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Final Technical Report

Cooperative Agreement NCC2-912

REPORT ON COSMIC DUST CAPTURE RESEARCH AND DEVELOPMENT FOR THE EXOBIOLOGY PROGRAM

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by

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Forward

The work summarized here was accomplished by SETI Institute, Mountain View, California under NASA Cooperative Agreement NCC2-912 with Ames Research Center (ARC), Moffett Field, California. The Principal Investigator was Kenji Nishioka supported by researcher David Stratton, both members of SETI's staff. Collaborators for various portions of the research activities included Mark Fonda, Ted Bunch, Glenn Carle, and Sherwood Chang from the National Aeronautics and Space Administration's (NASA) Ames Research Center (ARC); Lockheed Martin Missiles and Space's Advanced Technology Center (LMMS), Palo Alto, California and A & M Associates, Bowie, Maryland; University of Paris (UOP), Orsay, France, University of California at Berkeley (UCB), Berkeley, California and State University of New York at Plattsburgh (SUNYP), Plattsburgh, New York. All their contributions are acknowledged and appreciated. Dr. Peter Schultz, Brown University, Providence, Rhode Island kindly allowed us to piggyback on his tests at the ARC's hypervelocity gun facility. Technical support for the hypervelocity gun facility was provided by the ARC's resident Calspan gun facility staff. Without Dr. Schultz's help, the breadboard trajectory sensor instrument test would not have been feasible. His help and that of the Calspan staff are gratefully acknowledged also.

Collaboration with Ames' personnel was in 1) grant administration, 2) intellectual science support, 3) collaboration with the University of Paris for the Mir flight experiment, and 4) arranging scanning and X-ray probe analytical support from UCB and SUNYP. LMMS provided access to 1) analytical research instruments, 2) chemical analyses support, 3) cleanroom facilities, and 4) design and fabrication expertise of hardware and electronics. They also supported the hypervelocity testing along with test data acquisition and its reduction for the breadboard instrument. A&M Associates provided technical expertise and support on determining the expected charges on orbital particles and a conceptual design for a breadboard particle charge detection sensor. University of California provided analytical support for the recovered Mir flight modules using their unique scanning capability to detect particle tracks in the aerogel. SUNYP, along with help from the University of Chicago, analyzed particle tracks found in the aerogel for biogenic compounds using an x-ray probe instrument. Dr. Schultz provided access to his experiments and the benefits of his considerable hypervelocity testing expertise at the Ames hypervelocity gun facility, and this proved beneficial to our development testing, significantly reducing the test time and cost for the breadboard instrument development testing.

The participants in this activity acknowledge and thank the National Aeronautics and Space Administration and its Ames Research Center for providing the necessary support and resources to conduct this investigation on instrument technology for exobiology application and being able to acquire some interesting results. Primarily, the newly identified technology problems for future research are the important results of this research.

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I. Background

Exobiologists are interested in solving the quintessential question of how life started on the Earth⁽¹⁾, and in order to help them answer this question it is necessary that they have information on the prehistoric origin and evolution of biogenic elements and compounds from the interstellar medium into early Earth. Investigation of cosmic dust particles (CDP) are expected to contribute to understanding this question of the chemical pathways taken by the biogenic elements and compounds from their origins in stars and surrounding environments to their incorporation into planetary bodies and the Earth itself. It is believed that CDPs have survived unchanged since the creation of the solar system. Thus, cosmic dust particles and their retention for study must be free from contamination so that their uniqueness can be preserved and be available for study by exobiologists.

The science of Exobiology includes study of the origins and distribution of life in the universe, and has a very special relationship with the element Carbon, one of the main building blocks of life on Earth. Carbon and carbon compounds from extraterrestrial sources are of special interest, both for comparison with Earth's carbon compounds (which have been processed by biological activity for millennia) and as possible sources of some of Earth's prebiotic compounds. Cosmic and interplanetary dust are exceptionally interesting as sources of prebiotic compounds because the size of the dust particles enables some of them to be brought to Earth intact, without the high temperature atmospheric processing characteristic of larger meteorites⁽²⁾. Although dust is ubiquitous in the universe, the structure and chemical composition of cosmic and interplanetary dust are not well characterized. The most common method of collecting these particles involves aero-capture by impact collectors which use a thin layer of silicone oil. Unfortunately, this oil contaminates the sample and prevents analysis of a critical region of its spectrum⁽²⁾. Thus, for uncontaminated cosmic dust samples, aerogel has been developed as a medium for CDP capture.

Intact CDP capture without contamination—especially contamination by organic materials—is a requirement unique to exobiology research, and has driven the development of pure mineral (organic-free) capture media, i. e., ultra-pure aerogel. Aerogel itself is not new having been discovered in the 1930's and, for example, used as an orbital capture medium for interplanetary dust particles and space debris in the Timeband Capture Cell Experiment (TICCE) aboard the European Retrieval Carrier (EURECA-1) and in space shuttle Getaway Special (GAS) flights by Peter Tsou at Jet Propulsion Laboratory. Fredrich Horz is using aerogel in his Orbital Debris Collector (ODC) experiment on the Passive Experiment Carrier (PEC) aboard the Piroda module on Mir, and this experiment has been flying since March of 1996. However, none of these applications (aerogel) have met exobiology requirements for purity.

Over these past four years a team composed of National Aeronautics and Space Administration's (NASA) Ames Research Center (ARC), SETI Institute, and Lockheed Martin Missiles and Space's, Advanced Technology Center (LMMS) have developed ultra-pure aerogel, containing about one part per million carbon, which thus provides a capability for the contamination-free capture of CDPs. Aerogels are sol-gel derived, supercritically dried materials with an extraordinarily large porosity, i.e. low density. It's a unique and unusual "solid": it is "foamed" silicon dioxide, glass with densities that can be tailored from less than 20 milligrams per cubic centimeter to several hundreds of milligrams per cubic centimeter. As such, high velocity collisions of particles (such as cosmic or interplanetary dust particles) with aerogel may result in their capture with minimal thermal processing of the particle. In hypervelocity testing, 60 mg/cc aerogel has successfully captured^(4,5) 50 micron to 1000 micron particles at velocities approaching 7 kilometers per second. Since aerogel can be manufactured with very low levels of organic contamination (ultra-pure), the chemical properties of the captured particles may be determined with greater certainty, which is of critical importance in assessing their importance to exobiology.

II. Introduction

This Cooperative Agreement was preceded by NCC2-565 under which the ultra-pure aerogel was developed and hypervelocity impact testing for simulated capture of CDPs begun. The success of this activity lead to a Memorandum of Understanding (MOU) for a collaboration between ARC and University of Paris (UOP) to flight test the aerogel as part of UOP's COMRADE experiment in the European Space Agency's EUROMIR flight experiment on Mir. The design and assembly of the flight modules for the COMRADE experiment were part of NCC2-565 and these results have been documented^(3,4). The recovery and evaluation of this flight experiment were accomplished as part of Cooperative Agreement NCC2-912 and reported herein. Additional modules are being flown and planned to be flown on Mir by UOP as a continuation of the ARC/UOP MOU but outside the scope of this Agreement. All tasks and results reported here were accomplished under Agreement NCC2-912.

