CATEGORY V COMPLIANT CONTAINER FOR MARS SAMPLE RETURN MISSIONS

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Introduction

Mars Sample Return Mission will bring to Earth a sample that may contain a life form of extraterrestrial origin. Requirements for such a mission are described in NASA "Planetary Protection Provisions For Robotic Extraterrestrial Missions". Mars Sample Return falls under Restricted Earth Return, Category V missions[1]. This document demands that

> *the highest degree of concern is expressed by the need for stringent measures to prohibit unplanned impact with the Earth, the need for sterilization of returned hardware which directly contacted the target planet, and the need for containment of any unsterilized sample collected there and returned to Earth.*

Currently, the only verifiable method of sterilization of an unknown life form is heating the entire structure (or at least its outside layer) to approximately 800K. Unfortunately, thermal soak may heat the sample inside the container to the levels that are not compatible with the science requirements. Short of subjecting the whole container to some agent that is capable of breaking all carbon-carbon or carbon-nitrogen bonds, sterilization techniques for unknown life forms are very hard to verify. Thus, an encapsulation and containment approach has been chosen in the described work to satisfy the Category V requirements*.

This paper describes how encapsulation and containment requirements imposed on the Mars Sample Return mission can be accomplished and verified using non-biological techniques. The general approach chosen in this work can be formulated as the following sequence of steps:

1. Develop a set of requirements that permits non-biological verification. These new requirements are stricter than the original Planetary Protection requirements expressed in biological requirement and guarantees that biological requirements

* Encapsulation and containment are only a small part of the overall Category V requirements. "Those requirements may affect all phases of the mission, namely the outbound leg; sample acquisition, transfer and storage; sealing of the sample container; monitoring of the sample; return phase of the mission; Earth entry phase; and sample receiving laboratory[1]." To simplify the language, in this paper all references to Category V, unless otherwise mentioned, refer only to the Encapsulation and Containment requirements of the Category V. Thus, even the PP Category IV requirements, that describe the cleanliness of all hardware that may be landed on Mars, will not be mentioned in this paper. We assume that the engineers know how to implement them, the requirements have been met, and all hardware on the surface of Mars is Category IV compliant.

are met. Concurrence of biochemists and planetary protection officers is essential to accomplish this task.
2. Develop a process that meets these stricter requirements.
3. Verify the compliance and design-in extremely high reliability.

The reliability estimates are based on meeting the stricter requirements. The latter allows the designers a margin of errors, since the actual Planetary Protection requirements are less restrictive. A case where the strict requirements are not fulfilled but the original planetary protection requirements most probably are met is described later in the text.

Category V Requirements And Their Implementation.

Category V requirements are minimum requirements that are imposed on the spacecraft. We believe that the following requirements are stricter but relatively easy to verify. The proposed container design is based on the following definitions for containment and encapsulation requirements:

1. ***All life forms are based on some chemical structures.***
2. ***All molecules and chemical structures that may be biologically active and have not been randomly generated on Earth by a natural process (e.g., lightning) are larger than some predetermined size.*** The magnitude of this size is much less important than the fact that the minimum size exists. ***We will assume that this size is larger than something very small, e.g., Kr, Xe, CO_2, or NH_3 molecule.*** None of the biologist we talked to believes that structures that are the size of CO_2 and smaller may constitute life. In addition, all chemical compounds that are smaller than CO_2 have been generated on Earth by some random events.
3. ***The Earth does not need to be protected from chemicals and atomic structures that are already here.*** In other words, the containment enclosure must be impenetrable only to objects and chemicals that are either not found on Earth or have low probability of being found on Earth (anything less than one).
4. ***All objects whose surfaces have been exposed to Martian contamination should reside within a vacuum tight container*.***
5. ***The container has to be impenetrable to any substance defined in (2 and 3).*** It may be penetrable to very small atoms and molecules such as He or H. The latter are easily found on Earth and do not pose any biological threat that Earth-based organisms have not been already adapted to.
6. ***No surface on the outside of the container described in (4), no matter how small, may have been contaminated with Mars artifacts that are lager than those described in (2 and 3).***

