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CRYSTAL GROWTH FURNACE (CGF)

FINAL REPORT

Contract No. NAS8-36637

Prepared for

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George C. Marshall Space Flight Center
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Prepared by:

C. E. Billingsley
Programs Support

Approved by:

L. D. Frederick, Manager
Crystal Growth Furnace Program

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TABLE OF CONTENTS

1. INTRODUCTION

This final report is submitted in response to the contract requirement specified in attachment J-2, entitled Reports of Work. The report covers the contract period from June 11, 1987 to December 30, 1992 and addresses the Contract Baseline, Contract Requirements Review, Contract Modifications, Contract Problem Areas and Conclusions.

2. CONTRACT BASELINE

The original contract Multiple Experiment Furnace Facility (MEPF), Crystal Growth Furnace (CGF) was awarded to Teledyne Brown Engineering (TBE) on June 11, 1987, for a total contract value of $5,800,823. This contract included Basic, Option I and Option II. At that time, the contract was for a furnace experiment, smaller and simpler in design, to be flown on an Multi-Purpose Experiment Support Structure (MPESS) in the Orbiter Bay.

A Realignment Proposal was submitted on March 28, 1989, and the contract was modified on December 1, 1989, for a total contract value of $14,150,751. Option II was deleted during negotiations. Subsequent modification to the contract, some of which are described below, increased the total contract value between December 1989 and December 1992.

3. CONTRACT REQUIREMENT REVIEWS

A Project Requirements Review (PRR) was conducted on May 12, 1988. Review item discrepancies (RIDs) and other actions from this review that indicated changes to requirements would be necessary for the program to meet the intended objectives. A Preliminary Design Review (PDR) was conducted on February 17, 1989, also with RIDs and other actions from this review that indicated changes to requirements would be necessary for the program to meet the intended objectives. The preliminary Contract End Item (CEI) Specifications at the PRR were upgraded later to reflect requirements for a larger system to fly within Spacelab.

The CGF program went through numerous major changes over a period of 18 months from contract award to late November 1988.

RIDs presented at the PRR resulted in extensive upgrading of the system and were incorporated into a detailed design after PDR.

As the CGF became recognized as a crucial payload for United States Microgravity Laboratory -1 (USML-1), the system and the program demanded greater scrutiny in the areas of reliability, maintainability, and program risk. All aspects of the program were carefully reevaluated to ensure that decisions and plans gave proper consideration to these factors.

The Ground Control Experiment Laboratory (GCEL) Program was given added significance and grew beyond original intentions to account for using the system as a pathfinder for design and manufacturing verification, for software development and verification, for furnace characterization, for input to control algorithms and PI use. Repeatability between the GCEL and the Flight Unit required that the differences between GCEL and Flight Units be identifiable.

Changes to the CGF Program, through December 1989, were made in five general areas with twenty-six specific technical changes.

Major areas of change include:

- CGF System Upgrade and Additions
- GCEL System Upgrade and Additions
- CGF Program Upgrade and Additions
- DTA/EDU Additions and Changes
- Crew Interface Changes.

4. CONTRACT MODIFICATIONS

All of the modifications to the contract are not addressed in this summary, only those that changed or added requirements. Administrative modifications are not included.

Eleven changes were made to upgrade the CGF system to satisfy new requirements. The Reconfigurable Furnace Module (RFM) design changed to improve performance. Fabrication was moved in-house to increase control over processes and reduce schedule risk. Configuration changes allowed easy changeout of RFM units more easily so that a wide range of objectives could be met by the CGF reconfigurable capabilities.

A dual-drive Furnace Translation System (FTS) was incorporated because motor drag would not allow proper operation of a single-drive system. A two voltage control was added to improve ability to properly park the RFM. Problems encountered with the AADSF design were avoided by improving the core hold-down mechanism design and the building of a special test/adjustment fixture.

A viewport was added to the Experiment Apparatus Container (EAC) to allow observation of the Sample/Ampoule/ Cartridges by the crew. This caused forgings to be much thicker, resulting in a much more complex manufacturing process. Increased complexity in the Base Ring area resulted from the addition of filters for the dual-drive FTS system and from weight reduction efforts. The EAC dome was redesigned to ensure safety codes for the container could be met with confidence and with a reduced weight.

Dynamic modeling showed the Internal Support Structure (ISS) was not adequately stiff, requiring the addition of a complex rib structure. A requirement for a more predictable alignment capability and for easier change out of the RFM units led to complete redesign of the ISS. Assembly and testing of the Development Test Appratus (DTA) demonstrated this new design, which improved program flexibility.

