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**STS-107 MISSION AFTER THE MISSION: RECOVERY
OF DATA FROM THE DEBRIS OF COLUMBIA**

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ABSTRACT

STS-107 was a 16-day, dedicated research mission that included over 80 experiments, spanning many disciplines including biology, physics, chemistry, and earth sciences, including many student experiments. The mission was considered a resounding success until February 1, 2003, when tragedy struck the Columbia and her crew as she re-entered the atmosphere over Texas. During the mission, approximately one third of the overall data was obtained but much more was stored in the flight hardware systems. This paper documents a new set of STS-107 experiment objectives, a "mission after the mission," in which several experiment teams attempted, and, in many cases succeeded, to recover data from their flight hardware, now debris. A description of the data recovery efforts is included for these five experiment facilities: Combustion Module-2, Critical Viscosity of Xenon-2, Commercial Instrumentation Technology Associates Biomedical Experiments-2, Biological Research in Canisters-14, and Commercial Protein Crystal Growth.

INTRODUCTION

The STS-107 mission was a dedicated 16-day research mission that included over 80 experiments that were part of two primary payloads: the SPACEHAB Research Double Module (RDM) and the Fast Reaction Experiments Enabling Science, Technology, Applications, and Research (FREESTAR). For general information about the experiments, see <http://spaceresearch.nasa.gov>.

By all accounts, the STS-107 mission was a complete success by day 15. The ground team and flight crew tackled and solved many problems during the flight such as Ku-band data system crashes, thermal control inside the SPACEHAB module, and, the numerous timeline with vehicle attitude and crew time constraints.

On February 1, 2003, only 15 minutes from "home" at Kennedy Space Center (KSC), the Columbia and her crew perished over Texas. In addition to the terrible loss of human life and the vehicle, the payload hardware and associated data were also assumed to be completely destroyed. The debris field spread from California to Louisiana, including thousands of Shuttle and payload debris pieces.

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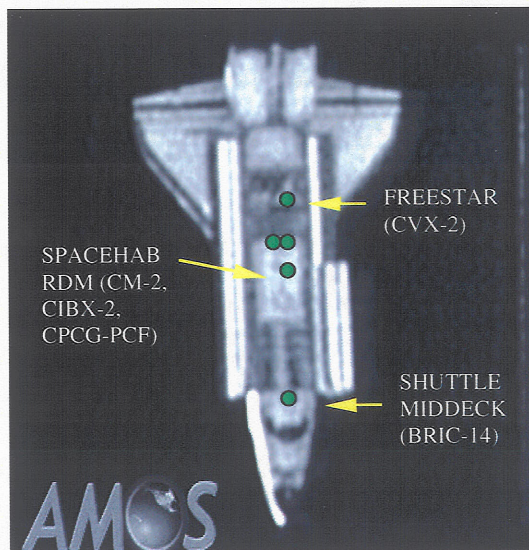


Figure 1: United States Air Force Maui Optical and Supercomputing Site (AMOS) photo of Columbia and her payload with highlights for the payloads discussed in this paper.

Only 30% of the data was acquired from downlink; most experiments required post-flight sample or data media download and analysis.¹

However, many of the experiment teams did not give up. They traveled to KSC to view the debris in hope of obtaining additional science data. In addition, some of the computer and video debris was retained at the Johnson Spaceflight Center (JSC) to support the Columbia Accident Investigation Board (CAIB).



Figure 2: Columbia debris at KSC hanger.

Hence, the "mission after the mission" began for experiment teams to utilize recovered flight hardware debris to regain lost science data. Given the sensitive nature of the flight hardware, there was a controlled, multi-step process to attempt data recovery.

This paper describes the successes (and failures) of five experiment facility teams in their "mission" to obtain data from the STS-107 debris.