These conditions, while sufficient to satisfy Category V requirements, are much more restrictive. There are many large molecules that are organic but either not biologically

* Within the context of this work, these requirements may be relaxed to describe a container that has a vacuum tight seam but whose walls may be penetrable to air but "impenetrable to life forms", such as a HEPA filter. This discussion, however, is beyond the point; since the return container is used to bring a sample of Martian atmosphere, thus, it has to be vacuum tight.

active or do not represent any biological threat. The outer walls of the proposed container will be free even from all even harmless chemicals if they were originated on Mars. We found out that these extended requirements are much easier to describe in terms that mechanical engineers can understand and verify. The ease and speed of verification simplifies the design process significantly.

Requirements (1 - 3) have been agreed with all biologists, astrobiologists, and Planetary Protection practitioners that we have interviewed. Since there is no formal definition of life that can be tested experimentally[2], the survey of the astrobiologists and Planetary Protection practitioners was the only option open to us. The statement that life cannot be based on molecular structures smaller than CO_2 makes sense from a thermodynamic point of view: molecules that small cannot carry any information since they are purely quantum-mechanical objects. In addition, all atomic structures that small had been generated on Earth by random processes (lightning, volcanic eruption, etc.) Had the life forms whose chemical structure can be easily and frequently generated by random processes on Earth existed, these life forms would have formed on Earth and the defense against them would have been incorporated in the genes of Earth based biological entities. Even if these objects happened to be very toxic, they cannot trigger a large-scale event that would make any significant damage to the Earth ecosphere as a whole. Assumptions (1 - 3) are judged correct and are not going to be discussed any further in this paper.

Requirement (5) describes a relatively leaky vacuum chamber or a pressure vessel. Engineers have known how to design those since the beginning of the century. State of the art ultrahigh vacuum (UHV) chambers satisfy much stricter sealing and leak requirements. Requirement (6), however, cannot be satisfied without development of a novel technology for the seam between the container and its lid. The design of this seam is the subject of the current paper.

Double Walled Can And The Seam

A sample return container with walls that have never seen Mars is surprisingly easy to design. If one covers the container on Earth with any material that constitutes a biobarrier and then removes the cover in space during the return flight, one has preserved the Category V compliant cleanliness of the container walls. Something as simple as aluminum foil or any sheet metal constitutes a reliable biobarrier. Figure 1 describes the concept of a double-walled can in detail. The volume between the walls of the container has been sealed on Earth and has never been exposed to Mars. When the container is closed and the outer walls removed, the internal container is clean everywhere with the possible exception of the outermost edge of the seam. Verifiable cleanliness, sterility, and impenetrability of the seam between the two parts of the container (or the container and the lid) are the key to the Category V compliance.

The Category V cleanliness of conventional seams cannot be easily verified. There is always a possibility that a small ($<1\mu m$) particle with a live Martian life form attached to it finds its way to the edge where the lid seam has been cut-off from the outer biobarrier.

In the double can design described in Fig. 1, the only point that can transfer the Martian contamination is the point at which the seam is severed (see Fig. 1c). The most obvious solution to this problem is to render a region within the seam sterile and separate the inner container from the outer wall by a cut through this sterilized region. The rendering can be accomplished in one of two ways: one either sterilizes the seam after it was established (1B) or one cleans the surfaces that form the seam during welding to the degree that no life, as defined by the assumption (2) above, can be present there (1A).