The research tasks reported here are three-fold: 1) analyses of the aerogel modules recovered from Mir; 2) the design, fabrication, and test of a breadboard aerogel capture module's trajectory sensor; and 3) analytical model development for the process of hypervelocity CDP particle capture in aerogel. Results from these tasks contribute some useful tools and data which will assist exobiologists in building a CDP capture instrument for the capture and study of CDPs. This will lead to helping them to understand the chemical pathways that may have been taken by the biogenic elements on Earth. These task results will also help to provide a basic understanding of aerogel and how it will perform in the space environment, the mechanisms at work in its capture of CDP particles, how to infer the captured particle's origin, and as a tool for analytically modeling the hypervelocity particle capture process in aerogel at velocities impractical to simulate in the laboratory. In addition, these results will benefit other researchers interested in a better understanding of the physics of hypervelocity particle impact and capture, assessing impact damage to space platforms by hypervelocity orbital particles, and for monitoring population change of orbital debris particles.

Task 1: The two exposed aerogel modules flown on the Russian Space Station Mir by UOP were recovered and returned to ARC on March 25, 1996 by Dr. Borg of UOP. These capture cells were the first test set of aerogel modules to fly on Mir, and their performance was analyzed by Ames, LMMS, UOP, UCB, and SUNYP. After preliminary visual inspection and evaluation, the module was tomographically examined at LMMS, but it was found that the original intent to use tomographic X-ray scanning to detect impact tracks was impractical due to the high lead content in the low temperature alloy (LTA) which was used to bond the aerogel to its aluminum casing. At that time, the aerogel could have been easily removed from its container, but because of cracks in the aerogel and the possibility that it might crumble if removed from the module (container), the decision was to not remove it but to use another scanning technique to find the impact tracks. At this point the team was expanded to include UCB in order to use their microscopic scanning technique to scan the aerogel surface for particle impact tracks, and SUNYP for their expertise in x-ray probe analyses, applying it to those particle tracks which were detected.

Task 2: Interplanetary (cosmic) dust particles (IDP or CDP) have unique orbital trajectories which reflect their asteroidal, cometary, or space debris ancestry. Thus, with velocity and intercept angle information (trajectory) the source of the particle can be identified. This provides essential information for the exobiology mission, to determine the possible origins of the biogenic elements and compounds that may have fallen to earth from space. If a sensor can measure the particle's velocity, impact angle, and the time and location of impact, this data, when combined with the space platform's ephemeris, can uniquely identify the trajectory of each captured particle. So, with its velocity and trajectory known, each particle's origin can be inferred. Two sensor concepts exist which, to our knowledge, can provide these measurements. They are based on polyvinylidene fluoride (PVDF) films and electrified wire grid. Particles are altered as they impact the PVDF film, whereas the wire grid concept is less likely to alter the particles and is therefore the only concept that meets the exobiology requirement for intact uncontaminated particle capture. Dr. Sigfried Auer⁽⁶⁾ is developing a trajectory sensor using this concept, which is also the basis for the conceptual breadboard sensor/instrument developed and reported herein.

This two-year program has determined that a CDP capture instrument concept capable of fulfilling the exobiology requirements of intact uncontaminated particle capture with trajectory data is feasible. A conceptual trajectory capture sensor based on Auer's instrument was designed, but there was a need to determine whether particles in hypervelocity test chambers where charged, a breadboard based on the Faraday cup principle to validate particle charge, the basis of the trajectory sensor concept, was fabricated and tested. The Faraday cup based breadboard here is really a Faraday tube with electronics which emulates Auer's wire grid sensor concept in detecting the charge on a particle. This breadboard concept, though simple, adequately provides a means to test the concept for detection of charge on a hypervelocity particle in a hypervelocity gun facility without placing Auer's valuable wire grid sensor in

danger. These tasks were accomplished with a team composed of SETI Institute, Ames Research Center, LMMS, and A & M Associates personnel.

Task 3: The computer modeling of hypervelocity particle impact and its capture process by aerogel media was started and brought to an interesting level, showing that modeling can become a useful analytical design tool if it continues to be developed. The collective expertise of the LMMS/SETI team acquired over the years concerning the physical properties of the capture medium (aerogel) was used to develop a model of the capture process using CTH, a coupled thermodynamic and hydrodynamic simulation program developed by the Sandia Corporation for the Department of Energy. The results of this modeling are reported in this document.

III. Description and Results of Tasks

A. Task 1: Design, Fabrication, and Recovery of Flight Test Modules for CDP Capture on MIR

Task 1: Description

In November of 1994, Dr. J. Borg from the University of Paris's Institute of Astrophysical Sciences approached Dr. T. Bunch to collaborate on flying aerogel on the European Exposure Facility as part of UOP's COMRADE experiment on the Russian Mir space station. This led to a Memorandum of Understanding between Ames Research Center (ARC) and University of Paris (UOP). A team including ARC, UOP, LMMS, and SETI Institute was formed, and during the four month period from January to April of 1995, an aerogel capture cell (module) concept was designed; twelve modules were fabricated and tested for outgassing and vibration survival; and four units were shipped to Dr. Borg on April 17, 1995. Two units were integrated into the COMRADE experiment (two were held in reserve) and system tested then integrated into the European Exposure Facility, shipped to Russia, and launched in a Soyuz vehicle to the Mir space station in September of 1995. The experiment was deployed on Mir by cosmonaut extravehicular activity. One of the two aerogel capture cells was exposed from early October, 1995 to early February, 1996, while the second capture cell was exposed for only ten days during the Orionids shower in October of 1995.

This collaborative activity resulted in several lessons learned in the manufacture and use of aerogel. Problems encountered and their solutions are not available in the literature even though the uses of aerogel to capture cosmic dust/interplanetary dust particles and space debris have been studied, developed, and have seen limited use. One lesson learned was that ultra-pure aerogel may be reactive during its manufacturing and subsequent integration processes. The term manufacturing as used here includes the forming of sol-gel from basic pure chemicals, the foaming/extraction process under closely controlled high pressure and temperature into finished aerogel, and shaping the aerogel to fit its containers. Initially machined aluminum extraction molds were used in the extraction process, but they literally disintegrated into a dark gray dust. This should not have happened based on historic experience and knowledge. Therefore, a material compatibility study was made and stainless steel was selected. After several attempts,

mold surface finish of 15 micro-inches was found to be necessary in order to prevent surface cracks in the aerogel. When the aerogel was pressed into the module with a glass platen during its integration into the module, it bonded to the glass. When platinum was substituted as the platen material, it also bonded. Without the necessary time to find a solution to this problem, the integration process flaw on the aerogel capture surface was accepted. The contact surface and flaw were minimized by using three parallel quartz rods to press the aerogel into the module.

Task 1: Results - Fabrication Lessons Learned

The lessons learned are indicative that current knowledge⁽³⁾ of aerogel is limited. Solutions or explanations for the problems identified here are not available in the current literature, so the solutions or explanations provided here, though not rigorous, are practical as put forth by those “experts” working with aerogel at LMMS, SETI Institute, and ARC. Much will be gained by rigorous future studies that will lead towards understanding the chemical and physical behavior of aerogel so that surprises such as those encountered need not reoccur in the future. This summary of lessons learned results from the success-oriented tasks that were scheduled for producing the CDP capture modules flown on UOP’s COMRADE experiment on Mir. They are presented to alert others of potential pitfalls in the use of aerogel, as in the case of the Discovery Mission, “Stardust”.