COMBUSTION MODULE-2 (CM-2)

CM-2 Background and Data Results

Many of the fundamental processes of combustion are obscured by gravity-driven convection. The objectives of CM-2's three experiments were to improve our understanding and modeling of key combustion processes which impact fuel efficiency, pollution, and fire safety on Earth and in space. NASA Glenn Research Center's (GRC) Combustion Module-2 (CM-2) and its three experiments successfully flew on STS-107/Columbia in three racks on the port side of the SPACEHAB RDM and provided the answers for many research questions. For more information, see <http://microgravity.grc.nasa.gov/combustion>. The summary of data is as follows.

CM-2 Experiment	Principal Investigator	Mission Data	Current Data
Laminar Soot Processes (LSP)	G. M. Faeth, University of Michigan	50%	52%
Structure of Flame Balls at Low Lewis-number (SOFBALL)	P. D. Ronney, University of Southern California	65%	65%
Water Mist Fire Suppression Experiment (Mist)	J. T. McKinnon/A. Abbud-Madrid, Colorado School of Mines	90%	92%

CM-2 Data-Containing Debris and Recovery Attempts

In terms of data storage devices, CM-2 had four types: soot particles collected on soot sampler grids, flame images stored on Digital Data Recorders (DDR), analog video stored on Hi-8 video tapes, and, sensor data stored on Targa's. All four types of device were found in the debris field and data recovery was attempted. The videotapes were processed by JSC, but CM-2 personnel identified and processed the other items.

The LSP soot samplers consisted of small probes containing Thermo-Electron Microscope (TEM) grids that were quickly inserted and retracted from the LSP flame to collect soot. Five of six soot sampler banks were recovered and every soot sampler probe was carefully examined at GRC by manually extending the probes out of the housing. The damage to all five was severe including sheared off probes and visible signs of aluminum slag entering the housing. No grids remained attached; hence no soot data recovery was possible.

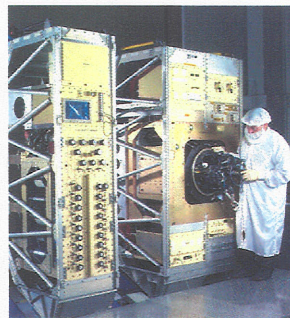


Figure 3: With KSC personnel help, CM-2 identified approximately 100 pieces of CM-2 hardware debris, representing only ~10% of the 620 kg (1375 lb) total mass. The faceplates and the two largest pieces, the 90-liter Combustion Chamber and the Optics Plate (large aluminum plate behind chamber, right center), were never found.

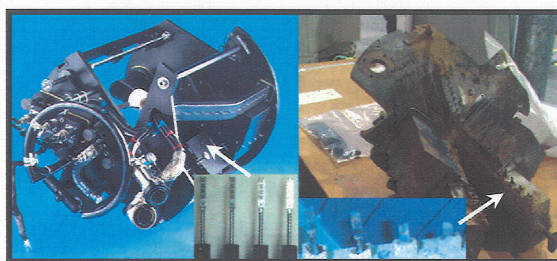


Figure 4: The LSP chamber insert is shown before (left) and after flight (right) with the soot sampler banks installed. The photo inset shows a close-up of the probes with (pre-flight) and without (post-flight) the soot-collecting TEM grids.

Recovery of the flame image data on the DDR that the LSP experiment utilized would have a significant impact on LSP science data, an improvement from 50% to over 90%. Out of the eleven DDR's flown, there was one in-tact DDR identified at KSC and five loose DDR hard drives identified from JSC photos. The DDR from KSC was in pristine condition on the outside due to the fact it was probably installed in CM-2 for landing, giving it extra protection. Another drive from JSC was in very good condition externally. Two data recovery experts^{2,3} attempted to retrieve data from the first drive and one attempted on the second drive. Unfortunately, there was no success because some of the internal drive platens were badly scratched. No data was recoverable from the six DDR's.

Two of the approximately 100 High-8 videotapes were recovered and contained LSP and SOFBALL flame images. These tapes were helpful, but did not enhance the science return significantly because LSP had downlinked this information in a digital format and SOFBALL needed multiple camera views for detailed post-flight analysis.