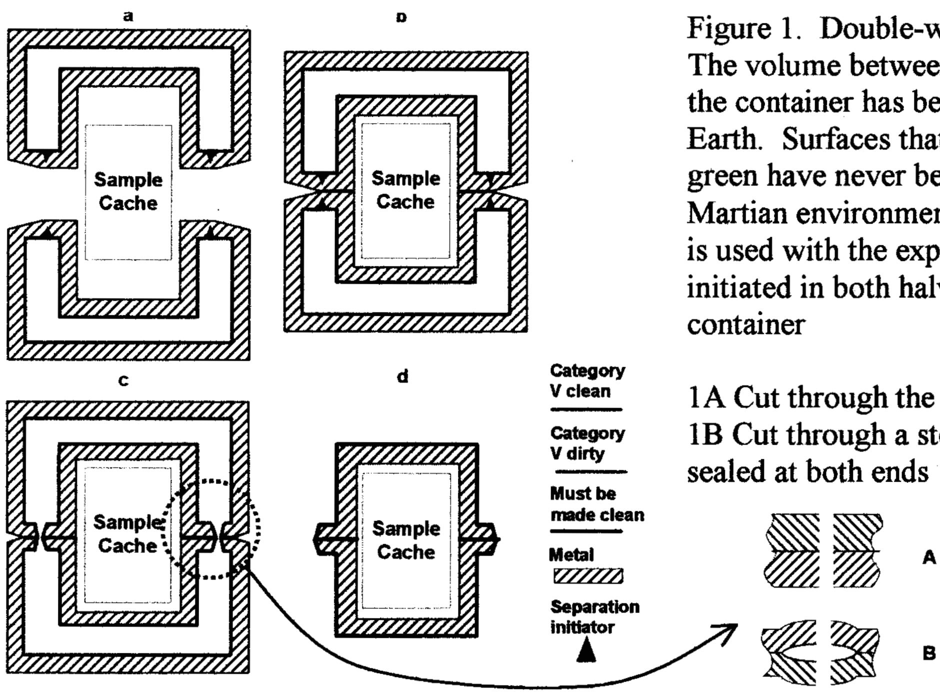

Figure 1. Double-wall container. The volume between the walls of the container has been sealed on Earth. Surfaces that are shown in green have never been exposed to Martian environment. This design is used with the explosion initiated in both halves of the container

1A Cut through the clean seam
1B Cut through a sterilized cavity sealed at both ends

The latter is the approach chosen by the authors of this paper.

Explosive Welding

Explosive welding or joining process uses a ribbon of explosive with a propagation velocity of propagation around 6500 meters/second, generating pressures in excess of 10 000 GPa. A variety of commercially available explosives can be used to accomplish the welding.

The joining is accomplished by explosively accelerating one (flyer) plate against a second (base) plate to achieve a high-velocity (~1000 m/sec), angular impact. At impact point, the kinetic energy acquired by the flyer plate strips the outer layers of the (oxidized) metal on the surfaces of the plates (see Fig. 2). The forces in apex of the closing angle eject these layers to expose pure metals. Clean surfaces of the flyer and the base plates are compressed together to such a degree that a metallic bond is established between the atoms within the plates. The value of the closing angle, the geometries of the flyer and base plates, and the impact velocity are critical parameters in the explosive welding.

Explosive welding possesses several properties that are important for the PP compliant containerization:

- The weld formed is based on the metallic bond; thus, the seam behaves like a bulk metal, i.e., it constitutes a bio-barrier.
- The weld is very tolerant of contamination and thus has an extremely low probability of failure and a high tolerance of the pre-welding contamination
- The surface cleaning is a mechanical process that does not use external tools that may be contaminated. The contaminants are stripped away by a very energetic process: the shear forces at the vertex point are well beyond the shear strength of the welded material. In addition, there are indications, that the conditions at the vertex point may be capable of destroying any carbon-carbon based chemistry and, thus, perform verifiable sterilization of even unknown life*. The proposed encapsulation scheme, however, does not rely on this possible sterilization mechanism.

