New Millennium DS-2 Electronic Packaging Smaller, Faster With "Managed" Risk

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Abstract - New Millennium DS-2 is the second project of the New Millennium Program series, managed by the Jet Propulsion Laboratory (JPL). The project consists of a pair of probes, that will be earned by the Mars '98 spacecraft. After release from the Mars '98 Lander cruise stage, both probes will autonomously enter the atmosphere and penetrate into the Martian surface upon impact, After impact and penetration, a soil sample is taken and analyzed for the presence of water. in addition, other atmospheric and meteorological science is also performed during descent and after penetration.

To create this small penetrator, several new technologies were chosen, including a modified Direct Chip Attach (DCA) packaging technology. This paper describes the development of the DS-2 DCA electronic packaging technology, particularly in the area of environmental protection, substrates, and interconnects, Additional topics include the collaboration between this development and NASA technology development programs, as well as follow-on developments for new programs at JPL.

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INTRODUCTION

Jet Propulsion Laboratory's hugely successful Mars Pathfinder is but the first in a line of "Smaller, Cheaper, and Faster" programs to come out of NASA. The subsequent New Millennium Program builds on Pathfinder's success in the areas of technology incorporation and program streamlining. One of the major goals of the New Millennium program is to validate state-of-the-art technologies for incorporation into future missions.

New Millennium DS-2 is the second project of the New Millennium Program series, A pair of probes will be released from the Mars '98 Lander's cruise stage, autonomously enter the Martian atmosphere, and penetrate the surface upon impact. During entry, atmospheric pressure measurements are made and descent deceleration profile taken. Additionally, an impact accelerometer will characterize the soil and depth of penetration. After impact and penetration, a soil sample is taken and analyzed for water content. Meteorological science, including pressure, temperature, and solar intensity measurements, is also performed. Precision electrical temperature sensors on the penetrator are used to measure soil conductivity (using differential temperatures between two sensors located in the probe) and study the daily temperature cycles. With two probes the concept of "networked instruments" is also demonstrated.

To create a small penetrator of this type (< 3.5 Kg.), several technologies were chosen or developed: an aerodynamically stable aeroshell, an advanced Micro-controller Application Specific Integrated Circuit (ASIC), a "Telecom-on-a-Chip" ASIC, a Micro Electro-Mechanical Systems (MEMS) laser diode assembly, as well as ultra-low temperature batteries and a modified Direct Chip Attach (DCA) packaging technology, both capable of surviving the 80,000-G impact, The DCA packaging technology development is the subject of this paper.

GENERAL DESCRIPTION

Figure 1 depicts the major assemblies within the New Millennium DS-2, or Mars Microprobe. DS-2 consists of two distinct subassemblies: the aeroshell, which is the Mars entry vehicle, and the microprobe, The microprobe itself consists of two pieces as shown in Figure 2: The aftbody, which contains the telecom subsystem and antenna, the batteries and various atmospheric experiments, and the forebody, which contains the sample collection assembly. the analysis/optical bench, and the associated electronics. Upon penetration of the planetary surface, the forebody separates from the aftbody, penetrating the Martian surface up to an additional 2 meters,. The aftbody is designed to stay at or near the Martian surface, to enable the DS-2 to communicate with NASA's Mars Global Surveyor spacecraft, which will be in orbit to relay data back to Earth, A four metal layer flex-print connects the forebody to the aft-body, enabling communication between the two assemblies,