Figure 5: CM-2 DDR outer case and hard drive before (left) & after (right) from KSC & JSC inventories. The top right hard drive was in near perfect condition on the outside, compared to other, unprotected hard drives as shown in two photos on the bottom right.

Seven of the ten Targa's flown were found at KSC and all were approved by the CAIB to be shipped to GRC for possible data recovery. Based on the disassembly and inspection at GRC, all but one of the internal flash cards and loose memory chips were sent to a vendor in an attempt to recover the data⁴. At the vendor, three of the six booted-up nominally and the other three were mounted on new circuit boards. All six were successfully booted-up at GRC and all the data was successfully recovered. Approximately 90% of the sensor data had been downlinked during the mission and this data recovery success enhanced the sensor data to nearly 100%.



Figure 6: Targa cartridge shown before and after (upper photos). Four of seven Targa's required some force to slide out the flash memory boards (lower photos).

CM-2 Summary

In summary, CM-2 had some success recovering a small portion of overall mission data. However, the most critical data that were lost, flame images and analog video, were not recovered. Hence, overall science data gain was about 2%.

CRITICAL VISCOSITY OF XENON-2 (CVX-2)

CVX-2 Background and Results

The NASA Glenn Research Center's (GRC) Critical Viscosity of Xenon-2 (CVX-2) experiment successfully flew on STS-107/Columbia. The objective of the experiment was to measure the viscosity of Xenon, one of nature's simplest fluids, very near its liquid-vapor critical point ($T_c \approx 16.7$ deg. C) more accurately than possible on Earth, and to compare data with theoretical calculations to improve mathematical models. See <http://microgravity.grc.nasa.gov/cvx2> for more information.

The CVX-2 hardware consisted of two canisters at atmospheric pressure containing an experiment section and supporting avionics. The summary of data is as follows.

Experiment	Principal Investigator	Mission Data	Current Data
Critical Viscosity of Xenon (CVX-2)	R. F. Berg, National Institute of Standards and Technology	86%	99%

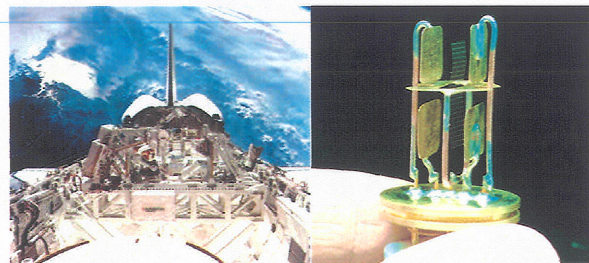


Figure 7: CVX-2 was mounted on the FREESTAR pallet in the cargo bay of Columbia. At the heart of the experiment was a nickel screen that vibrated in the bath of xenon fluid, measuring just millimeters across and weighing less than one milligram.

CVX-2 Data-Containing Debris and Recovery Attempts

Most of the CVX-2 flight hardware was found heavily damaged. However, the two components that could provide scientific benefit were the viscometer (or sample cell) and the system hard drive.⁵

With help from KSC personnel and the GSFC Hitchhiker Team the CVX-2 flight sample cell found in the debris of the Columbia was returned to GRC for evaluation. The flight sample cell and ground cell were both placed within a thermal chamber to chill the units below the critical temperature. This enabled the CVX-2 PI team to evaluate the liquid-vapor meniscus line and determine that the flight sample cell lost less than one percent of its xenon sample. This result validated the viscometry measurements taken near the critical temperature obtained during the flight.

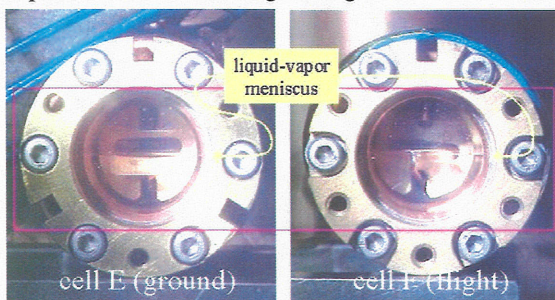


Figure 8: The height of the liquid-vapor meniscus in cell E (ground) was compared to cell F (flight cell, in-tact inside CVX-2 sample cell debris). The cells were photographed in a chamber whose temperature was controlled at 16.0 ± 0.1 °C.