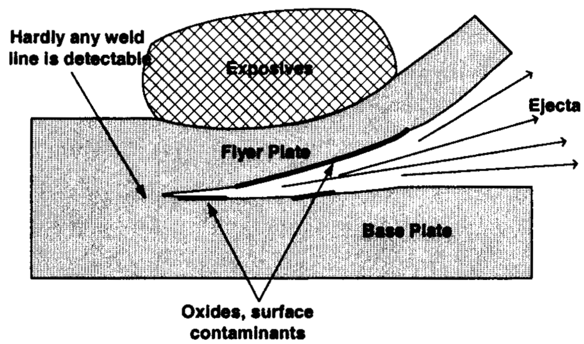

Figure 2. Schematic description of explosive welding.

The main disadvantages of the explosive welding process, from a planetary protection point of view, are the small thickness of the stripped layer and the propensity of the bond to form interface waves that may prevent ejecta from completely leaving the bonded area and trap some surface particles within those waves. Both of these problems have been solved by the introduction of a sacrificial layer.

The sacrificial layer is a layer of soft metal (we used aluminum) that is deposited on both the flyer and the base plates. During welding the total thickness of the layer is ejected from the surfaces. We were able to demonstrate that a sacrificial layer with a total thickness of over 12 microns can be stripped completely from the surfaces of the welded parts. Pure metallic bond is established between the parts that have been welded together. The wave formation was decrease drastically. An insignificant interfacial wave formation was limited to the areas removed from the breach in the seam and did not interfere with the sacrificial layer ejection in that area.

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* We demonstrated that large organic molecular structures, e.g., polyethylene, are reduced to carbon in the conditions that exist within the explosive welded seam. However, this ability of explosive welding to perform sterilization requires biological tests and verification that has not been established yet. The latter contradicts the overall approach of the current work. Thus, this capability was not used in the design of the Category V compliant seam. This sterilization process is another instance where the failure of container under self-imposed strict conditions may not, most probably, lead to a failure under the original PP requirements.

Expulsion demonstration experiments consisted of the following steps (see Fig. 3):

- The surface of the sacrificial layer was coated with a marker (gold in our case).
- The explosive welding was performed and multiple cross-sections of the seam were obtained.
- Expulsion of the aluminum layer was verified (e.g., using SEM; pure aluminum is easily distinguishable from the base metal even if the latter is an aluminum alloy)
- The sample was analyzed for the presence of the marker (gold)

We were able to demonstrate full expulsion of both aluminum and gold. The details of the demonstration will be published elsewhere[3]