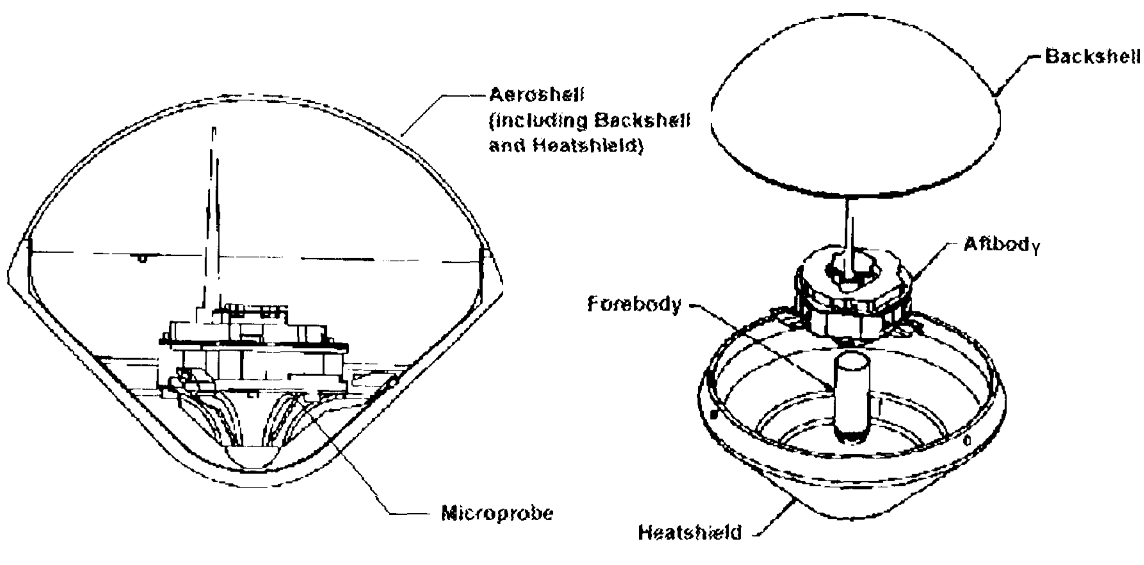

Figure 1: New Millennium DS-2 Configuration

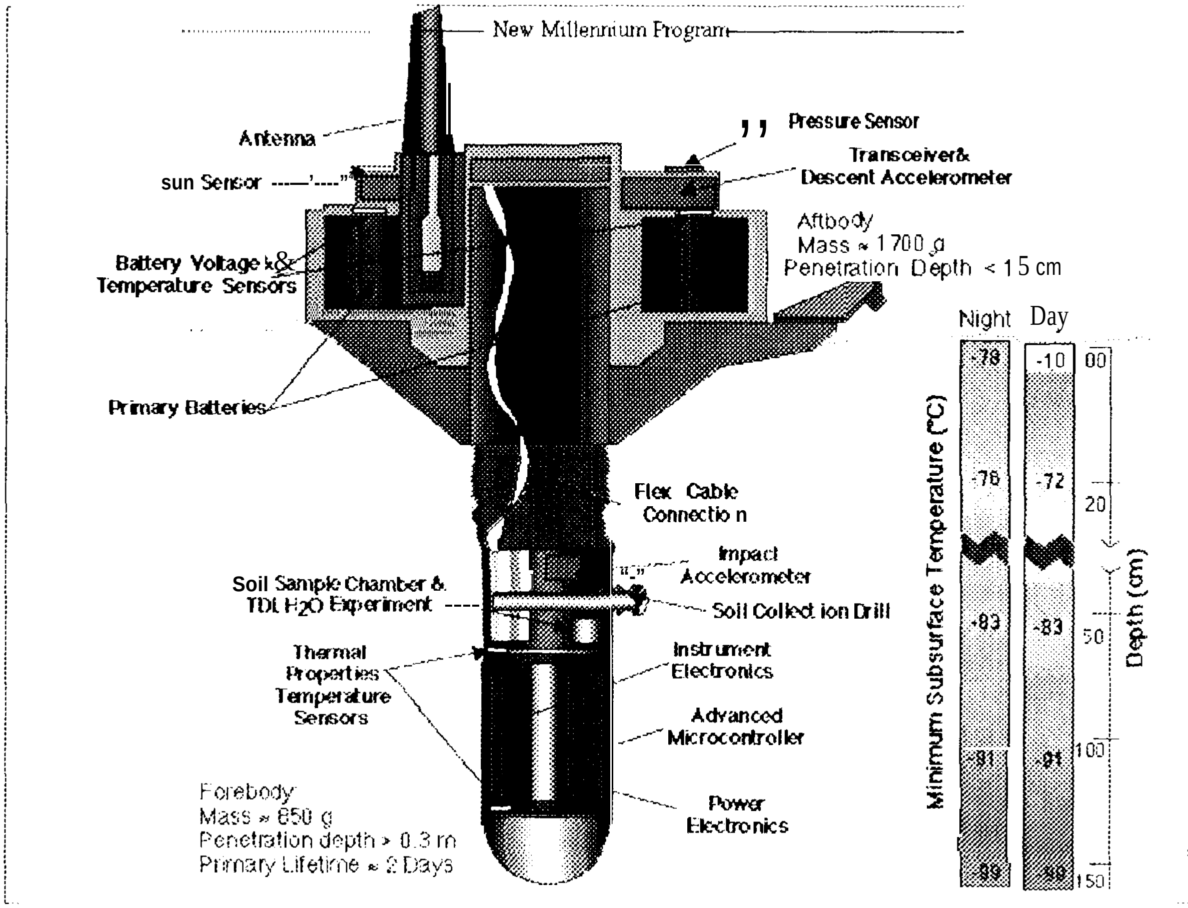

Figure 2: Microprobe Configuration

Project Requirements

The nature of a Mars penetrator mission puts unusual environmental requirements on this project. For JPL spacecraft missions over the past twenty years, the emphasis has been on the vibration/acoustic environments associated with launch, and the thermal cycling environment driven by electronics power dissipation in particular. The DS-2 mission requires an entirely different emphasis, especially in the areas of shock and cold temperature thermal cycling.

The mission profile for DS-2 calls for an impact on the Martian surface at a probe speed of approximately four hundred miles per hour. Estimated shock from this impact is 80,000 Gs for the aftbody (which is designed for minimum penetration). This high shock value represents a challenge to the designers of all manner of hardware, particularly electronics.

The thermal environment is also different from the JPL norm. Both the size and the mission profile for DS-2 limits the amount of energy storage on the probe, precluding major power dissipation, Subsurface temperatures on Mars are estimated anywhere between 0 to - 120°C. These two factors create a thermal environment significantly colder than the 25 ± 25°C normally experienced by the electronics in larger spacecraft. Including prelaunch operation temperatures (up to +30°C), this leads to an environmental requirement of +30 to - 120°C for the forebody electronics assemblies. Aftbody assemblies suffer slightly less exposure, with a requirement of +30 to -90°C.

A summary of the critical environmental requirements is in Table 1.

Why Direct Chip Attach?