The CVX-2 experiment hard drive recorded and processed all the data for the entire mission and approximately 15% was missing from the downlink data set. It was assumed lost until months after the mission when the JSC debris photos were released. CVX-2 received permission from the CAIB to send the drive to GRC and a data recovery expert for processing.



Figure 9: With the help of GSFC personnel, the CVX-2 team identified the CVX-2 hard drive that was mounted to a unique support plate.

As with all Columbia debris, the drive showed signs of excessive temperature exposure and all wiring connections had burned away. However the vibration isolation mounting plate provided protection and structural support to the drive and the PCB on the exposed top surface also provided a level of thermal protection. The hard drive was sent to a data recovery expert² and a total of 792 files were obtained from the disk, equivalent to ~15.4 days of mission data files,

close to the duration of CVX-2 operations. This successful data recovery operation increased the CVX-2 data success to nearly 100%.

CVX-2 Summary

In summary, CVX-2 had great success recovering nearly all the flight data, raising the overall data obtained from 86% to 99%. In addition, on-orbit measurement quality was validated by assessment of the sample cell.

COMMERCIAL INSTRUMENTATION TECHNOLOGY ASSOCIATES (ITA) BIOMEDICAL EXPERIMENTS-2 (CIBX-2)

CIBX-2 Background and Results

The Commercial ITA Biomedical Experiments-2 (CIBX-2) experiment successfully flew on STS-107/Columbia. CIBX-2 was unique technically and programmatically. The CIBX hardware hosted 11 separate experiments including cancer research (e.g. high-purity Urokinase enzyme that causes cancer to spread), commercial experiments (e.g. micro-encapsulation drug delivery for cancerous tumors), and student experiments from 10 schools as part of Space Outreach's Hands-On Student Microgravity Experiments Program⁶ (see <http://www.spaceoutreach.com/>). Programmatically, CIBX was 100% privately funded by ITA, Inc., unique for this mission, and was flown through a Space Act agreement with JSC. See <http://www.ITASpace.com> for more information.

The CIBX-2 flight hardware flew in a Middeck locker integrated into the aft bulkhead of the SPACEHAB Research Double Module. The hardware consisted of two Dual-Materials Dispersion Apparatus (DMDA) flight units and 14 Liquids Mixing Apparatus (LMA) trays. The DMDA's, which made up approximately 80% of the total CIBX payload volume, were recovered. The LMA units have never been found.



Figure 10: CIBX-2 included two DMDA units that were mounted inside a locker on the aft bulkhead of the SPACEHAB Research Double Module. STS-107 astronaut Kalpana Chawla (K.C.) is pictured in front of the CIBX-2 payload (upper left).

The following is a summary of CIBX investigators and the current state of the data obtained (the mission data obtained were each at 0%).⁷