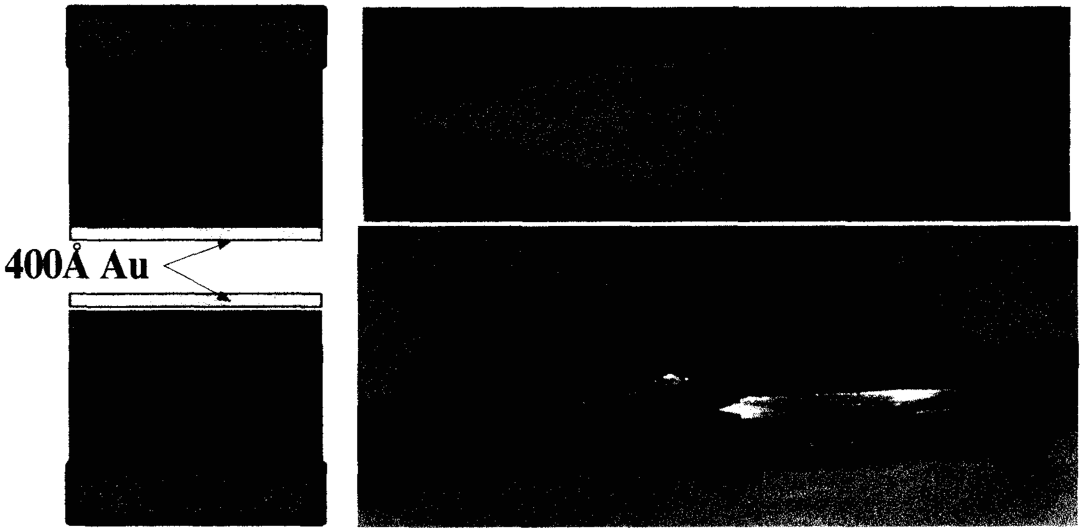

Figure 3. Typical experimental coupon used for expulsion verification. The charges were placed on both sides of the weld and exploded simultaneously. . The welded seam is established on both sides of the cut. The sacrificial layer is fully expulsed. No interfacial wave formation is detectable. Metallographic cross-section above shows a seam with an undetectable weld line.

Full expulsion of the sacrificial layer guarantees Category V cleanliness of the stretch of metal within the created explosive welded seam. The sacrificial layer itself is a biobarrier that protects the metal below it. Thus, the metal surfaces that are underneath it are Category V clean (they did not have a chance to be exposed to Martian environment). No molecular structures present at the surface of the sacrificial layer when the welded parts were apart will stay within the seam area after welding. The latter satisfies requirements (2) and (6) described above. Thus, the explosive welded seam can satisfy all the requirements for breaking the chain-of-contact described previously (see Fig 1A).

Vacuum tight sealing capabilities of the explosive welded seam are barely affected by the presence of the surface contamination. A range of particles from talcum to silicon carbide was used in these experiments. Vacuum tight seal was achieved with contaminants levels as high as 20 mg/cm^2. At these concentrations, one cannot see the metal of the seam behind the dust before welding (the thickness of the dust layer is on the order of 0.3 mm). Neither sub-micron particles nor particles with sizes in excess of 50 microns prevented the seal from being vacuum tight at contamination levels less than 10 mg/cm^2.

Sample Container Design

The geometry of the double walled container used in these test is very similar to the one proposed for Mars Sample Return missions (see Fig. 4). The container uses a concentric design that permits the use of only one set of explosives (compare to Fig.2). The cache is placed in a double-walled container (4a, b). The volume of the container between the walls is free from Martian contaminants. Surfaces that will be welded are covered with a sacrificial layer. During the explosion, the sacrificial layer is expulsed, the Category V clean surfaces that used to be covered by the sacrificial layer are welded to each other, and the weld is cut-through (4c). As a result, the outside surface of the inner can has never seen Mars (4d). It has been exposed only to the inner surface of the outer can that is also Mars contamination free.

