is a need to re-evaluate the test requirements. Military Standard 1540B is not the major problem. The major question is, "What tests are necessary in order to insure spacecraft performance and lifetime?" Therefore, it is necessary to develop a good test criteria to satisfy both the program offices and contractors that their satellites will meet lifetime requirements.

Several major efforts were already in progress. The Aerospace Corporation was studying possible improvements to Military Standard 1540B. Another Aerospace initiative was the Vehicles/Satellite Environmental Test Simulation System (V/SETSS) which was evaluating large quantities of historical test/failure data. One V/SETSS interest was investigating possibly deriving cost/benefit insights from various spacecraft tests.

Unfortunately, this thrust was just in its initial stages when the funding was cut. Therefore, the MODIL was not able to follow up on keen interest from several key SDIO contractors in test and assembly.

7.0 SDIO Producibility Support: Producible Technology Working Groups

The Producible Technology Working Groups have been established to assist in assuring that the manufacturing and processing capabilities and industrial capacities are sufficient to meet the SDIO element production schedule and cost targets. The organization and leadership is the same as described last year¹

except that Arnold Johnson, the Software MODIL Leader, is the Software PTWG leader. Meetings have been held with the Brilliant Pebbles, Brilliant Eyes, Ground Based Interceptor contractors. The BE and GBI interactions were constrained due to the imminent issue of a Request for Proposal for a major program follow-on. A typical visit started with a plenary session which included an overview of the purpose of each MODILs and the PTWGs and an overview briefing of the program requirements and manufacturing needs. Then separate meetings were held with the PTWGs and the contractors' (and appropriate/available sub-contractors') personnel. Sometimes PTWGs were combined depending on the representation of the PTWG visit.

The PTWG process has been one of the major sources of the MODIL obtaining information of producibility needs of the SDIO community. Numerous detailed discussions were held ranging from information on specific materials information to potential sub-system problems. In one case separate trips were taken to potential future sub-contractors to assess current state-of-the-art and related producibility issues. Other specific discussions included topics such as outgassing, dimensional stability, repeatability of properties, maturity of processes, and software compatability for a concurrent engineering environment. A specific component design was even evaluated and suggestions made to make the design more producible. In other cases specific design philosophy errors were detected and reported. As mentioned in section 6.0 the Test and Assembly Thrust was initiated in response to PTWG findings.

The PTWG mechanism and interaction have significant potential benefits for enhancing producibility. A key hurdle is overcoming the contractor's sensitivity in disclosing their manufacturing weaknesses. As projects proceed beyond the bidding stage (selecting fewer contractors from those currently participating) and the realities of meeting schedule and budget arise, their openness should increase. Another important element is for the MODIL and the PTWG process to provide contractors real help in solving production problems.

8.0 First Briefing to Industry

The first SF&T briefing to industry was held at the Lawrence Livermore National Laboratory in September 1992. There were two objectives of the briefing:

- Explain the mission, goals and progress of the SF&T MODIL and solicit industry's and SDIO program's participation and support.
- Demonstrate and show LLNL capabilities available to solve SDIO producibility issues.

It was extremely well attended, and the feedback was very positive from the attendees. Dr. James D. Carlson was the featured speaker at the evening banquet giving a perspective on SDIO's future. In pursuit of the second objective, tours of several major LLNL facilities were arranged as well as a half day of presentations

regarding key LLNL technologies of potential use to the spacecraft fabrication community. These technologies are seeds for potential future SF&T MODIL thrusts.

9.0 Summary

The SF&T MODIL is off to a good start to achieve its objective of establishing a producibility culture in the spacecraft fabrication community. The SF&T MODIL has been organized into five thrust areas:

- Automated Spacecraft & Assembly Project (ASAP)²
- Materials and Structures³
- Cryocoolers⁴
- Precision Technologies
- Assembly & Test.

Interest has been high from the SDIO contractors, and progress has been made gaining support of the SDIO program offices. Current work has been severely limited by funding cuts, and future contributions of all the MODILs will depend on future SDIO direction and funding of the MODILs.