Schedule: Probably the easiest identifiable problem faced was the short, success-oriented schedule spanning only three months from collaboration agreement in January, 1995 to delivery of the completed experiment modules at the end of March 1995 (actual delivery date slipped to April 17, 1995). Primary tasks were to: 1) identify key tasks and develop a schedule, 2) develop mission, system, and design specifications, 3) design and fabricate hardware for aerogel capture cells, 4) manufacture the aerogel, and integrate it into the capture cells (modules), 5) obtain shipping authorization (to satisfy technology export compliance) from the Department of Commerce, 6) vibration and outgassing qualification testing, and 7) packaging and shipping.

Aerogel capture cell: Agreement on the final dimensions (5.06 cm wide by 9.48 cm long and 1.7 cm deep) of the capture cell occurred in real time at a face-to-face meeting with the University of Paris’s Project Manager on February 7, 1995. This was not an issue in itself, but because of the short schedule, it caused unnecessary stress to the team since the program was already 5 weeks into its three-month schedule.

Aerogel manufacturing: With the dimensions of the capture cell defined, aerogel extraction molds were designed and fabricated from aluminum having the same dimensions as the capture cell so that the manufactured aerogel could be taken from the mold and placed in the flight cells without further shaping. To everyone’s surprise, much of the aluminum molds literally disintegrated into dark gray dust although some areas of the molds showed no signs of corrosion—aluminum molds had been successfully used in the past⁽⁶⁾. Apparently, if the aluminum surface is passivated or allowed to oxidize after machining, it will not react during the aerogel extraction phase. A quick study showed that stainless steel, titanium, tantalum, nickel,

or Pyrex are all good candidate mold materials. Stainless steel was chosen. Oversized extraction molds were used and the extracted aerogel was shaped to fit the capture cell. Harvest from these molds was poor with several shallow cracks occurring at the stainless steel mold weld interface. These cracks were later attributed to the sharp corners and surface finish of the stainless steel mold. Later testing indicated that 15 micro inches or better surface finish would largely alleviate the surface cracking problem. In shaping the aerogel, the initial cuts with a bandsaw were generally successful but the second and third cuts to round off the corners resulted in some cracking. Further shaping with #400 grit emery paper was generally successful. Cracking during shaping was mostly due to handling but it was speculated that residual stresses from extraction and initial cutting may have contributed. Innovative capture cell designs that minimize cutting, sanding, and handling would be helpful.

Integration of aerogel with capture cell/modules: Shaped aerogel was bonded into the capture cell using a low temperature alloy (LTA), commonly called “woods metal”, composed of 55.5% lead, 40.5% tin, and 4.0% bismuth, this alloy provided a customized melting point of 198 degrees Centigrade, about the lowest temperature that meets the required design specification⁽⁷⁾ for this application. The requirement for organic free bonding led to the choice of LTA. Aerogel was pressed into the cell containing molten LTA so that the metal flowed up between the aerogel and cell walls to encapsulate 4 sides and the bottom of the aerogel. The integration plan called for the use of a glass platen to provide full contact with the aerogel surface as it was pressed down into the cell, but when this was attempted the aerogel bonded with the glass platen. This was not expected based on preliminary tests and historical experience—glass molds have been used to extract aerogel⁽³⁾. Not having the time to experiment, and deducing that the bonding resulted from silicon dioxide in both the platen and the aerogel, platinum foil was wrapped around the platen, but it also bonded to the aerogel. It was eventually agreed that some surface artifacts (flaws) would be acceptable, and a platen composed of three quartz rods longitudinally oriented was used, resulting in three longitudinal surface defects, each about half a centimeter wide, which marred the aerogel surface. This bonding issue for aerogel should be resolved; it would be interesting to determine whether this is caused by ultra-purity and/or outgassing/purification thermal bake treatment of the aerogel, or due to other presently unknown factors.

Handling: To maintain the non-contamination requirement that the aerogel be kept pristine and free from the absorption/adsorption of organic contaminants, its handling had to adhere to strict laboratory cleanliness procedures. In this hurry-up environment, simple lapses occurred, e.g., placement of some aerogel test coupons on aluminum foils, resulted in organic contamination from the small amount of residual oil on the foil from its manufacturing process. Another contamination event occurred during the integration process when some aerogel and aerogel test coupons were placed under a chemical hood with uncapped bottles of acetone and methyl ethyl ketone (MEK) used for cleansing the glass platen, platinum, and quartz rods, and no special care was taken to keep evaporative fumes from the bottles away from the aerogel. Later analysis of the aerogel test coupons showed higher than normal levels of acetone and MEK indicating possible absorption of acetone and MEK from the underhood atmosphere.

Vibration testing: The modules were flight qualified per the vibration test requirements specified in the EuroMir '95 Qualification Report⁽⁷⁾. The only anomaly encountered was a longitudinal crack resulting from the 3500 seconds random vibration with levels of 100 g's X, 50 g's Y and Z for 20–30 milliseconds duration using semi-sinusoidal loading, applied once in each axis except for the X-axis, but this crack did not progress and the module went on to successfully complete all vibration tests. The aerogel survived intact as a unit with no separation from the module.

Shipping: As expected, the modules survived shipping from Moffett Field, California to Paris, France without problems. The modules were bubble wrapped, placed in a cylindrical aluminum container and covered and sealed. The container was placed in a plywood box with foam to eliminate movement and shipped via Federal Express.

Ground handling, launch, and deployment: No problems were reported with the integration of the modules into COMRADE nor in its system test, its launch on SPEKTR in September of 1995, and deployment on Mir/SPEKTR in September 1995, nor during its recovery in February, 1996.

Task 1: Results - Recovery and Analysis of MIR Flight Test Modules

Summarized below is what was learned from the engineering and chemical analysis of the recovered flight modules. Strict handling procedures were followed to ensure that any changes detected in the recovered modules—including contamination—resulted from either exposure to the space station environment, from shipping (packing material), or from the captured particles. Initial opening of the sealed modules utilized the class 10,000 clean room at LMMS's Palo Alto Research Laboratories. Aerogel samples were taken later for contamination analysis.

Initial Physical (visual) Examination: The modules were examined in the 10,000 class clean room. When they were uncovered, the integrity of the aerogel and module was verified. They survived shipping, launch, orbital exposure, and recovery with minimal structural problems. Problems noted were stretching of the platinum retainer wires and some cracking of the aerogel. This stretching of the wires was probably the result of entrained air in the aerogel not being able to escape quickly enough to equalize its internal pressure to the rapidly decreasing external pressure during launch, causing the aerogel to bulge and perhaps crack as it pressed and stretched the wires. Structurally, the wires and LTA bonds performed as designed and effectively held the aerogel in the mold so that it was able to fulfill its mission requirement.

In the recovered modules, the blemished aerogel surface areas noted earlier appeared noticeably darker and rougher whereas the unblemished surface areas appeared unaffected by exposure in the space environment. Microscopic examination of the surfaces later confirmed the initial visual observations, the blemished areas were indeed rougher and darker. This condition adversely affects impact detection in these areas, thus a solution to this assembly problem should be found before the aerogel is used in future missions. Apparently these initially blemished areas are susceptible to the space environment, with ozone probably the cause of the erosion and

darkening. Figure 1a and 1b illustrate the as-manufactured module with aerogel and the recovered module which shows the three blemish lines and the stretched retainer wires, respectively.