Packaging of the power signal conditioning system (PSCS) circuits and modules for increased power requirements produced a much more complex system than envisioned at the PDR. The PSCS was divided into two units having over three times the volume of the PDR concept. The increased volume required weight reduction measures be taken, as well as ensuring adequate EMI protection to the system and to the interfaces. These were major drivers in the PSCS redesign.

Documenting of the data acquisition system (DAS) printed wiring assemblies used in the command and acquisition data system (CDAS) became necessary to decouple the CGF from other programs using the DAS.

Fifteen cables required to interconnect the CGF units in the Spacelab, supplemented with thirty-five additional cables for ground testing of the flight unit, were added. The use of remote-controlled circuit breakers as a way to increase the system reliability were added. This required changes in the power distribution system (PDS), cables, and the CDAS.

A greatly enlarged CGF avionics system required integration into a double rack. Ground racks were added to support the GCEL.

The amount of ground support equipment (GSE) greatly increased. Only one set of mechanical ground support equipment (MGSE) was included in the contract but two sets became necessary. Much growth in complexity of the MGSE and electrical ground support equipment (EGSE) occurred. Electrical checkout equipment (ECE) was added for checkout of the Avionics. Furnace checkout equipment (FCE) capabilities were increased. These additions provide the program much more flexibility and long-range capability for future missions.

System Reliability was enhanced by using software to manage redundancy and to provide workarounds, additional computational capabilities, and controls.

Changes made the GCEL unit essentially identical to the flight unit so that it could be more effectively used as a pathfinder to identify potential system design and manufacturing problems. This high-fidelity unit was used for software verification and furnace characterization tests. This unit became an invaluable tool to support PI activities and future missions. RFM units can be exchanged to accommodate a wide range of test conditions and objectives.

A Development Test Article (DTA) was added to the program to confirm that the BeO core would be adequately durable for space flight and for use at the required temperatures.

In order to fabricate the DTA, a complete RFM was assembled using flight drawings with minor changes. A holding fixture was designed and fabricated. Cables were built to provide power and instrumentation. Computer control and monitoring were added to increase the data-collecting capability. A hot test was performed with this configuration with continuous testing for a full 13 cycles to the required temperatures. Special wipes of the interior of the test chamber and test hardware were taken to confirm that BeO was not being released by the high temperatures. NASA requested a special test using an instrumented probe. Special test fixtures were designed and fabricated to support this test.

A complete IFEA Experiment EAC assembly and many of the IFEA subsystems were assembled to provide a realistic vibration test environment for the RFM. The SEM was not available for this test so a mass simulator was provided. The assembly was instrumented and transported to MSFC for vibration testing. Special steps were taken to confirm that BeO was not released during vibration testing.

A glovebox became a necessity for providing crew access to the samples in the IFEA without contact to BeO particles. Design concepts were developed and demonstrated to the MSFC CGF Tiger Team. After a review of the glovebox concept, a decision was made to defer work since it would not be needed for the first mission. This was later rescinded and a Glovebox was provided to support the USML-1 Mission.

Modifications to the DTA were necessary to support and conduct new cartridge material testing for up to three weeks. TBE supported continuous GCEL testing for approximately five months and performed an evaluation of the testing results and provided reduced data to MSFC.

Numerous tasks related to GCEL testing were added. GCEL testing around the clock began after refurbishment, in early November. Testing support included obtaining test requirements and objectives from MSFC; drafting, reviewing, and releasing test procedures/plans; engineering and manufacturing support; formatting and reduction of test data; completion of development of GCEL PI MUX 1/0 graphics, and Quality Control coverage as required.

Additional thermal probes to support follow-on testing in the Crystal Growth Furnace (CGF) Development Test Article (DTA) and Ground Control Experiment Laboratory (GCEL) was issued by MSFC on September 10, 1991. This modification directed the fabrication and checkout of two new thermal probes to support follow-on DTA/GCEL and flight unit testing. One probe was configured with six Type K thermocouples and one with six Type S thermocouples, to support both low and high temperature development testing, respectively.

A modification was issued by MSFC on September 18, 1991 which directed TBE to conduct efforts in four areas: DTA Upgrade; PCTC Mockup; PI Thermal Analyses; and, PI Materials Compatibility Studies. TBE analyzed the requirements and developed a set of detailed individual task descriptions that represented the required efforts. The requirements to upgrade the DTA and then implement Peltier Pulsing for sample cartridges was more complex than originally envisioned. The special compatibility studies made to develop a cartridge concept using PBN, the mixture of thermocouples, and considerations relating to Peltier Pulse increased the complexity of this modification above that originally envisioned. Costs savings were realized by not including unnecessary EMI filters and by fabricating the SEM from stainless steel instead of titanium. TBE was directed to refurbish the DTA to have the capability, in order of priority, to support materials compatibility sample processing, furnace characterization with Peltier Pulsing, and sample pre-processing. The intent of this modification was to upgrade of the DTA such that it may be used as a test bed for the Peltier Pulse breadboard.