10.0 Acknowledgments

I'm grateful to the fine leadership each thrust leader has given: ASAP - Dave Sanders, Materials and Structures - Gordon Spellman, Cryocoolers - Gill Cruz, and Precision Technologies - Lee Griffith. I also thank them for their help in preparing this manuscript. Dr. Mohan Aswani, of the Aerospace Corporation, has continued to play a key role in helping the SF&T MODIL as well as serving as a chairperson for the Materials and Structure PTWG. I thank Dr. Larry Fehrenbacher and his team from Technology Assessment and Transfer Incorporated for advice and tireless efforts in keeping all the MODIL teams coordinated.

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Appendix A: MODIL Cryocooler Producibility Demonstration Project Results, Gilbert E. Cruz, R. Marks Franks, June 24, 1993

Appendix B-Error Budget Model-Viewgraphs of Phillips Lab Sep 1993 Presentation, Stan Edson, September 23, 1993

Appendix C: MODIL Publications, C1, MODIL Cryocooler Producibility Demonstration Project Results, Gilbert E. Gruz, R. Marks Franks, April 7, 1993; C2, Recent Results from the Spacecraft Fabrication and Test MODIL, Theodore T. Saito, April 12-16, 1993

Appendix D: Proprietary ASAP Information from Lockheed and Rockwell (UCRL # , separate document, not attached)

SPACECRAFT FABRICATION AND TEST MODIL

MODIL Report 93-1

EXECUTIVE SUMMARY

This report covers the period from October 1992 through the close of the project. FY 92 closed out with the successful briefing to industry and with many potential and important initiatives in the spacecraft arena. We prepared to initiate these initiatives once FY 93 funding became certain. Due to the funding uncertainties, we were directed to proceed as if our funding would be approximately the same as FY 92 (\$2M), but not to make any major new commitments. However, the MODIL's FY 93 funding was reduced to \$810K and we were directed to concentrate on the cryocooler area. The cryocooler effort completed its demonstration project. The final meetings with the cryocooler fabricators were very encouraging as we witnessed the enthusiastic reception of technology to help them reduce fabrication uncertainties. Support of the USAF Phillips Laboratory cryocooler program was continued including kick-off meetings for the Prototype Spacecraft Cryocooler (PSC). Under Phillips laboratory support, Gill Cruz visited British Aerospace and Lucas Aerospace in the United Kingdom to assess their manufacturing capabilities. In the Automated Spacecraft & Assembly Project (ASAP), contracts were pursued for the analysis by four Brilliant Eyes prime contractors to provide a proprietary snap shot of their current status of Integrated Product Development. In the materials and structure thrust the final analysis was completed of the samples made under the contract ("Partial Automation of Matched Metal Net Shape Molding of Continuous Fiber Composites.") to SPARTA. The Precision Technologies thrust funded the Jet Propulsion Laboratory to prepare a plan to develop a Computer Aided Alignment capability to significantly reduce the time for alignment and even possibly provide real time and remote alignment capability of systems in flight. The promising plan was proposed to BMDO but adequate funds were unavailable. In addition the Precision Technologies

Thrust identified and proposed a method to make quick micro-thrust measurements needed for precise propulsion of small and quick space vehicles . The Test and Assembly Thrust identified a very promising on-going effort, the Aerospace Corporation's development of Vehicles/Satellite Environmental Test Simulation System (V/SETSS). V/SETSS is evaluating large quantities of historical test/failure data. We had found a leader for the Test and Assembly Thrust.

The PTWG activity was much diminished during this period, and included our responding to a request from the Materials and Structures PTWG for a summary of PTWG needs.

I. CRYOCOOLER THRUST

The objective of the Cryocooler Thrust is to provide the means to develop and transfer to industry emerging production and manufacturing technologies. The cryocooler MODIL effort will facilitate identification and implementation of high-payoff producibility thrusts that will mitigate production risks and costs through the use of concurrent engineering techniques.

The MODIL utilized the cryocooler Producible Technology Working Group (PTWG) to establish cooperative working relationships with the appropriate working-level engineers and technical specialists at each contractor and their suppliers. The PTWG was the primary technical support and focal point for the producibility effort.