Surface and subsurface samples were taken from the aerogel in the modules for analysis in a clean hooded area at LMMS's Palo Alto Chemistry Laboratory. The results from organic chemical analyses of these samples are summarized later in Table 1.

X-Ray Tomography: Following physical examination and samplings, the modules were taken to LMMS's X-Ray Tomography facility to be scanned for particulate impacts. Unfortunately, the use of LTA as the adhesive to hold the aerogel in the mold made this examination technique impractical. The high lead content in the LTA required high voltage settings for adequate x-ray penetration resulting in reduced resolution. Removal of the aerogel from the mold (and LTA) would have resolved this problem, but was not elected at that time to protect the aerogel during later handling, so the analytical methods described below were substituted.

Automated Microscopic Scanning and X-Ray Probe Analysis: An automated microscopic scanning system at UCB was used to scan the modules for particle impact tracks. This system was originally developed for quick and efficient scanning of large areas of glass sensors to locate etch-pits in track-etch detectors due to galactic cosmic rays and relativistic heavy ions, and has been in use for that purpose for several years⁽⁸⁾ at UCB. Several candidate impact points with tracks were found and later analyzed by X-Ray probe technique at Brookhaven National Laboratory by Staff from the SUNYP and the University of Chicago. The X-Ray fluorescence spectra results for a 0.25 mm track failed to detect particulate matter at the end of the track. The track showed the presence of "chondritic" elements Ca, Fe, Ni, Mn, Ti, and Cr which could indicate the breakup of a pyroxene particle, however the small amounts of Pb, Zn, Cu, Sr, and Zr that were also found strongly suggest the possible presence of an orbital debris particle or possibilities of perhaps other contamination.

Chemical Analyses Results of Aerogel Surface and Interior Samples: Chemical analyses of the surface and interior of aerogel samples from the recovered flight modules and from a control module are summarized in Table 1 below. Organic analysis of the aerogel surface samples showed high levels (2 percent) of contamination by dioctyl adipate, a plasticizer. This was an unanticipated finding and no reports on this contaminant as a concern for orbital experiments were found in the current literature. Analyses of additional samplings from the modules confirmed these high surface contamination levels. Interior samples were free of dioctyl adipate and showed that the contamination was confined to the surface, and did not migrate.

Table 1: Summary of Aerogel Contaminants (ppm)

Aerogel Samples *	Methanol	Octene	Aliphatic Ester	Acetone	Diocetyl Adipate	Others	Total
A	311	770	128	26	21,544	637	23,416
B	163	1,570	692	81	16,229	1,229	19,963
B-1	236	23	131	22	0	93	505
C	84	0	0	7	0	34	125
C-1	406	0	6	107	0	616	1,135
Comm.	174	19	95	159	0	3,134	3,581

Legend: *Samples; A: Space exposed 10 days surface sample, B: Space exposed 4 months surface sample, B-1: Space exposed interior sample, C: As manufactured and cleaned sample, C-1: same as C, stored 1 year and used for shipping simulation test sample and Comm.: sample of commercial aerogel of unknown history.

B. Task 2: Design of Breadboard CDP Trajectory and Time of Impact Sensor

Task 2: Description

Cosmic/interplanetary dust particles have unique orbital trajectories reflecting their asteroidal, cometary, or space debris ancestry^(9,10). The trajectory information (velocity and intercept angle) to identify the source of the captured CDP particle is one of the essential pieces of data needed for the exobiology mission. Additionally analyses of the captured particles will provide insight into the characteristics of extraterrestrial carbonaceous compounds in support of the exobiology mission's principal goal, understanding the origin and evolution of life.

The term trajectory sensor here encompasses the ability to measure the particle's parameters: velocity, orbital intercept angle, and time and location of impact. With these measured data and the ephemeris from the host space platform at time of impact, the particle's trajectory can be calculated and the origin for each captured particle can be inferred. The aerogel capture cell collects the cosmic dust particles as intact as possible, without contamination, for chemical analyses. As stated above, the ultra-pure silica aerogel, which was developed and tested earlier in the preceding program, helps to meet the non-contamination requirement for exobiology science.

Task two was a two-year program to build a conceptual breadboard CDP capture instrument capable of fulfilling the exobiology requirements, that of capturing CDP particles intact without contamination, with their trajectory data, and time and location of impact. The first year focused on developing a detailed plan for the design, fabrication, and interface testing of the breadboard capture instrument's subsystems (conceptual trajectory sensor, aerogel capture cell, and support electronics). A breadboard CDP capture instrument incorporating a conceptual trajectory sensor and capture cell was designed⁽¹¹⁾. But, during the second year, the original plan from year one had to be revised to reflect the reality of available funding while still being capable of validating the trajectory sensor concept's key requirement, the detection of particle charges. Hardware and electronics component designs reflecting the revised plans were drawn up and components based on these designs were fabricated and integrated into a complete breadboard unit, which was then tested and the results evaluated.

When the original task plans for hardware and electronics design and integration were evaluated and compared with available funding, it became obvious that revisions to the original plans would be necessary, because of two factors: 1) the risk of damage (repair costs) to Dr. Auer's trajectory sensor (originally planned as the trajectory sensor component for the breadboard instrument and shown in Figure 1) during hypervelocity testing and, 2) the lack of data on whether particles used in hypervelocity gun testing were charged. Thus, when alternatives were reviewed, the team decided that the paramount issue was the resolution of whether particles used in hypervelocity gun tests acquired charges as they sped along the gun barrel. The decision was to design a simple instrument capable of detecting charges on hypervelocity test particles and also functioning as an analogue in emulating the charge detection function of Auer's trajectory sensor but without measuring particle direction and velocity. This design resolved the above issues of risk, cost, and particle charge detection capability. LMMS surveyed its in-house surplus electronics gear and provided much of the necessary electronics components to effect the assembly of a simple breadboard/conceptual charge detection/trajectory sensor at low cost. This successful conceptual charge detection sensor design, a Faraday tube, was tested in Ames' Hypervelocity Gun Range.

The Faraday tube assembly and associated electronics⁽¹¹⁾ (the electronic schematics and assembly design sketches are found in reference 11) were installed in the target vacuum chamber at the NASA Ames Hypervelocity Gun Facility on March 24, 1997. The Faraday tube assembly was composed of a 1 inch diameter copper tube 4 inches long surrounded by larger aluminum tubes acting as signal and chassis grounds (see Figure 2).

The tube assembly also included the FET (field effect transistor) and feedback-resistor and capacitor for an AMPTEK A250 charge sensitive preamplifier located in an electronics box near the tube assembly. Two AMPTEK A275 pulse amplifiers completed the electronics in the box, the output of which went to a Tektronix 2440 digital storage oscilloscope. PostScript plot files were produced of the original scope traces.

An electronically noisy environment was expected as a number of potentially large RFI (radio frequency interference) and EMP (electromagnetic pulses) sources occur directly before and after each shot. For this reason an external trigger, approximately 250 microseconds before the test particle enters the tube, was arranged. Considerable effort went into ensuring timely triggering of the scope to ensure that the particle charge data would be acquired during a shot. The gun room was off-limits during shots, so no one could watch the scope to see whether it triggered at the right time. A second 2440 scope was brought in and used from shot 10, and for all subsequent shots to more closely monitor triggers and whatever noise pulses might be present in the Faraday tube signal.