CIBX-2 Experiment	Principal Investigator	Affiliation and/or Co-sponsors	Current Data
1. Urokinase Cancer Research (13 DMDA Sample wells and 1.5 LMA Trays containing 6 sample vials)	D.Morrison J. Cassanto U.Alvarado J. Bognacki	ITA, Inc., Nu-Millennium Research, NASA JSC	Urokinase crystals believed to have gone back into solution due to lack of temp control & time.
2. Micro-encapsulation of Drugs (14 Sample wells)	D.Morrison J. Cassanto	ITA, Inc. NASA JSC	~90% - Good microcapsules formed. Data still being analyzed.
3. Food Products in Space (15 Sample wells)	E.Schenker	Israel Aerospace Medicine Institute (IAMI), Materna	0%
4. Growth of Bacterial Biofilm on Surfaces During Spaceflight (GOBBSS) "Peace in Space Experiment" (5 Sample wells)	T. Adwan, Y. Landau, D. Warmflash, E.Schenker	Palestinian and Israeli Students - Tel Aviv University, The Planetary Society, Israel Aerospace Medicine Institute (IAMI), NASA JSC Astrobiology Center, Seeds of Peace Orgn.	Recovered all samples however due to long time on ground before inspection 0% data.
5. Lockheed Martin Space Operations Inorganic Crystal Growth in Microgravity (7 Sample wells)	R. Mohler	LaVance Stewart Elementary, Kemah, TX; Sam Houston Elementary, Bryan TX; Helen M. Knight Intermediate School, Moab, UT; Eagle Nest School, Eagle Nest, NM Lockheed Martin Space Operations	100% - good crystals obtained. Involved many students from various schools.
6. Tin Crystal Formation (3 Sample wells)	B. Perlman	Pembroke Pines Charter Middle School, Florida	60% (material recovered similar to tin crystals but tin crystals did not survive due to elevated temperatures

7. Bacteria with Expression of Antibiotic Resistance (7 Sample wells)	N. Bean	Milton Academy, Massachusetts	80% - Samples still being analyzed.
8. Biofilm Formation (6 Sample wells)	Robert McLean	South West Texas State University, Texas	80% - Samples still being analyzed.
9. Regeneration of Nerve Cell Growth Factor (2 Sample wells)	E. Gwebu, B.Vardaman	Oakwood College, and Biospace Group, Huntsville, Alabama, and ITA, Inc.	0% - (Not enough fluid volume to analyze.)
10. Bence-Jones Bone Cancer Experiments (1.5 LMA Trays containing 6 samples)	A. Edmundson	Oklahoma Medical Research Foundation, ITA, Inc.	0% (flown in LMA hardware which was not recovered).
11. Osteoblast/ Osteoclast Osteoporosis Experiments (1 LMA Tray containing 4 samples)	E. Schenker	Israel Aerospace Medicine Institute (IAMI)	0% (flown in LMA which was not recovered).

CIBX-2 Data-Containing Debris and Recovery Attempts

Data for these experiments were harvested from the more than 100 physical experiment wells from the DMDA containing flight samples and then analyzed post-flight. Within 24-hours, ITA engineers from the CIBX launch team identified their hardware shown in

TV news programs and a newspaper photograph.⁸ The CIBX Team was able to identify the hardware and eventually obtain permission from the CAIB to attempt data recovery. The two DMDA hardware units miraculously survived re-entry but showed evidence of elevated temperatures and charring. However, the seals that isolated the sample wells held during re-entry, impact with the ground, and throughout the months in the KSC hangar before the data recovery efforts commenced. Fluid samples were obtained from all of the DMDA experiments (9 of the 11 total for the payload). The quality of the data was good for about half of the experiments, including proof of success in creating and/or growing microcapsules, inorganic crystals, and, biofilms.



Figure 11: The CIBX-2 team quickly identified one of the two DMDA units that was found in Texas shortly after the debris search began. The photos shown going clockwise from the upper left are the pre-flight unit, a DMDA found in Texas with other Columbia Debris, the New York Times photograph⁸, and, a DMDA at KSC.



Figure 12: From left, Valerie Cassanto, ITA, Inc., and Dr. Dennis Morrison, NASA Johnson Space Center, analyze one of the experiments carried on mission STS-107. On right, Microcapsules of Doxycycline [antibiotic] recovered May 6, 2003 from CIBX-II apparatus found in debris from Columbia breakup [100x]. Photo courtesy of NASA-JSC.

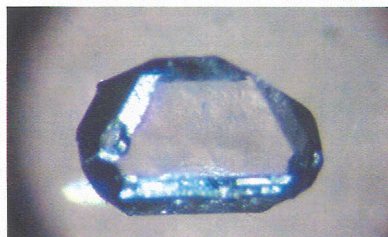


Figure 13: Inorganic crystals were successfully grown on Columbia during the mission and recovered after the accident. The aluminum potassium sulfate crystals grown in space had the classic cubic pyramid structure. The space-grown crystal facies appear more smooth and gem-like in appearance than the ground controls."