A mockup of the PCTC was built and delivered to MSFC. The need for this mockup was urgent. TBE responded quickly, and designed, fabricated, and delivered this all metal mockup in two weeks time.

Several meetings with MSFC science and technical advisors were needed to clarify the SOW requirements for the PI Thermal Analysis effort. These requirements and their implementation were more complex than originally thought. Optimization thermal analyses had to be performed to determine the best Gradient Zone configuration and set point temperatures, given the processing requirements for each PI sample. By understanding the optimum processing parameters for each sample, the best single RFM configuration for each of the samples was determined. The first phase involves development of a test-correlated empty RFM model. Thermal models of the USML-l PI SACAs were developed during the second phase of the analysis; they were be integrated into the RFM model developed in the first phase. In the third and final phase of the optimization analysis, the effects of changing the gradient zone thickness, thermal control plate thickness, and heater set points on sample temperature distributions and gradients were quantified. At the completion of this task, the analyses, results, conclusions, and recommendations were documented The optimum RFM configuration for each sample was translated and delivered in COSMOS/M form to provide compatibility with the earlier PI analysis models.

Special studies were conducted concerning the compatibility of cartridge materials with thermocouples and insulation in the RFM and with thermocouples in the SACA, which had shown evidence of degradation during CGF testing. The materials compatibility studies consisted of several sequential efforts. First, an extensive literature search was conducted for information on appropriate cartridge materials (e.g. refractory metals, metallic ceramic composites, ceramics and double wall quartz) to find data regarding incompatibility with thermocouples or other furnace materials. An intensive effort to develop a suitable cartridge for sample processing was also included in this materials compatibility study. Investigations into PB, N and Alumina required TBE to acquire sample cartridges and make checkout runs in the DTA. PBN cartridges, provided to TBE by MSFC, were evaluated. Modifications to the cartridge fabrication process were made, samples fabricated, cartridges built up with thermocouples, and checkout processing performed.

TBE was directed to develop and furnish PCTC software to accomplish simulation of the on-orbit Bootstrap Loader software loading by the crew. To enhance the quality of the training, this work was performed as quickly as feasible to furnish the required software. In addition, changes were required to the Application Dependent Software (ADS). Efforts by TBE related to the ADS were performed with a very high priority, in order to support the then on-going CGF integration activities at KSC. TBE provided changes/corrections to the Application Dependent Software (ADS) Version 1.6 which were necessary for success of the USML-1 mission. Those changes resulted in the implementation of a new ADS Version 1.7.

A modification issued on April 16, 1992, required that TBE provide six personnel to support POCC positions during USML-1 Mission. TBE provided staffing for the positions during six 24-hour days for training operations, and during 14 days for flight operations, with a small amount of related POCC documentation support.

MSFC required two months of GCEL testing, in support of post flight PI SACA processing. This support included timeline generation, software support, GCEL and facilities maintenance as well as data reduction and PI graphics during the specified two months of dedicated 24 hour a day GCEL operations.

Three shifts with a chief test conductor and assistant test conductor were run, with software engineering, technician, and management support on call or as required during round the clock operations. Dedicated PI graphics computers with real time data displays were provided to maximize PI interaction and involvement with the SACA being processed.

The last modification to contract, NAS8-36637 was issued by MSFC on September 22, 1992. Basically, this modification required TBE to perform post flight testing and checkout of the flight hardware, and to submit the testing and checkout procedure and post flight testing plan to the COTR for final approval.

5. CONTRACT PROBLEM AREAS

Technical problems arose during the CGF test program that threatened a timely delivery of the CGF system and turnover to KSC. TBE responded in numerous ways to minimize the impact of these problems. Additional resources were applied and a high priority effort within the company was maintained and extended beyond earlier plans to ensure that the best chance was given for meeting schedule. Even with these efforts to minimize schedule impact, delivery to KSC was delayed by approximately 13 weeks. Numerous workarounds were implemented to reduce the impact to KSC Turnover. Turnover to KSC only slipped from the planned May 15 date to June 28 and there was minimal, if any, real impact to KSC and associated integration operations.

These problems include the following:

Failures of the remote controlled circuit breakers (RCCBs) used in the power distribution system required removal of the RCCBs from the PDS on two different occasions. Additionally, the RCCBs were disassembled and modified by the vendor. Substantial schedule delays resulted from this problem for both hardware and software elements.