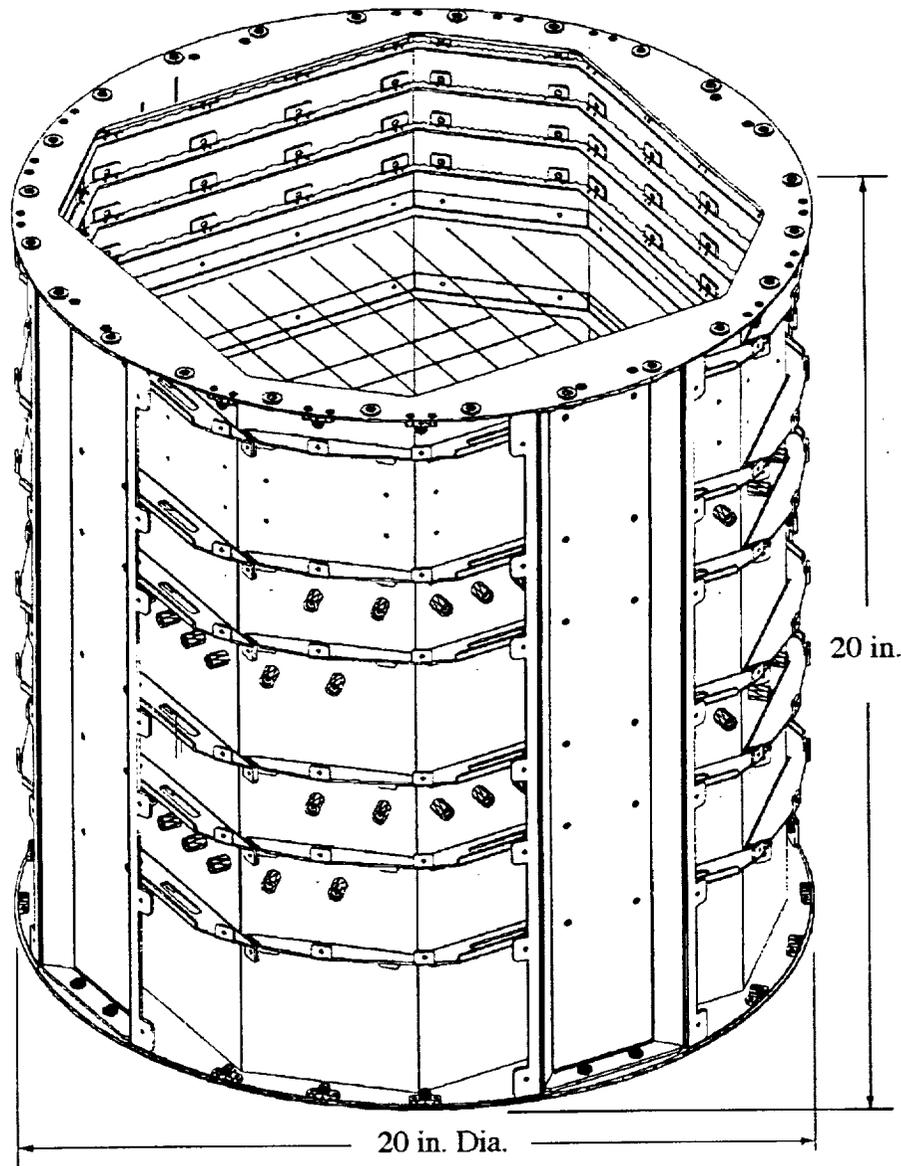


Figure 1: Auer's breadboard trajectory sensor

Task 2: Results

A breadboard test instrument based on an in-house design concept was assembled from surplus electronics hardware at LMMS's facility and necessary mechanical components were fabricated in their machine shop. This breadboard emulating a trajectory sensor as economical and its ability to detect charged particles was tested in the Ames Research Center's hypervelocity gun facility and it validated that test particles in

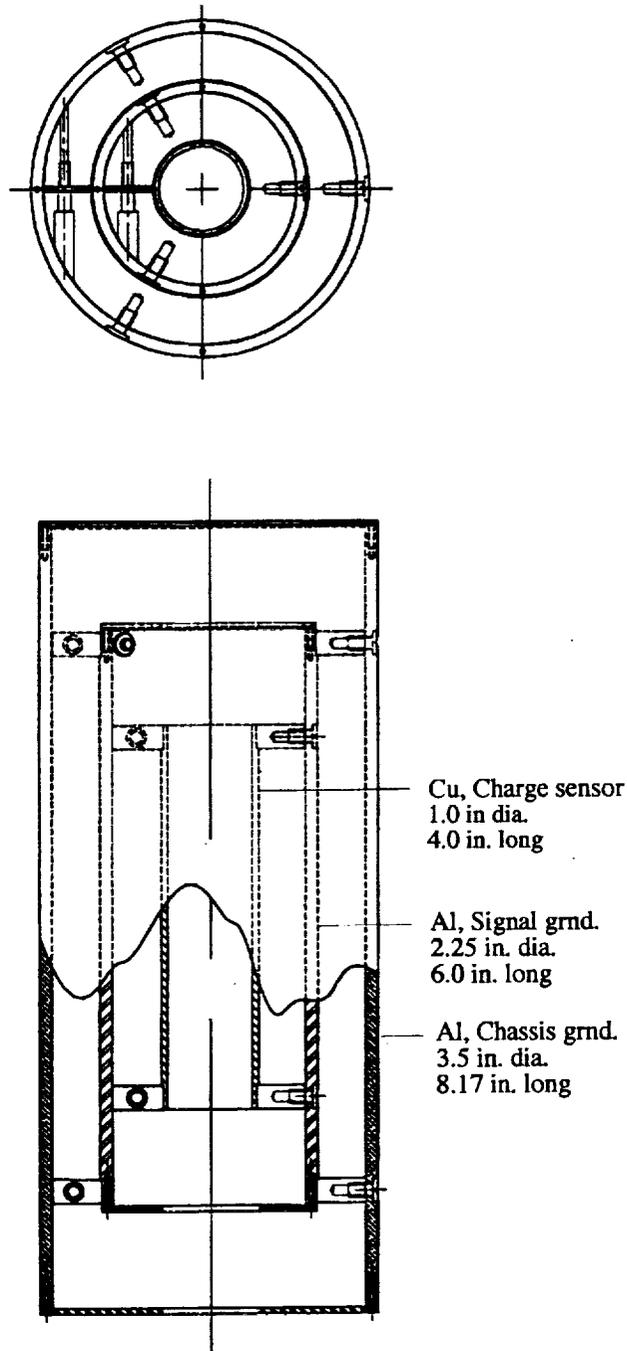


Figure 2: Conceptual charge detection sensor-Faraday tube

hypervelocity gun facilities are charged. As explained above, this unique design approach was chosen so as not to endanger our collaborator's instrument and still adequately determine whether particles fired by hypervelocity guns become charged and also validate trajectory sensor's charged particle detection concept, a key element of a CDP capture instrument.