A producibility demonstration project, involving the two Standard Spacecraft Cryocooler (SSC) contractors and their manufacturing suppliers, and an error budget model project, involving one of the contractor cryocooler designs, were successfully completed.

The following sections of this report present detailed explanations of the demonstration project, error budget project,

PTWG activities and activities performed in support of Phillips Laboratory.

CRYOCOOLER PRODUCIBILITY DEMONSTRATION PROJECT

OBJECTIVE

The Cryocooler Producibility Demonstration Project was established to demonstrate the need for cryocooler designers and manufacturers to concurrently interact with one another in the initial stages of the design process. The project was designed to demonstrate the cost and effect of producing components that were initially designed with minimal producibility issues taken into account.

Since we could not address building a complete cryocooler, we focused on a generic component geometry producibility issue that was common to all cryocoolers. The geometry was a thin-to-thick wall transition that necessitated precision tolerancing. With this geometry, our objective was to develop a production process that would be developed, in real time, with the selected cryocooler manufacturer's suppliers. Our objective was accomplished at both LLNL and Modern Industries (with Hughes Aircraft) in Phoenix, AZ, and at both LLNL and Westfield Gage (with Creare) in Westfield, MA.

The process developed at Livermore was taken to Westfield Gage, and the first part produced by Westfield machinists with the new process was in compliance with the specification. We also suggested inspection techniques to Westfield Gage that were implemented into their method of operation.

We influenced Westfield Gage to approach their work assignments in a manner that would generate the most efficient and productive effort from their people. They were considering giving a project to the shop manager who in turn discusses it with the machinist who would then determine the most efficient process to use to manufacture the component, rather than using the method of giving a project to the machinist and telling him/her what process to

use, which was there current method. Crafts person interaction with management and engineers is the important issue, because everyone involved now is part of the problem/solution. What optimized their approach was our introducing the Wire Electro Discharge Machining (EDM) process to Westfield to solve a producibility problem, one of which the EDM process would never have been considered.

The process development and technology transfer with Modern Industries were equally successful. We were instrumental with building a higher level of confidence within the Modern organization between the quality assurance staff and the production staff. We validated the producibility and inspection techniques utilized at Modern at LLNL by working issues in real time with Modern crafts people.

The results of the first phase of the demonstration project show that LLNL is now being considered as a resource for manufacturer suppliers, and that LLNL has developed, and can develop, a high level of trust in which to work closely with private industry. One example of this trust and confidence in LLNL is that Hughes has modified one of their cryocooler component designs based on our recommendations. Reference *MODIL Cryocooler Producibility Demonstration Project Results*, in Appendix A.

CRYOCOOLER ERROR BUDGET MODEL PROJECT

A design error budget is a necessary step in the design process, because it allows the designer to approach the design as a system instead of a combination of individual entities. Error budgets provide an understanding of the design requirements dictated by the system's function, and they allow the designer to examine and budget error sources at the conceptual design phase of a project. The primary benefit of an error budget is that any change to a design can be accurately analyzed to determine the effect of the change at any level in the design. In effect, this tool allows the designer to design for function, manufacturability, and assembly. It also optimizes

production costs, because most of the tolerance issues are addressed in the design phase.

The project entailed generating a cryocooler expander assembly computer model using nominal dimensions without tolerances. An existing Standard Spacecraft Cryocooler (SSC) design was used. The SSC component relationships to one another in the assembly were analyzed for inconsistencies and interferences. Parametric modeling techniques, with Unigraphics CAD software, were used to relate individual part features and related features in the cryocooler assembly.

The error budget model delineates individual parts that show mathematical expressions and dimensions which illustrate geometric relationships that control critical features on assembly components and on critical features between those components. The effect of dimensional changes between related components within an assembly are exhibited in the model.

The project results showed that the SSC design has errors with the nominal dimension application and the method in which the parts relate. Had tolerances been applied to the model, more errors would have become evident. Producibility, based on this design, will be a problem.

The project results were presented to the Thermal Management Branch of Phillips Laboratory in September 1993. Reference Appendix B for the viewgraphs of this presentation.

BRILLIANT EYES (BE)/AEROSPACE/PHILLIPS LABORATORY SUPPORT

MODIL activity involved reviewing BE contractor cryocooler designs through contract kick-off meetings, preliminary design reviews, specific in-house design reviews, and design drawing evaluations.