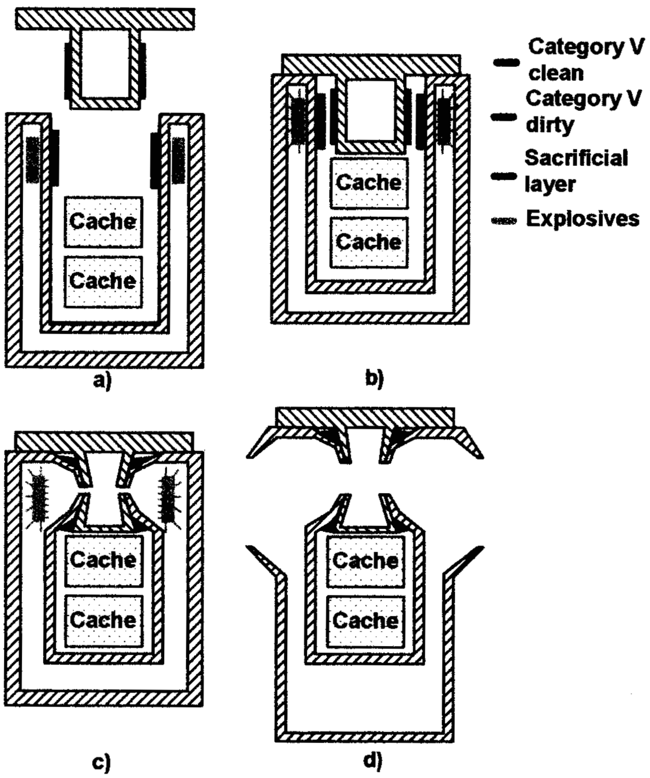

Figure 4. The cache is placed in a double-walled container (a, b). The volume of the container between the walls is free from Martian contaminants. Surfaces that will be welded are covered with a sacrificial layer. During the explosion, the sacrificial layer is expulsed, the Category V clean surfaces that used to be covered by the sacrificial layer are welded to each other, and the weld is cut-through (c). As a result, the outside surface of the inner can has never seen Mars (d). It has been exposed only to the inner surface of the outer can that is also Mars contamination free.

Contamination of the seam before welding may effect Category V compliance of the proposed design. All object smaller than 10 microns will be expelled from the seam area and, thus, will not be present at the lip of the seam cut-off. At this point, to guarantee the Category V compliance using requirements (1 - 6), all particles larger than 10 microns have to be removed before welding by some mechanical means. Several techniques may be employed. Brushes or scrapers can remove large particles before the sealing sequence is initiated. A protective film can be placed on the seam and then removed just before welding preventing large particle contamination of the seam. Protection from contamination with large particles is a well-established art in the engineering field.

The seam may meet Category V requirements even if the full expulsion of the particles within the sacrificial layer did not take place. A particle embedded in the seam that is not near the outmost tip of the seam after separation does not influence the Category V compliance. Only the particle embedded exactly at the tip of the cut-off may break the PP requirements. That point, however, is the point where explosive forces are at their strongest (see earlier footnote with the description of polyethylene film experiments). An investigation of the state of such a particle after explosion may remove the 10-micron particle size limit that guarantees verifiable compliance with Category V requirements.

A full-scale demonstration of an explosive welded sample return container has been performed. Figure 5 shows an aluminum container sealed by explosive welding next to the full-scale mock-up of the Mars Orbiting Sample Return container (OS) as it was envisioned in 1999. A detail of the welded inner can next to the welded outer can is presented in the same picture. In this demonstration, only the portion of the outer can that is near the weld was manufactured. The remaining part of the outer can should not influence the weld performance.

Figure 5. Full scale model of OS and the weld sealed can. The picture of the right shows details of the separation of the sealed outer can from the inner can. The part with the visible threaded holes used to be a part of the lid of the inner can. The cut-off ring used to be a portion of the outer can.

The performance of the seal was optimized to increase the width of the area where the sacrificial layer is fully expulsed. The larger this area is the less critical is the alignment of the can and the lid. An example of a seam that was welded by a single side explosion is reproduced in Fig. 6