As the conceptual design for DS-2 evolved, the project team sought a volume-efficient method for packaging the electronics. Given the project profile and environmental requirements, DCA using chip and wire techniques appeared to be quite compatible with project requirements. The strengths of this technology (volume efficiency, ability to adapt to low-quantity builds, high shock capability) can be utilized to great effect on the Mars Microprobe.

By coincidence, the project profile for DS-2 also mitigates two of the known concerns with DCA technology. The first of these weaknesses, that of environmental protection against the effects of humidity and corrosive atmospheres, is of minimal concern for DS-2: the development time for the flight hardware is very short (approximately one year from fabrication to launch) and the environment during this period can be controlled to a certain extent. once launched, the corrosion driving forces arc removed, thus limiting possible damage. Primary operations at Mars arc on a short time scale, and the humidity at Mars is expected to be negligible. Overall, opportunities for corrosion-induced failures arc minimal. This is quite different from years of uncontrolled temperature and humidity exposure typical of earth service conditions. Therefore, environmental coatings specified for DCA need not pass some of the more rigorous temperature/humidity tests to be effective for this mission, particularly when used with die passivations.

The second concern involves wire bonding of printed wiring board materials: early development of DCA technology at JPL indicated that the gold plating specifications for printed wiring boards arc inadequate for wire-bondable surfaces. Early testing yielded wild variations in wire bond quality on printed wiring boards from different manufacturers. This is a particularly problematic since JPL does not have in-house printed wiring board fabrication capabilities, and must rely on outside contractors.