CIBX-2 Summary

In summary, CIBX-2's "mission after the mission" was a great success, using the DMDA flight hardware that survived re-entry to raise the overall data obtained from

0% to nearly 50%. Success regarding the student "hands-on" experiments can not only be measured by how much science was obtained, but also how much students became involved and engaged. ITA and Space Outreach personnel plan to publish and present a detailed analysis of the harvested samples, an engineering chronology of the re-entry and survival of the CIBX-2 DMDA hardware, and the unorthodox procedures and decisions made in real time to disassemble the hardware to recover the samples.

BIOLOGICAL RESEARCH IN CANISTERS (BRIC-14)

BRIC-14 Background and Results

The NASA KSC developed Biological Research In Canisters-14 (BRIC-14) experiment successfully flew on STS-107/Columbia in the Shuttle Middeck. The objective of the main plant experiment was to determine how gravity and illumination levels influence the internal structure and growth of *Ceratodon purpurea* moss cells, expanding the knowledge from a previous shuttle flight in which moss specimens grew in a spiral pattern. A second experiment was added shortly before launch to validate a proposed new food source for the round worm *Caenorhabditis elegans*. See <http://spaceresearch.nasa.gov/> for more information.

Within one Middeck locker, the BRIC-14 hardware provided 99 moss samples with growth media, chemicals for fixation, growth inhibitors, and lighting controls. Also, hundreds of round worms were provided growth media and atmosphere control. The summary of data is as follows.

BRIC-14 Experiment	Principal Investigator	Mission Data	Current Data
Development of Gravity Sensitive Plant Cells (<i>Ceratodon</i>) in Microgravity	F. Sack, Ohio State University	0%	87%
C. elegans Evaluation Experiment	C. Conley, Ames Research Center	0%	80%

Note: Data quality is under review.

BRIC-14 Data-Containing Debris and Recovery Attempts

The sample cell hardware, the BRIC-LED canisters and the BRIC-60 canisters, were the critical part of the two experiments. In addition to the samples, some temperature sensor data were stored on loggers located inside three of the BRIC-60 canisters and one BRIC-LED canister. Over the course of the debris search, a total of seven BRIC-LED and five BRIC-60 canisters

were recovered intact, within a 12-mile radius in eastern Texas.⁹

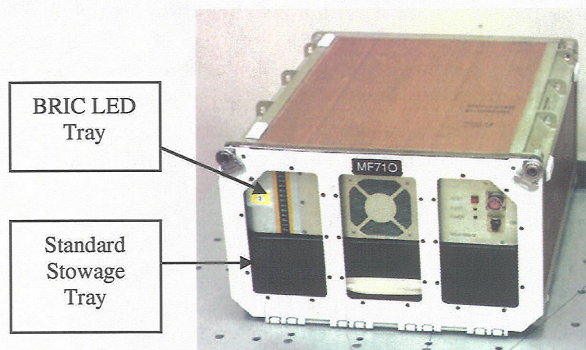


Figure 14: The BRIC-14 flight hardware was subdivided into the payload and stowage trays. The payload tray contained eight Biological Research in Canisters-Light Emitting Diode (BRIC-LED) canisters, each containing six Petris Dish Fixation Units (PDFU) for the moss cells. The stowage tray contained six BRIC-60 canisters containing *C. elegans* worms and other BRIC-14 support hardware.

Following CAIB Board approval, the flight canisters were shipped to Hangar L at KSC for disassembly. The BRIC-60 canisters were opened first. Although there was clearly some damage on the outside surface, the seal to the inside was not broken and the petri dishes remained intact. In fact, only one petri dish showed any heat damage (protected by Velcro™ and Teflon™ spacers) and two petri dishes were cracked (possibly due to ground impact).