Rework of flight hardware, including previously qualified boxes, was required. While the actual rework effort was notable, the bulk of the program impact came from the increased testing, verification, qualification, and other activities. Many of these activities were required to be completed in serial. Contingency schedules were used to minimize these impacts.

Problems were encountered on the CDAS operating system software. Troubleshooting was very complex. One major problem occurred in the commercially procured operating system and was resolved using an upgrade version to the system, but not until an estimated two weeks of program impact was incurred.

Flow sensors and various temperature sensor devices did not perform properly and required repair and replacement. Modification and adjustments were made to the SEM mechanism to improve performance and reliability. Problems with the furnace translation system were encountered when operated at upper temperature limits. Assembly of the IFEA proceeded more slowly than planned due to numerous small problems related to the wiring harness interference. Wiring and the support mechanisms had to be repaired and modified to eliminate an abrasion that could possibly have caused a cable failure during the mission.

Additional hardware items were required to adapt the CGF system to MSFC test facilities for the offgas testing.

The PI Sample Test Program was planned to be performed between October 15, 1990 and January 15, 1991. TBE was required to provide 24 hour, 7 days a week support for this level-of-effort activity. Although this testing started on schedule, problems in developing the Sample/Ampoule/Cartridge Assemblies made it impossible to complete the program within the allotted 3 month window. NASA/MSFC worked very closely with TBE to plan to minimize the program impacts from these problems. This resulted in additional thermal probe runs to minimize schedule impacts. TBE made staff available around the clock in order to test the samples immediately as they became available. In most cases, the TBE team was ready to take action on samples within minutes after receipt. However, the PI Test Program completion had to be extended from January 15 to May 20. This change from a 3 month test program to a 7 month test program impacted the total program through the addition of PI related tasks. It also delayed planned work, required continual re-planning of PI testing activities, took resources away from work on the flight system and caused a delay in the flight system schedule. Testing of the flight system could not be completed until the PI Testing was completed. The extension of the PI testing program was a major contributor to the flight hardware schedule delay.

Extensive, unexpected contamination of the CGF resulted from the emission of Molybdenum Oxide from the Sample/Ampoule/Cartridge Assemblies furnished to TBE during the PI Test program. The furnace had to be cleaned by performing "bake-outs" at high temperatures and by manually cleaning the surfaces in the IFEA. The efforts to perform these tasks were substantial and directly contributed to schedule delay. Further impacts were realized due to multiple material samples that had to be analyzed to determine if toxic materials were present in the furnace subsequent to contamination. The contamination was also identified as a prime contributor to severe degradation of the insulation materials in the RFM. Due to this contamination, the RFM was disassembled multiple times and parts were replaced. The impact of the contamination due to GFE also raised questions about the flight system that had to be investigated; this required changing plans for the flight system testing, and required the team to divert its efforts and emphasis to this very serious problem. There are unresolved questions about the consequences of this contamination on critical furnace elements such as thermocouples.

Within the general scope of PI testing, TBE conducted pre-processing of MSFC samples. These activities were not part of the planned test program but were requirements that evolved during development of the testing program.

In order to satisfy the schedule mandate, without compromising quality, TBE committed every possible resource to CGF and gave this program the highest possible priority and attention by all levels of management. TBE did whatever was required to accomplish the program requirements. For example, EMI/EMC testing was performed at TBE in a special facility, built in a few days time, specifically for the purpose of testing CGF at TBE instead of at MSFC. The EMI/EMC testing was performed on third shift to gain the maximum schedule benefit. Above all, performance, reliability and documentation requirements were not compromised.

6. CONCLUSIONS AND RECOMMENDATIONS

The total commitment of the NASA/TBE CGF team made the timely delivery of CGF possible.

The CGF performed as designed and, based on the many comments by persons associated with the program, more than met the expectation of the users. The experiments conducted on orbit attest to this conclusion.

TBE recommends that the Peltier Pulse capability be added to the CGF System, and that SACA production be coordinated closely to optimize program performance.

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Charles Billingsley
Larry Frederick

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Teledyne Brown Engineering
300 Sparkman Dr.
Huntsville, AL 35807-7007

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13. ABSTRACT *(Maximum 200 words)*
The report addresses the contract baseline, contract requirements review, contract modifications, contract problem areas and conclusions. Contract baseline was established 11 June 1987 and updated 1 December 1989. Significant changes were introduced into the 1989 baseline as compared to the original baseline. Contract modifications were made to add requirements as the program matured and as definition of requirements were completed. Problems were solved in real time through the contractor/customer team involvement and relationship to assure a timely and successful mission. The conclusion is that the CGF performed as designed and the experiments performed during the USML-1 Mission supports the conclusion.

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