As a member and co-chair of the cryocooler PTWG, Gill Cruz visited on numerous occasions Aerospace Corporation, TRW, Hughes Aircraft, Rockwell International, USAF Phillips Laboratory, TASC, TATI, and Lockheed Missile and Space for the purpose of reviewing and evaluating producibility issues pertaining to space qualified cryocoolers. This effort was an on-going effort throughout the project duration.

As a result of the PTWG meetings, kick-off reviews, and the fact that two contractors affiliated themselves with British Aerospace cryocooler suppliers (British Aerospace and Lucas Aerospace), Gill Cruz visited the British cryocooler suppliers to assess the status of cryocooler producibility in the U.K. Additional companies and agencies were visited for the same reason. The trip report dated May 7, 1993 is included in Appendix_____.

Culminating the first year of MODIL activity, Gill organized and chaired the Cryocooler Industrial Briefing Subsession, which was a part of the LLNL SF&T MODIL Industry Briefing.

In support of Phillips Laboratory, Gill was an advisor for cryocooler RFP contractor selection.

SPIE PUBLICATIONS

The paper *MODIL Cryocooler Producibility Demonstration Project Results*, was presented at the April 1992 and April 1993 SPIE Small Satellite Technology and Applications Conference. These papers detail the producibility demonstration project from planning through the project completion. Both papers are included in Appendix C.

POSSIBLE FUTURE PROJECTS

Two proposals have been submitted to Phillips Laboratory and Hughes Aircraft that address error budget tools and cryocooler producibility respectively. The Phillips proposal is comprised of

these scenarios that would address generating an error budge tool for their cryocooler projects and an actual error budget for an existing cryocooler design.

The Hughes proposal is comprised of producing an error budget and a cryocooler drawing package for a new cryocooler design. In addition, a manufacturing effort for the new cryocooler was proposed. This proposal is in response to a Broad Agency Announcement from ARPA of which LLNL is a member of the proposal consortium headed by Hughes Aircraft.

II. Automated Spacecraft and Assembly Project

Anticipating the initiation of a pilot study in FY 93, the MODIL issued contracts to TRW, Martin Marietta, Lockheed, and Rockwell,. These four were chosen because they were participants in the down select process for the Ground Based Interceptor (GBI) as well as two of them already were down selected for Brilliant Pebbles. These four were not only major contractors involved in DOD spacecraft fabrication, but also leading candidates for (then) near term SDIO production.

In order to research the spacecraft manufacturing processes and generate recommendations regarding the implementation of an automated spacecraft assembly system each contractor was asked to provide information on:

- 1) the prime contractors' needs, current status, and future directions for soft technologies,
- 2) soft technology development efforts by OSD and the commercial sector,
- 3) SDIO and System Program Office (SPO) directions.

It was anticipated that the report would provide information on:

- 1) a model of how the prime contractor, their sub-contractors and suppliers function together to manufacture weapons systems,

- 2) description of their existing Integrated Product Development (IPD) use,
- 3) description of inter-networking with their sub-contractors and suppliers, and
- 4) future plans for the preceding items.

The above requirements were created in light of the generic requirements anticipated for a pilot project. It was felt that a pilot study would have the following characteristics:

- 1) Transferability
- 2) Multiple Weapons Systems Applicability
- 3) Standards Based
- 4) Near Term Focus
- 5) Scalability
- 6) Measurability

TRW¹

TRW formed an integrated product development team consisting of members from the Data Management, Manufacturing, Systems Engineering, Design, and Integration and Test disciplines to document the current "As-Is" processes and to look at existing automated tools in use at TRW.

The TRW team defined an architecture, shown in Figure 1, to integrate the various aspects of spacecraft manufacturing electronically. The proposed system would integrate all of the various functions of the spacecraft program and have the following benefits:

- Reductions in production and support costs associated with manufacturing cycle time, engineering change orders, scrap, rework and repair costs
- Inventory reduction through implementing electronic just-in time material and parts ordering
- Facilitation of paperless documentation implementation.

- Improved costs models from better program wide actual-costs data.