Fortunately, because of the size of the Microprobe, none of the substrates arc larger than eight centimeters across. This opens the door for the widespread use of thick film ceramic substrates and Low-Temperature Co-fired Ceramic (LTCC). substrates The ability to use hybrid substrates has effectively avoided the problem of specifying gold plating on printed wiring board substrates.

COLLABORATION WITH NASA CODE Q AND OTHER ORGANIZATIONS

Implementation of new technologies such as DCA is often expensive, time-consuming, and risky. Historically, implementing new technologies has been at odds with the fast track development schedules and tight fiscal constraints typical of the Mars Microprobe. With this in mind, the DS-2 program entered into a collaboration with the Advanced interconnect Program (AIP) funded by NASA Code Q (Reliability and Quality Assurance). Coincidental to the development of the Microprobe, AIP funded a project to investigate DCA technologies for usc in NASA programs. Projects such as these arc called Research and Technology Operation Plans (RTOPs), and are multi-year funded projects. One of the stated goals of these projects is new technology validation and insertion into NASA projects, making a collaboration with DS-2 particularly attractive.

In addition, the New Millennium Program has developed a set of industry partners, under the auspices of the Integrated Product Development Teams (IPDTs). These teams were set up by the program to bring additional, high-expertise resources to bear on new product developments. The Microelectronics IPDT is currently involved in a number of aspects of DS-2, bringing expertise in the areas of interconnect technology to the electronic packaging effort.

Table 1. Environmental Requirements

Environment (Qualification)	Requirement
Shock	30,000 Peak Gs forebody, Z-Axis 80,000 Peak Gs aftbody, Z-Axis
Vibration	0.2 G^2/Hz, -10-1000 Hz
Acoustic	Maximum 132.6 dB @ 250/315 Hz
Thermal/Vacuum	+30 to -1200 C (Operating Requirement), 10^{-13} tom
Thermal/Cycling	No Specific Test Requirement
Temperature/Humidity	Humidity <70% RH, No Specific Test Requirement

Leveraging these resources has allowed the DS-2 project to accelerate the development of Direct Chip Attach within the constraints of the DS-2 budget. in the past, developments similar to this have been nudti-year projects. DCA development for DS-2 is currently at about the one year point, with flight hardware scheduled to be fabricated within the next two months.

DIRECT CHIP ATTACH DEVELOPMENT

DS-2 is considered a technology-dri~cn program and therefore, there has been a certain flexibility in using the mission as a development test bed for DCA. Thus, the preliminary development process for DCA technology at JPL led to different DCA configurations on DS-2, depending upon their location within the probe. For the aftbody electronics, aluminum wire-bonds were chosen because of the additional stiffness and lower mass that aluminum provides. In addition, efforts were made to minimize wire-bond lengths for the aftbody (ultra high-G) environments. This precipitated the usc of LTCC, which can be fabricated with cavities for die, thus minimizing wire-bond length, To minimize the number of cavities, thick-film resistors arc conductiw-epoxy bonded to the substrate. All parts arc bonded to the substrates for mechanical support, Aftbody packaging configurations arc shown in Figure 3.

Requirements for the forebody packaging arc somewhat less stringent because of reduced shock levels. Dic cavities arc not required and therefore, standard, thick-film substrates arc used. Because of their smaller form factor, thin-film resistors have been specified. Similarly to the aftbody, all parts are bonded to the substrates for mechanical support. Forebody DCA configurations arc shown in Figure 4.