Figure 15: BRIC-60 canisters are shown side-by-side, pre-flight on left and post-flight on right. When the canister is opened, the stack of petris dishes is in excellent shape. Scanning electron micrograph of ~1 mm long adult *C. elegans* worm is shown in lower right (photo credit: Juergen Berger and Ralph Sommer Max-Planck Institute for Developmental Biology).

Remarkably, four of the five BRIC-60 canisters contained live round worms. Scientifically, this is significant; however, not all the original objectives could be completed due to the differences in environment and post-flight conditions (e.g. temperature) between the flight and control groups. Also, the data were successfully recovered from all three temperature loggers.

Seven of the eight moss-containing BRIC-LED canisters were recovered and approved for data recovery processing. Six suffered surface damage only

and one had a breach through the outside shell. Moss samples were recovered from all seven.

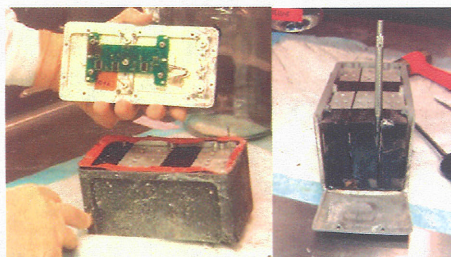


Figure 16: Four of the LED Canisters opened easily (left). Various methods were used for the other three to disassemble and access the moss samples.

Of the 87 total possible moss cultures (up to three per dish) in the recovered canisters, 86 were isolated and removed intact from the hardware, although some of these samples may be degraded or difficult to interpret due to the extreme conditions they encountered. Data were also recovered successfully from the temperature data logger. The investigator teams will continue to analyze specimens and several journal articles are already being prepared by both teams.

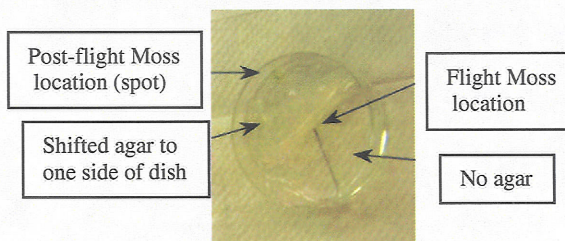


Figure 17: The small green spot in the upper left section is the moss culture. All the moss cultures and agar substrate were shifted from their original position during the break up event.

BRIC-14 Summary

In summary, the BRIC-14 Team was able to raise their return of data from 0% to 80-87%; however, the data quality may be degraded. Further analyses will be required to determine the true scientific yield from the recovered material.

COMMERCIAL PROTEIN CRYSTAL GROWTH- PROTEIN CRYSTALLIZATION FACILITY (CPCG-PCF)

CPCG-PCF Background and Results

The Center for Biophysical Science and Engineering experiment Commercial Protein Crystal Growth in the Protein Crystallization Facility (CPCG-PCF) successfully flew on STS-107/Columbia. This work

was in part supported by NASA Cooperative Agreement NCC8-246 to Larry DeLucas as Principal Investigator and the Schering Plough Research Institute. The objective of the experiment was to grow high-purity crystals to provide statistically significant information about the purification potential of microgravity protein crystallization. See <http://www.cbse.uab.edu/> for more information.

The CPCG-PCF hardware consisted of a single Middeck locker integrated on the aft bulkhead of the SPACEHAB RDM. Within the CPCG-PCF main facility is the PCF that contains 98 sample bottles to accommodate protein crystal growth. The summary of data is as follows.

Experiment	Principal Investigator	Mission Data	Current Data
Commercial Protein Crystal Growth (CPCG-PCF)	L. J. DeLucas Center for Biophysical Science and Engineering	0%	tbd%

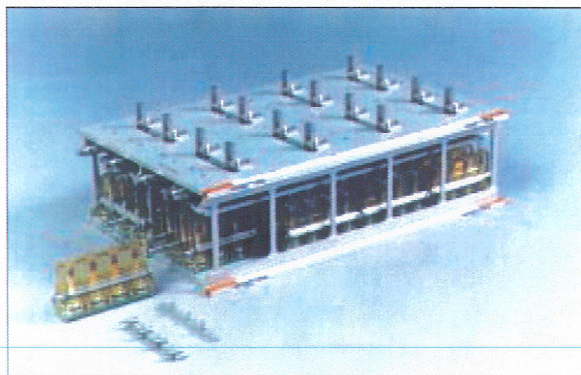


Figure 18: CPCG-PCF was flown in the SPACEHAB Research Double Module and included 98 sample bottles in the PCF.