Figure 1 - TRW Proposed Integrated Architecture

Electronic document review offered the potential of up to 40% time savings of the many individual sequential steps in the review of a CDRL (Contract Deliverable Requirements List) document. Developing electronic tools to support the concurrent process would address functions such as automated routing, status monitoring, and configuration management functions to support administrative tasks. Time sharing of data over a geographically large area would be made possible.

In addition an electronic document library would make specifications, drawings, and interim reports available in a "desktop" environment. Proper data formatting would allow text search capabilities to be exercised. Electronic storage of programmatic data enhanced retention of corporate knowledge so often lost when key persons leave a company.

A Product Data Management System has the goal to provide tool sets to control all aspects of engineering data. It would have a capability to electronically distribute drawings for reviews and establish a multi-tier, iterative review environment utilizing a desktop platforms.

TRW saw the requirement to implement a concurrent engineering automated environment to remain competitive as a spacecraft manufacturer. Funding and development of this environment offered a major challenge.

Martin Marietta²

Martin too recognized the value and need for integrated product development in the spacecraft area. Some on-going activities included:

- Computer-Aided Acquisition and Logistics Support (CALS)
- Shared Program Information Network (SPINE): a government developed electronically integrated information system for use by the Brilliant Eyes System Program Office
- Product Data Exchange using the Standard for the Exchange of Product Model Data (PDES/STEP): an international effort to advance the Initial Graphics Exchange Standard (IGES) to move data from one CAE/CAD/CAM application to another
- USAF Manufacturing Technology Directorate's Integration Technology section

Martin described the enterprise models for Brilliant Eyes and Brilliant Pebbles. The large number of estimated transaction per day between the SPO and sub-contractors, literally from coast to coast vividly illustrated the benefit of an automated information exchange and monitoring system. Martin has addressed requirement and advantages of establishing strategic partnerships with their major suppliers and listed key requirements for improvements as:

1. A prime contract significant dollar size
2. A stable prime contract
3. Multi-year funding
4. Revisions to the Competition in Contracting Act.

Martin observed that (the then) current SDIO development activities were at a disadvantage in providing the funding and contractual environment which would support and facilitate the development of robust and effective partnerships.

Martin uses a three level network architecture:

- Level I - Wide Area Network

- Level II - Metropolitan Area Networks
- Level III - Local Area/Organizational Networks

Their approach manages information with each team member able to share information in areas including: analysis, finance, metrics, schedules, office automation, drawings, documentation, specifications, operations concepts, and briefings. Careful attention has been given to insure that adequate security is present to control access to the networked information. The current system with transmission speeds of ~10 MB/sec easily handles textual files but other requirements such as multi-media would be difficult.

Martin described their near-term future network architecture as well as future IPD plans. The transition strategies were responsive to some key dependent variables including, the pace and direction of standards and technology development, the congruence between developing standards and technology, and funding constraints. Potential information sharing examples of the future were: Ad Hoc Information Sharing; Electronic Team Meetings; On-line Trade Studies; Collaborative Analysis Activities; Electronic Design Review Boards, Electronic Schedule Management, and On-line Interactive Cost Management.

Martin outlined the steps they recommended for an expeditious transition to an effective IPD environment. These steps were broken into three major categories:

1. Adopt a single set of standards and technologies
2. Change their processes and work culture to incorporate the optimal use of information system standards and technologies.
3. Apply standards and technologies and process and cultural change to the way they do business.

In addition they outlined some specific steps to address requirements such as a CAD Neutral Formal Processable File Exchange and Text and Graphic Scanning and File Compression.

Lockheed Missiles & Space Company (LMSC), Inc³

Lockheed Missiles and Space Company (LMSC), Inc, (hereafter referred to as Lockheed) defined IPD as the use of cross-disciplinary teams empowered to develop quality products that meet physical, functional, cost, and schedule requirements for all phases of the products life-cycle. Their definition gave insight to the ensuing paradigm shift in manufacturing.

Past efforts at Lockheed reflect a true commitment as well as progress in IPD. It was impressive that Lockheed recognized the significant inertia that any large organization would experience when they said:

Companies demonstrating the most success at IPD are those where the drive was impending bankruptcy. ... Clearly, implementation means addressing cultural, procedural and technological issues. Just as clearly, upper management must aggressively promote IPD, not just permit it.