The test parameters for the eighteen actual shots conducted at the NASA Ames Hypervelocity Gun Facility over a period from March 24, 1997 to August 13, 1997, are presented in tabular form in Table 2. Shots 1-6 were conducted to establish a trigger signal for data acquisition. Shots 7-10 acquired particle signals, but the amplifier gain on these shots was set too high resulting in severe clipping of the signals. On each of these shots a large fluctuating signal followed the particle's passage also. On shots 11-14 the gain was reduced 10x and ion deflector plates were installed to deflect any ion cloud suspected of following the particle. No ion cloud was found. Shots 11 and 12 still showed clipping of the signal. For shot 12 the amplifier gain was again reduced by a factor of 10, giving a total reduction now of 100x. The mylar diaphragm was suspected of causing a higher signal because of particle impact. In shot 13 a mylar diaphragm with a hole in it was used, and clipping of the signal was reduced. Shot 14 gave the first trace without clipping. Shot 15 used a helium atmosphere to minimize the effect of extraneous charging of the particle.

Table 2. CDP trajectory sensor test parameters

Shot #	Velocity (km/sec)	Particle Type	Particle Diameter (inches)	Vacuum (torr)	Trigger Delay (μ sec)	Mylar Diaphragm Present?	Target
1		aluminum	0.25	0.5	60	yes	N/A
2		quartz	0.25	0.5	300	yes	N/A
3		quartz	0.25	0.5	200	yes	N/A
4		quartz	0.25	0.5	absent	yes	N/A
5		copper	0.125	0.5	absent	yes	N/A
6				0.5	0	yes	N/A
7		quartz	0.25	10	250	yes	N/A
8		quartz	0.25	10	250	yes	N/A
9	5.5	quartz	0.25	0.5	300	yes	N/A
10		quartz	0.25	0.5	200	yes	N/A
11	4.9	aluminum	0.25	0.5	250	yes	Al cyl-side
12	4.74	aluminum	0.25	0.5	250	yes	Al cyl-side
13	4.74	aluminum	0.25	0.5	250	with hole	plastic in well
14	4.03	quartz	0.25	0.5	250	with hole	plastic in well
15	3.97	quartz	0.25	0.7 (He)	250	with hole	Al cyl-side
16	4.42	quartz	0.25	0.42	250	no	well
17	4.42	quartz	0.25	0.44	250	with hole	well
18	4.31	quartz	0.125	0.47	250	with hole	well

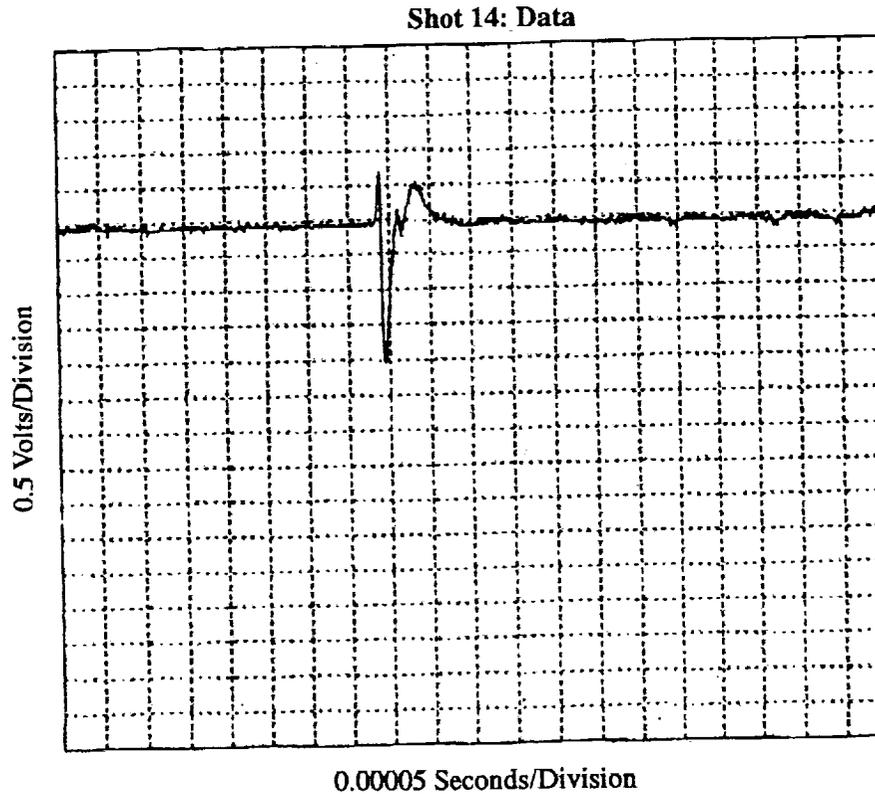


Figure 3: Charge detection sensor particle charge trace Ames' HVGF

No particle signal was observed for this shot, but a signal trace was recorded coinciding with the calculated time for target debris to return through the sensor. Shot 16 did not use any mylar diaphragm, and the signal recorded showed a large extraneous signal following the particle signal which was still clipped. Shot 17 again used a mylar diaphragm with a hole in it, and the signal trace was again cleaner. The signal, however, was still clipped. Shot 18 was similar to shot 17, but the particle size was reduced to a one-eighth inch diameter. The amplifier gain was reduced again by a factor of 10 (now 1000x from the starting point), improving the signal trace and reducing the clipping. The trigger delay is defined as the delay between the Station 3 spark gap trigger and the "start acquisition" trigger to the oscilloscope. The time from the scope's trigger to the first detected signal varied from 50 to about 100 microseconds.

As detailed above, the preliminary tests successfully detected charges on the hypervelocity particles. Additional testing validated the preliminary findings of charges on particles in hypervelocity gun shots as illustrated by a typical detection trace from the breadboard sensor shown in Figure 3. Although results seem to confirm the principle of detecting a particle by detecting its charge presence as valid, thus validating the concept's feasibility for use as a trajectory sensor, additional testing is necessary before committing to this concept. Development work to understand the magnitude of charges on CDPs in space and the assembly and calibration of a full-up brassboard (wire grid) sensor are necessary.

C. Task 3: Modeling CDP Capture in Aerogel

Task 3: Description

Experiments with particle impacts into aerogel have been limited to velocities less than about 7 kilometers per second, a facility limitation. Two-stage gun facilities are planned⁽¹²⁾ that would increase test velocities to 15 kilometers per second and higher, but will introduce problems with test particle integrity during its acceleration. Therefore, an analytical characterization capability for high velocity impacts would be useful in analyzing aerogel's ultimate potential as a dust collection medium. Collisions between an Earth-orbiting collector and an interplanetary dust particle may be as high as 72 kilometers per second for a particle in a retrograde parabolic orbit. Although successful capture at this velocity is not likely, computer modeling of particle impacts into aerogel will provide insight into possible impact characteristics and could identify the expected range of velocities between 0 and 72 kilometers per second where capture is feasible with at least a portion of the particle intact.

This modeling effort for the aerogel/particle impacts use the Coupled Thermodynamic and Hydrodynamic code known as CTH. Developed by Sandia National Laboratories for the United States Department of Energy and Department of Defense, CTH is a flexible generalized software system designed to treat a wide range of shock wave propagation and material motion phenomena. Physical parameters and initial conditions (temperatures, velocities, etc.) for each material are specified in an input script for the CTH program. Equations of state for the modeled materials are specified either analytically or in a tabular (SESAME) format. The program then calculates material positions, densities, temperatures, pressures, etc. at subsequent times⁽¹³⁾.