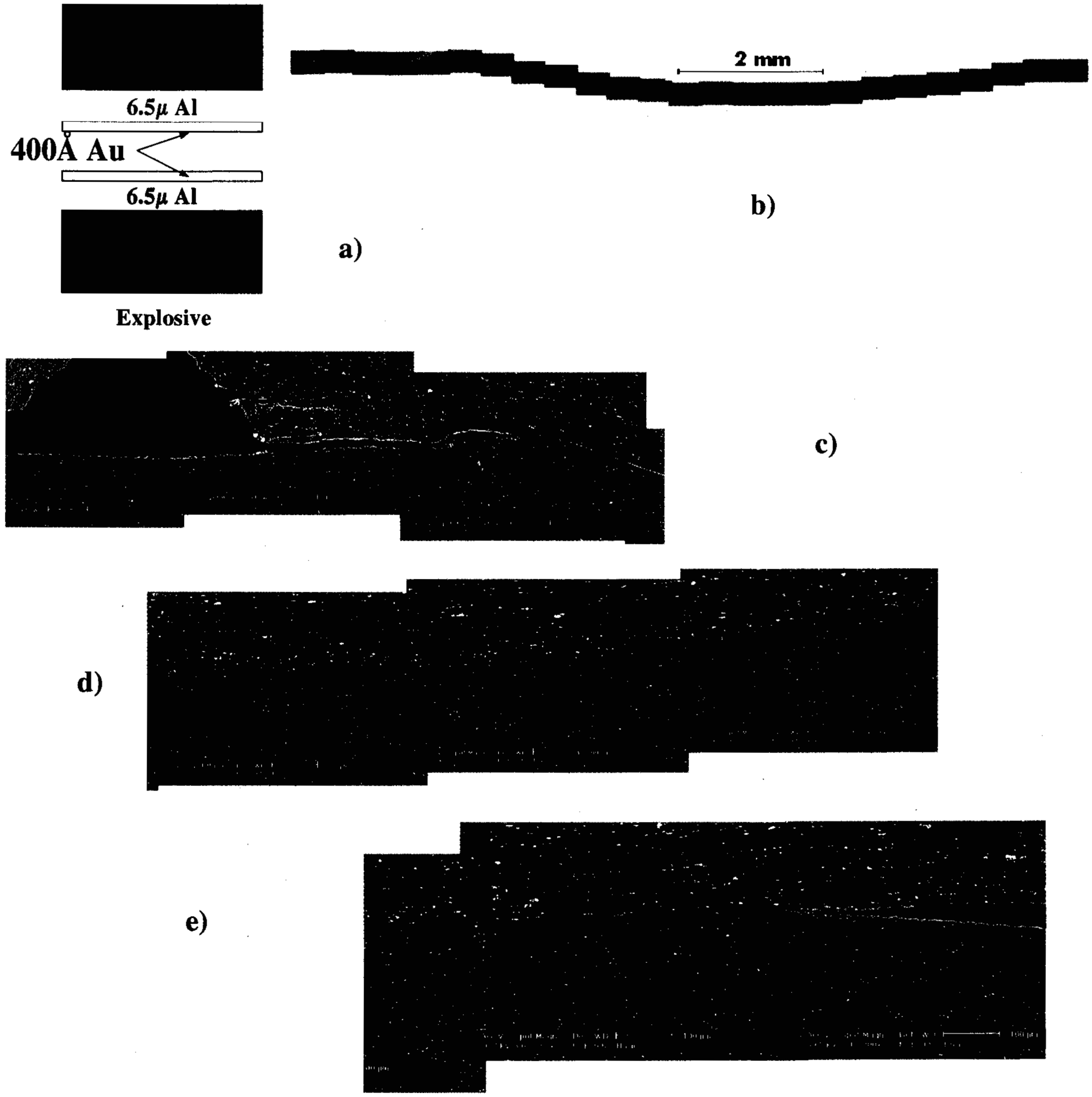

Figure 6. Seam optimization for single side explosion. The seam was initiated at the right end of the micrograph. The direction of the sacrificial layer expulsion is also from the right to the left. The SEM micrographs are taken in back-scattered electrons. The bright spots in the left side of c) is the only remnants of gold marker in the picture.
a) Seam schematics. b) Overall view of the seam (SEM). c) The last segment that has been welded together. d) Segment with no interface waves. e) The first segment that was welded together.

Conclusions

A Planetary Protection Category V compliant sample return container design has been demonstrated. The design permits a full verification of Category V requirements without necessity of defining what extraterrestrial life may look like or if it can be detected. The verification protocol permits fast non-biological testing of the device. Since the verification procedure is formalized and does not use any properties of extraterrestrial life, a meaningful assessment of containment reliability can be performed. A very large safety margin separates the proposed design from the minimum requirements of PP Category V. The container does not use any conditions specific to Mars environment and can be used for sample return from any celestial body.

References:

[1] NASA "Planetary Protection Provisions For Robotic Extraterrestrial Missions" (NPG 8020.12B), Section 2.2.5.2 "Restricted Earth Return" Missions.

[2] Dr. Kenneth H. Nealson, Private communications.

[3] J. Sanok, B. Dolgin, L. Bement, "Use of the sacrificial layer in explosive welding", to be published.