Onc exception of note is the Analysis Chamber electronics which, for thermal conductivity reasons, requires the usc of a printed wiring board, As stated earlier, the use of organic laminates has caused wire-bond problems due to gold-plating impurities. For this isolated case, the use of a single, JPL-qualified vendor will circumvent the problem and minimize risks, This vendor has in-house gold plating baths specifically set up for wire-bondable printed wiring boards. The gold plating is being specified to Mil-G-45204, the standard PWB gold plating requirement, with additional specifications, These additional specifications include a requirement to eliminate brighteners in the plating bath, and lot qualification of the gold plating via wire bond pull testing

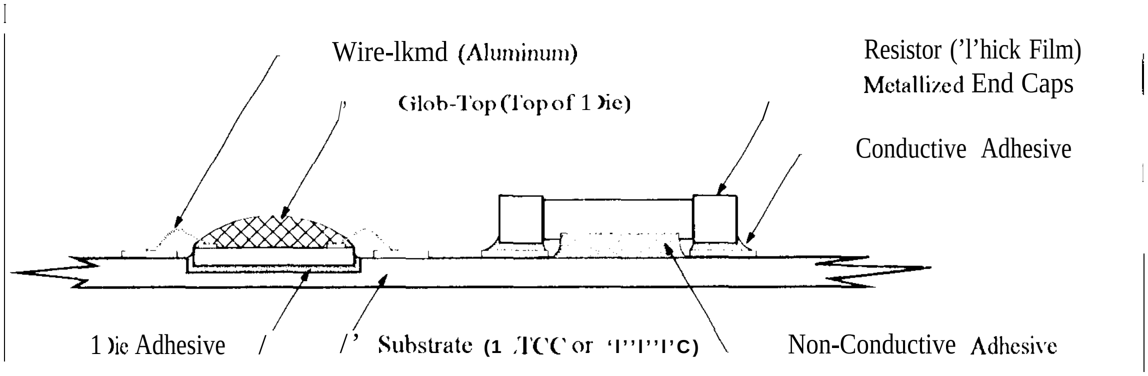

Figure 3. DCA Configuration Baseline(s) for Aftbody

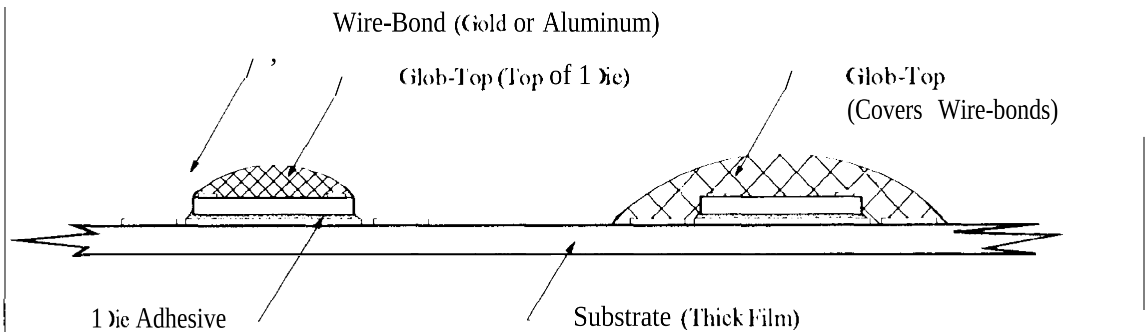

Figure 4: DCA Configuration Baseline(s) for Prism/Forebody

Two different configurations were selected for die sealing/environmental protection, A combination of epoxy glob-top and Parylene coating was chosen based on a literature research of industry performed testing. [1,2,3,4,5] While the use of Dexter Hysol FP 4460 for *glob-topping* and Parylene for coating have been baselined for use in DS-2, the configuration of the glob-top will differ based on the location within the Microprobe. The forebody has certain electronics that are non-reworkable in fully assembled configurat ion, and are susceptible to damage during assembly. Glob-top for these assemblies will cover the entire die and wire-bonds. Other areas may utilize top-of-dic glob-top only, to facilitate rework.

The usc of a number of different configurations during development phases of a technology is in direct contrast to previous spacecraft projects at JPL. previously, variations of new technologies were incorporated only after the basic technology was qualified. Fortunately, the testing to date has not indicated problems with any of the various configurations, as discussed in the next section.