CPCG-PCF Data-Containing Debris and Recovery Attempts

The sample cell hardware, including the 98 bottles, was the critical part of the experiment. A total of 22 bottles were recovered and most were scorched on the outside and vaporized on the inside.¹⁰ Since most of each sample was lost, the CPCG-PCF Team could not determine in a statistically significant way how microgravity could enhance protein purification. However, since a small number of samples were intact, other useful information is expected and the analysis is ongoing.

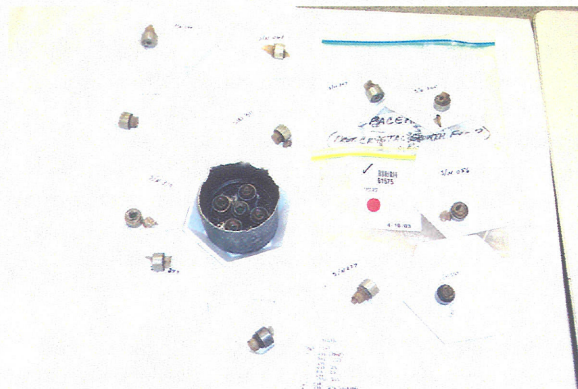


Figure 19: Recovered CPCG-PCF sample bottles

CPCG-PCF Summary

In summary, a small number of CPCG-PCF samples were recovered intact. When data analysis is complete, the experiment data recovery is expected to be greater than 0%.

Conclusion

The "mission after the mission" was a success for these five facilities and 18 experiments with relative data gains from immediately after the mission to the present from 2% to over 90%. One experiment facility, CPCG-PCF is still analyzing their data and their data return is not yet quantifiable. In all cases, the scientific benefits of this additional data will be addressed in separate publications by the individual investigators.

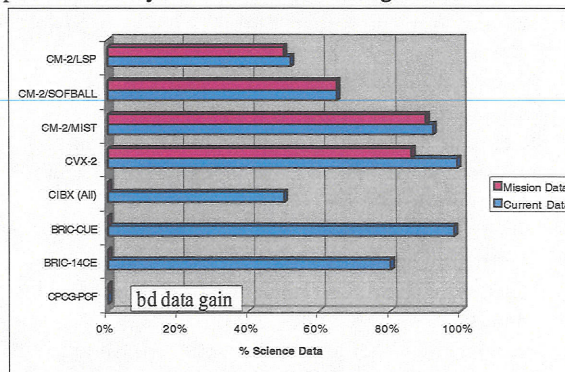


Figure 20: Overall summary of the science data gains for five experiment facilities on STS-107/Columbia.

In addition to the success stories in this paper, there are probably several more from the STS-107 payload community. The author was recently informed of another experiment data recovery success story from the Zeolite Crystal Growth experiment, sponsored by the Center for Advanced Microgravity Materials Processing at Northeastern University, which might be the topic of another paper.

Also beyond the scope of this paper would be a study to compare the relative flight hardware condition as a function of the location in the Shuttle during re-entry. Based on the small group of experiments reviewed here, it appears that payloads located in either the Shuttle Middeck or the FREESTAR pallet in the cargo bay fared better than those in the SPACEHAB RDM in terms of the amount of hardware and the relative condition of the hardware recovered.

The authors wish to acknowledge the support of the STS-107 experiment PI's and teams, the debris search and cataloging teams, mission and payload management, and, the CAIB members for their efforts to maximize science data recovery. These recovery efforts were not only important scientifically, but also serve as an additional legacy to the work of the STS-107 crew during their 16-day mission.

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