One particular impact experiment with well defined initial conditions and results was chosen as the test case for modeling. This experiment involved a roughly spherical Carnelian particle with a mass of 1.03 milligrams and an average diameter of 0.92 millimeters, which was shot into aerogel at a velocity of 3.58 kilometers per second. The target was a high purity (less than 1 part per million residual carbon) silica aerogel in the form of a cylinder 8 centimeters in diameter by approximately 12 centimeters high with a density of 64 milligrams per cubic centimeter. The impact track formed was 8.25 centimeters long with an average entrance diameter of 2.7 millimeters. The particle was recovered intact from the aerogel, with the leading edge encased in a thin layer of glass⁽³⁾.

The model used a Mie-Grüneisen equation of state (EOS) for the carnelian impactor. For the aerogel, a porous material/two-state option of the CTH program was employed which allowed the material to be described by two different equations of state⁽¹⁴⁾. The low-density initial state of the aerogel was described by an analytical Mie-Grüneisen EOS, but in its compressed or melted state a tabular SESAME EOS for quartz was used. Between these two extremes, the EOS was calculated from a combination of these two sources.

Several variations in the input script were tried in an attempt to better reproduce the experimental results. Among these variations were changes in the porous material equation of state for aerogel (reversible or irreversible transition from the Mie-Grüneisen EOS to the SESAME EOS); changes in particle geometry (sphere, cylinder, double cone) with no change in particle mass; and different resolutions in the spatial grid used by the CTH program. The parameters for the modeling test cases tried with the CTH program are summarized in Table 3.

One of the major puzzles of this model concerned the apparent destruction of the impactor. With every input script, small pieces began to separate from the particle within a few microseconds of impact, and within 40 μ s of impact the main body of the particle had disappeared. As an example, the beginnings of particle fracture are visible at only 1.9 microseconds in figure 5, a plot of density and temperature generated from test case i100. One theory to explain this is that the glassy coating of fused aerogel material that was found on the recovered particle after the experiment was not forming on the modeled particle, and that this coating was needed to protect the particle from shear. Closer examination of the model results shows that the particle temperature remains relatively low (much lower than the melting temperature) and that a high density "plug" of relatively hot compressed aerogel (probably the source of the glassy coating) does form in front of the particle.

Changing the spatial resolution of the model was not very productive because of the associated increase in memory requirements and processor time required to calculate the results of the model, but this approach did indicate the answer to the problem of the disappearing particle. In one test run (input script i105), the spatial resolution changed with location within the aerogel; the grid spacing in the y-direction (along the direction of the particle motion) was 0.01 cm at the top of the aerogel and increased with increasing depth, with an average grid spacing of 0.0343 cm. On this particular run, it was noticed that the particle slowly shrank in size as it penetrated the aerogel until, when it reached a depth where the particle size was approximately equal to the grid spacing, the particle suddenly disappeared. This implies that the problem is directly related to the grid spacing, but as already stated, decreasing the grid size was not practical because of increased computer run times.

The CTH program uses a Lagrangian (mass-tracking) grid to calculate mass flow in each calculated time step, but then remaps the resulting mass positions onto an Eulerian (fixed in space) grid. For Eulerian grid cells that are only partially occupied by the particle, the exact placement of the particle within this grid cell is undetermined. Therefore, as the particle moves through the grid, the uncertainty in particle shape and position increases with each time step. Since, in the i105 model run, the grid spacing also increased with increasing depth, the particle eventually penetrated to a depth at which the grid size was approximately equal to the size of the particle. At this point, the uncertainty in shape and position was greater than the size of the particle itself, and the particle was lost (disappeared). In order to more accurately model the particle penetration into aerogel, the grid size must remain constant (and small compared to the size of the particle) over the entire path of the impacting particle. In fact, for the glassy coating to form on the impacting particle and protect it from damage (if that is indeed the mechanism

involved), the grid spacing should be small with respect to the thickness of glassy coating, which may be on the order of 10 microns or smaller.

Task 3: Results

Although none of the models have successfully calculated the entire journey from particle impact to the particle at rest in the aerogel, the first several microseconds of these impact simulations are expected to be fairly accurate recreations of the capture experiment. Some interesting observations can be made from the results of these simulations.

The first observation concerns the thermal energy released by the impact. The temperature increases in the aerogel are primarily confined to the shock region in front of the particle; the surface of the aerogel shows no appreciable increase in temperature. This indicates that a system to record the time and location of impact may not rely on temperature variations on the aerogel surface to indicate a particle impact. Figure 5 shows the temperature and density in the aerogel and particle at 1.9 μs after impact as calculated from impact run i100. The black outlines in this figure are interfaces between different materials (aerogel, impacting particle, and void).

Table 3: Test Cases-CTH impact modeling

Test Case ID	Impactor Description	Spatial Grid	run speed [μ s modeled per CPU hr]	Final/Initial Particle Velocities	Penetration Depth [cm]	Stop Time [μ s]	Notes
i97	<ul style="list-style-type: none"> • Sphere • $v_0=3.58$ Km/s • Mie-Grüneisen EOS 	Coarse 0.01 cm	157	25%	3.3	20	Particle begins to fragment by 2 μ s and has lost significant mass by 20 μ s. Impact tract looks similar to experiment.
i100	<ul style="list-style-type: none"> • Sphere • $v_0=3.58$ Km/s • Mie-Grüneisen EOS 	Coarse 0.01 cm	2.5	67%	.89	3	Particle begins to fragment by 2 μ s. Not significantly different from i97 in the first few micro seconds. Discontinued due to CPU use.
i101	<ul style="list-style-type: none"> • Sphere • $v_0=3.58$ Km/s • Mie-Grüneisen EOS 	Fine 0.001 cm	0.033	100%	0.02	0.05	Too slow to be practical.
i102	<ul style="list-style-type: none"> • Sphere • $v_0=3.58$ Km/s • Mie-Grüneisen EOS 	Medium 0.002 cm	0.38	99%	0.43	0.12	Still too slow.
i104	<ul style="list-style-type: none"> • Double Cone (total height equal to diameter) • $v_0=3.58$ Km/s • Mie-Grüneisen EOS 	Coarse 0.01 cm	2.4	75%	0.6	1.9	Particle fragmentation has begun by about 2 μ s. Secondary fragment is smaller than in i97 and i100 models.
i105	<ul style="list-style-type: none"> • Cylinder (height equals diameter) • $v_0=3.58$ Km/s • Mie-Grüneisen EOS 	Coarse 0.01 cm	178	8%	6.5	86	Particle disappeared at 4 μ s after reaching a depth where the grid spacing was approximately equal to the particle thickness.

Aerogel Description:

- Density 0.0648 g/cm³
- Reversible transition between porous Mie-Grüneisen and quartz SESAME EOS: Test cases i97 and i105.
- Irreversible transition between porous Mie-Grüneisen and quartz SESAME EOS: Test cases i100 through i104.
- No elastic-plastic option: Test Cases i97 and i105.

- Elastic-plastic option: Test Cases i100 through i104.