TEST RESULTS TO DATE

To validate DCA technology specifically for the Mars Microprobe, DCA test vehicles arc being subjected to three of the most difficult environmental conditions: Shock, temperature cycling and temperature humidity. Testing the Microprobe in thermal/vacuum, vibration and acoustic environments is planned at the system level after the completion of penetration shock, temperature cycling and humidity tests.

To verify that the DCA configurations chosen would survive the penetration shock, the project utilized resources from the Sandia National Laboratory (which owns an airgun capable of propelling test vehicles to the required speed) and New Mexico Energetic Materials Research Test Center (EMRTC) to perform a series of shock/penetration tests. The airgun propels the test vehicles to speeds of 400 miles/hr. into prepared targets (with parameters similar to expected Mars soil conditions). As the project progressed, higher fidelity models were tested with varying degrees of success, The latest test vehicles for both forebody and aftbody arc shown in figures 5 and 6, respectively. To date, testing has indicated that the basic configurations defined for the forebody and aftbody will survive impact.

Temperature/humidity and thermal cycling tests are being performed on test samples under the auspices of the DCA RTOP. Since there are no project specific environmental requirements in these areas, criteria used for testing were derived from a combination of JPL and "industry standards." Final test parameters and criteria arc shown in Table 2.

To date, test samples have survived the full thermal cycle test and 100 hours of Highly Accelerated Stress Test (HAST). Test equipment limitations prevent electrical continuous monitoring of the test samples, and the first generation of test samples are limited in the number of die tested, However, results to date have all been positive.

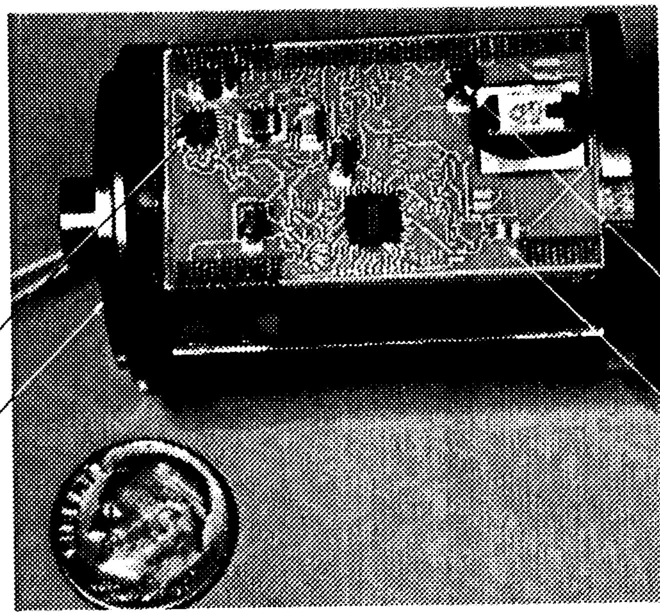

Figure 5: Forebody Prism Test Vehicle for Airgun shot

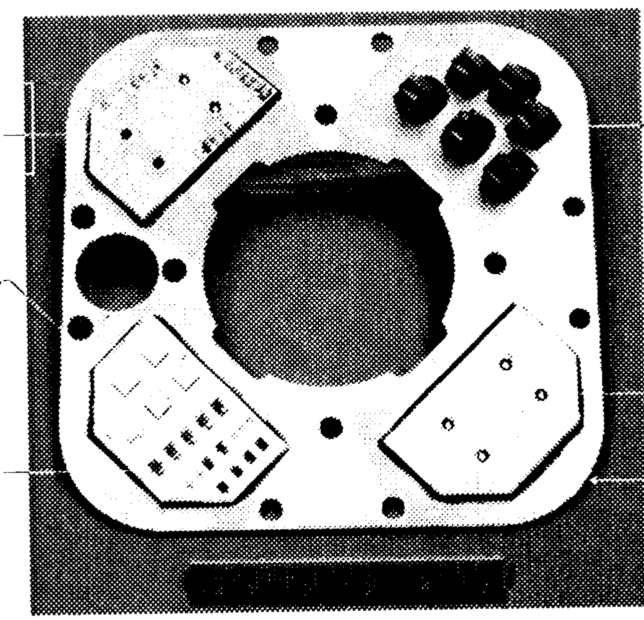

Figure 6: Aft Body Electronics Plate Test Vehicle for Airgun shot

Table 2. Test Parameters and Success Criteria

Test	Test Parameters	Criteria
Thermal Cycling	-120° C to +100° C.	No failures; No physical damage