Furthermore Lockheed has taken steps to actively promote IPD by securing and developing in-house software creation capability to facilitate IPD, identifying and improving their quality programs, reorganizing to facilitate IPD implementation (including forming key project offices) and actively and formally educating their engineers.

Lockheed demonstrated excellent insights into the resistance to change stimulated by IPD. We have noticed these resistances in various MODIL interactions with most contractors, and Lockheed has done an excellent job of describing these changes and ways to overcome them. Re-organization and a vibrant training program with three thrusts were just two of their keys.

Lockheed recognized that a successful implementation of IPD requires integration of culture, process and technology.

The following section of the report contains proprietary information and is in the appendix which has a limited distribution.

ROCKWELL⁴

Rockwell described the IPD team which it proposed for their proposed and on-going work. Rockwell created Integrated Product Teams (IPTs) in an organization to ensure "ownership" of specific products and to provide in-depth integration and risk management to deliver a system that meets all requirements, on cost, and on schedule. However, they seemed to rely on co-location of teams more than an electronically created IPD environment.

The Program Management IPTs was in charge of the planning process and had five primary tasks:

1. Establishing a traceable numbering system that aligns specification, contract work breakdown structure and SOW
2. Defining the IPT structure
3. Defining top-level events, accomplishments, and criteria
4. Defining and allocating resources
5. Assigning product responsibility, authority, and accountability (RAA) to individual IPTs.

The IPTs were tiered analogously to the work break down structure. Each IPT started from the customers requirements and used its respective allocated requirements and resources to plan, manage and control the production of its specific product. Proper attention was given to cost, schedule, technical performance, risk and configuration management. The IPT leader was accountable for all costs associated with his team's product. Representation on the IPTs included appropriate sub-contractors and appropriate functions from all engineering and design activities through-out the life of the program, from design definition through production and support.

Risk avoidance was accomplished by a management planning process to accomplish:

1. Clear and definitive statement of work, specifications, and tailored data requirements.
2. Team participation in the subcontractor tasks.
3. Constant oral and electronic information exchange
4. Formal program review and action status
5. Built in schedule margins.

Rockwell also strove to have team member representatives in residence at each others facilities.

The existing networks described by Rockwell included several interesting systems. The Aerospace Information Management System (AIMS) included an enterprise process data manager, an automated logistics system, and a material requirements planning system. Other systems discussed included: a computer aided system engineering tools system (CASETS) supporting BMDO, the NASA orbiter project management information system (OMIS), and the group tele-communications system (GTCS) (software providing electronic presentation and distribution of a presentation). Further discussion is included in the appendix which contains proprietary information.

In implementing IPD, Rockwell recognized that significant personnel development is required. Some of the areas involved are: design for competitiveness training, concurrent design training, systems engineering organization, systems engineering training, empowerment training, principle based leadership training, organization excellence, and continuous improvement culture. Furthermore they saw that existing systems must be adapted to IPD needs to help change the way of doing business in the former matrix organization.

III. Materials and Structures

The evaluation of parts from the "Demonstration of Partial Automation of Matched Metal Net Molding of Continuous Fiber Resin Matrix Composites" was completed in this period. The \$250 K contract to SPARTA, Inc., was completed in FY 92, but the final evaluation of parts by LLNL and SPARTA's final report was received during this period. Most of this information is extracted from SPARTA's final report⁵, Demonstration of Partial Automation of Matched Metal Net Molding of Continuous Fiber Resin Matrix Composites, K. Cook, K. Cheverton, and G. Wonacott, SPARTA Report No LJ 93-53-TR.

The objectives of this project were to:

- Demonstrate automated closure and opening of the Matched Metal Net Molding external tooling without disturbing the prepreg wrapped on the inner mandrel.
- Demonstrate reproducibility of the automated process by measuring and verifying repeatability from compression and bending ultimate load testing at LLNL.

The objectives were successfully met.