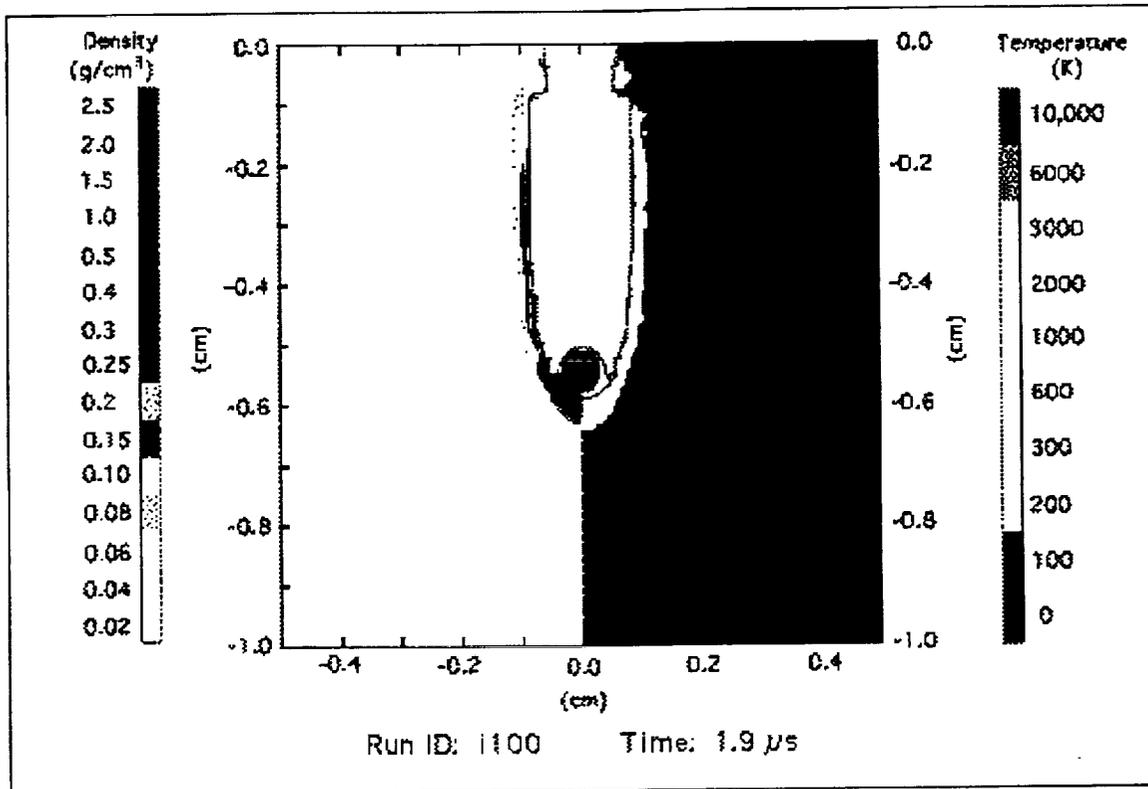


Figure 4: CTH model generated Carnelian particle impact into aerogel

A second observation involves the temperature of the aerogel and the impacting particle. Again, looking at Figure 4, it is clear that the temperature of the particle is much lower than that of the aerogel in the particle's path. Here at 1.9 microseconds after impact, the temperature of the particle is close to its highest value, but still only a small portion of the particle has been heated to above 600 degrees Kelvin, with most of the particle still below 200 degrees Kelvin.

The third observation involves the model itself and suggestions for improving its output. Table 3 shows information on a number of different model runs. It is interesting to examine the run speed (in microseconds of model time per hour of processing time on the Cray C-90), calculated from the first segment of each run (usually the first 20 minutes of processor time). By comparing i97, i104 and i105, we see that a cylindrical particle gives the best run speed, which makes sense because the model uses cylindrical geometry (assuming axial symmetry about the center of the particle track). We also see that the run speed decreases dramatically with a decrease in grid size. Because of the problems mentioned above with the uncertainty in particle shape and size being linked to the grid spacing, a more accurate model would require a much larger computer budget than this project could afford. Runs i100 and i101 differ in spatial resolution by an order of magnitude, with a difference in run speed of two orders of magnitude. The run speed of i101 is still optimistic, though, since this run also allowed the grid spacing to increase with increasing depth in the aerogel, which allows the particle uncertainties to grow to unreasonable levels long before the particle comes to rest. Based on this information, a run with

cylindrical particle geometry, reversible transitions in the aerogel, and fine (0.001 centimeter) grid spacing could have a run speed of less than 1.8 microseconds of model time per processor hour. At this speed, tracing the particle from impact to rest would require a minimum of 56 hours of supercomputer processing time.

IV. Conclusions, Comments, and Recommendations

Activities described above provide valuable insights into: 1) the manufacture, fabrication, and use of aerogel in IDP/CDP capture instruments; 2) the conceptual design of a CDP capture instrument and the design, fabrication, and testing of a particle charge detection sensor that validates the trajectory sensor component concept of the CDP capture instrument; and 3) the start of a capability for modeling the hypervelocity impact capture processes in aerogel using the CTH code. Many important questions concerning these activities are still unresolved and, unfortunately, lack of continuing funding will leave them unanswered. Several of these unresolved questions are identified and summarized below for these three task areas.

Task one showed that aerogel as a capture medium performed as expected; it is robust and should hold together for launch, IDP/CDP capture impact, recovery, and ground handling loads. A particular surface contaminant, dioctyl adipate, from exposure in the space environment, does not appear to migrate to the interior. As expected in research, questions addressed were largely answered but new questions have arisen, e.g., "Where did the high concentration of dioctyl adipate come from? Is it unique to Mir? Is it a quirk of this particular flight? Is it a general problem to be expected in orbital operations?" Identification of the source of dioctyl adipate will remain unresolved. Do particles, especially at the micron or tens of micron size, survive capture, and how will these micron size particles and their tracks be found and analyzed cost effectively? The scanning method described above is probably the best technique available at this time, but it is time and equipment intensive with limitation on operational flexibility which translate into high analytical cost. It is clear that development emphasizing faster scanning capability (on order of a square meter), greater focal depth capability (accommodate larger surface irregularities), and better resolution of micron size particle impact holes/tracks is required. Further developmental testing of the x-ray probe technique to validate analytical procedures and data is also desirable.

In Task two, the issue of whether particles in hypervelocity tests are charged or not has been resolved. Preliminary results indicate that residual atmospheres of 0.5 torr are adequate to produce charges on aluminum and quartz particles. The use of a mylar diaphragm apparently enhances the particle charge but contributes noise to the particle's signal, but when the mylar diaphragm was not used, the charged combustion products produced a very noisy signal. When helium was used as the chamber's atmosphere, the quartz particle did not acquire a charge. Use of mylar diaphragms with a hole about equal to the particle appeared to stop the charged combustion products from affecting the particle's signal. Apparently, the test configuration of choice is to use a standard atmosphere in the test chamber at about 0.5 torr and a mylar diaphragm with a hole in the gun barrel. All these findings from the charge detection sensor tests have interesting anomalies that should be resolved including; "What are the particle charge

density differences for different particle materials? Is this effect due to the type of gas and residual pressure in the test chamber on the particle's charge? These questions beg to be studied and resolved.

For Task three, excellent progress has been made in understanding how to use the CTH program for impact modeling and some interesting results were obtained, but this effort ends without resolution of how the many parameters should be defined in the model and how they interact with one another. These include the equation of state of the aerogel (in particular the transition from porous aerogel to fused silica), the processes involved in the build-up of a glassy coating on the particle's leading edge, and especially, the relationship between these processes and the intact capture of the particle. An understanding of the choice of cell size and its effect on how the model treats the impacting particle's behavior has begun and should be brought to closure.

These are all important issues which, if resolved, will provide the basic foundation that will assure successful modeling and hardware capabilities for exobiology CDP capture. Therefore it is recommended that these identified issues be addressed when funding becomes available, possibly within the new "Origins Program".

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