	100 Cycles, <5° C/Min. Ramp 15 Minute Min. Dwell	
Temperature Humidity	Highly Accelerated Stress Test (H AST), 85% RH, 121 °C 200 Hour	No failures; No physical damage

Overall, the RTOP test program has verified that the configurations successfully tested in the air gun tests can survive the temperature cycling and temperature humidity tests intact. This provided the DS-2 project with up-front DCA validation data for these environments prior to the Microprobe formal qualification. In return, the test shots performed on DS-2 provide shock data for DCA validation being performed by the RTOP program. This sharing of data and resources is a particularly good example of resource leveraging exemplified by the RTOP program,

CONCLUSIONS

While Direct Chip Attach technology does not appear to be a panacea, it is proving to meet the needs of the New Millennium DS-2 Project. DS-2 will be the first project to make wide use of Direct Chip Attach at JPL, and will undoubtedly serve as a development model for incorporation of this packaging technology into other JPL projects,

The collaborative efforts between the DS-2 project and NASA Code Q validation RTOPS has allowed the integration of DCA technology into this effort with minimum, "managed' risk, Development of the technology within industry was used as a guidepost for early decision making. Environmental testing and technology validation was accomplished in parallel with the spacecraft design. This, combined with the "smaller, cheaper, faster" philosophy gaining acceptance in the NASA community, has produced a successful technology validation program for DS-2, and will allow for more rapid incorporation of new technologies into NASA programs for the future,

Further work remains to be accomplished within the DCA RTOP program: In addition to ongoing DCA testing and development, RTOP personnel arc pursuing the formation of a Direct Chip Attach consortium. The purpose of forming this consortium is to not only validate DCA technology for a wider set of programs, but also to address some of the problems encountered on the DS-2 project (e.g. gold plating, environmental protection, known good die, rework issues, etc.). It is hoped that, through efforts such as this, advanced packaging technologies including Direct Chip Attach. Micro-Ball Grid Arrays and Chip-Scale packaging will be quickly validated and facilitate true "Smaller, Cheaper, Faster" NASA programs,

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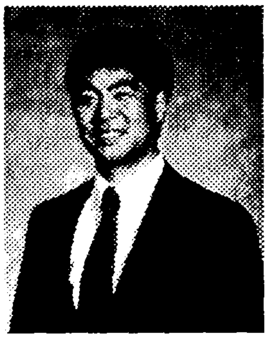

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Saverio D'Agostino, graduated from The University of Illinois, Champaign/Urbana in 1970 with a B.S. in Metallurgical Engineering. His career began at a Navy Materials Lboratory in Crane Indiana studying thin-film structures, electromigration and supporting the Navy's "captive" ASIC fabrication lines with process control and failure analysis. He left Crane as A 1anager of the Engineering Materials Branch and joined the Materials Applications Group at JPL in 19'9. W bile there he worked as the Materials Engineer on Wide Field and Planetary Camera and the Galileo Spacecraft structure and RPM. From '83 to '93 he was Technical Section Head of the Advanced Packaging Section at Hughes Missile Systems and developed pattented designs for stacked and high-G (100,000 Gs), chip-on-board electronics. Upon returning to JPL in 1993, he was the packaging engineer for the MISR instrument and then Task Leader for Direct Chip Attachment in NASA's Advanced interconnect Program. He is currently also the Electronic Packaging Lead for the Mars Microprobe Project, which incorporates COB electronics tightly integrated into its structure for high-G survivability and high-volume efficiency.