The contract was managed by Gordon Spellman of LLNL. From the outset efforts were made to introduce concurrent engineering and computer technology to reap the maximum benefits for the process. Furthermore, this work capitalized on earlier work by the Strategic Defense Initiative Office such as SPARTA's funding by the Army Research Laboratory - Materials Directorate (US Army ARL-MD Contract DAAL04-86-C-0045 and DAAL04-92-C-0031). The advantages of precision net shaped composite compression molding were evident from these and other developments, and the Fabrication and Test MODIL saw the benefit from automating the process for future SDIO system requirements. For example, SPARTA estimated a cost savings of \$30.5 M (33%) for four components for a

11 year production of the US. Army's JAVELIN shoulder-launched anti-tank weapon. There were numerous other potential projects already being considered by the Army. Furthermore SPARTA anticipated that a single molding machine could accommodate a wide family of components simply by changing the internal and external tooling. This project focused on automated closure of the mold. However, there were many manual operations in the process, with potential automation payoff:

1. Automated tool design given the part design on CAD
2. Automated/autonomous control of the cure process
3. Automated placement of the prepreg on the mandrel
4. Automated closure/cure/and opening of the external tooling
5. Automated punching of penetrations in prepreg prior to cure
6. Automated tool cleaning
7. In situ dimensional verification

The contract called for components which were 10 inches tall cylinders of 9 inches diameter with a wall thickness of 0.8 inches. The cylinder design consisted of four layers of cloth and 10 layers of tape.

The mold was made with NAK 55 tool steel because of its hardness (R_C 45) uniform and consistent grain structure, machinability and dimensional stability. SPARTA used its internally developed hydraulically operated mold closing machine which has full two dimensional motion with limited displacement in the vertical direction. Cartridge heaters, with a heating capacity greater than the $50 - 100$ F per miniature ramp rate requirement, were used to heat the mold to a uniform temperature. Attention was given to the location and wiring of the heaters to achieve a balanced load on all circuits and establish separate heating zones.

The process development initially varied the dwell temperature while keeping other parameters constant. Four cylinders were made during this phase of the contract. It was found

that after 10 minutes at a temperature of 195° F, the mold closed using a nominal constant pressure of 2200 PSI. Four tool modifications were made as a result of the first tests. Three of these modifications were made to accommodate the resin escape path and one was adding heaters to compensate for the loss of heat through the bass plate into the machine structure. In addition the mold closing machine was modified to improve the fabricated part.

Twenty demonstration parts were produced. The parts are of high quality both visually and dimensionally. Some test results, discussed below, indicate that the production run is producing parts with performance virtually identical to predictions and with exceptional repeatability.

Visual inspection of the parts was very encouraging indicating high quality. Initial indications are that dimensions are all within the specification of the Statement of Work with the exception of the diameter. The diameter is small by 0.008" due to errors in tool design. This is the type of error which should be minimized by thorough process knowledge and control. Variations in wall thickness are about 1.5 mils, and the radius varies about +/- 4 mils on a 4.5" radius.

Parts were tested to failure in tension and in compression. The modulus in tension were 15.5, 15.5 and 16.2 MSI, and in compression they were 12.9 and 13.2 MSI. Two of the tensile specimens failed in the fixture at a point about 75% of ultimate, and the one component failed at an ultimate stress of 140,000 PSI which is essentially the same as the predicted value. The compressive failure stresses were 39 and 44 KSI and the mode was buckling. The main results to date are predictability and repeatability which are very high for these components. The MODIL believes this is a key feature of this type of automated process.

Some of the major conclusions from this project include that partial automation of matched metal net molding of continuous fiber

resin matrix composites was successfully achieved. A partially automated mold produced parts that were of equal or superior quality to those produced using the current state of practice with manual tool closure. More reproducible part properties may be achieved through an automated process. Resin viscosity was an extremely critical parameter. (However complete evaluation and *optimization* of viscosity was not within the scope of this contract.) Since resin viscosity is a function of time and temperature, varying the ramp rates, dwell times, and temperatures could improve the process. Gaps at the point of initial high pressure closing and the eventual equilibrium point were noticed. Two facts influence these: machine design not optimized for a 10 inch tall part and the tool locating design and method used for initial loading and positioning of the tool on the machine.

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