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Target Fabrication for Sandia's Z-Pinch Accelerator

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***Abstract*—Sandia's Z-pinch accelerator is used to study stockpile stewardship, high energy density physics, equation of sate (EOS) experiments, and fast ignition studies by driving 0 MA of electricity to create either high temperature plasma (>1 keV), or high magnetic fields (>1000 T), and high pressures (megabar to gigabar) M.K. Matzen, et al., Phys. Plasmas 12, 055503 (2005). The Z targets are designed to study the same physical concepts as the targets used for the laser drivers, such as Omega at the University of Rochester, but the differences between the drivers could make the Z target unrecognizable to a laser experimenter. The targets do not have laser entrance holes; instead the target is designed to be bathed in soft x-rays produced by nested wire arrays or driven by the strong magnetic field. There is a notable difference in the size, Z-pinch hohlraum targets are 10 to 20 mm long and 4 to 6 mm wide. The EOS targets vary greatly in size, but the smallest panel is roughly 20 mm wide and 30 mm tall. Furthermore, multiple EOS samples are tested simultaneously on Z shots as there are two to four panels per experiment and each panel contains one to five samples.**

The differences in the targets present unique challenges and opportunities for target fabrication. The larger scale lends itself to micromanipulators and bench top presses, but assembly tolerances are not scaled with the larger size thus high precision is required. Characterization of these larger targets to the required precision is problematic. This paper will outline examples of the targets that have been fabricated for Z with details of their fabrication and characterization. Potential targets for the future ZR accelerator will also be presented.

Keywords: Target Fabrication, Z-pinch targets, ICF targets

I. INTRODUCTION

Sandia National Laboratory (SNL) houses a megajoule-level pulsed power facility called the Z-pinch accelerator (Z). When fired, Z delivered about 20 MA load currents to create high magnetic fields (up to 1000 T) and high pressures (up to a gigabar). There were two basic types of targets: wire arrays and equation of state (EOS). See Fig. 1 for depictions of typical target types. In a wire array target one or two cylindrical arrays of wires were supersonically imploded as plasma by the magnetic pressure. When this plasma stagnated on center it could produce conditions as extreme as 10 MJ/cm^3 energy density with >1 keV temperatures. In the EOS experiments the large magnetic pressure directly drove isentropic compression experiments to pressures >3 Mbars [1] or accelerated flyer plates to >30 km/s [2]. The experiments described above were referred to in the past tense because in August of 2006, Z was dismantled for refurbishment and upgraded to operate at higher energies. This, after 10 years of operating as a pulsed power driver that in the last 6 years averaged 180 shots per year. When Z is brought back on line it will be configured to operate as a Users Facility. This will probably result in unique new target designs, but some predictions can be made as to how the previous target designs will evolve to shoot on the new Z.

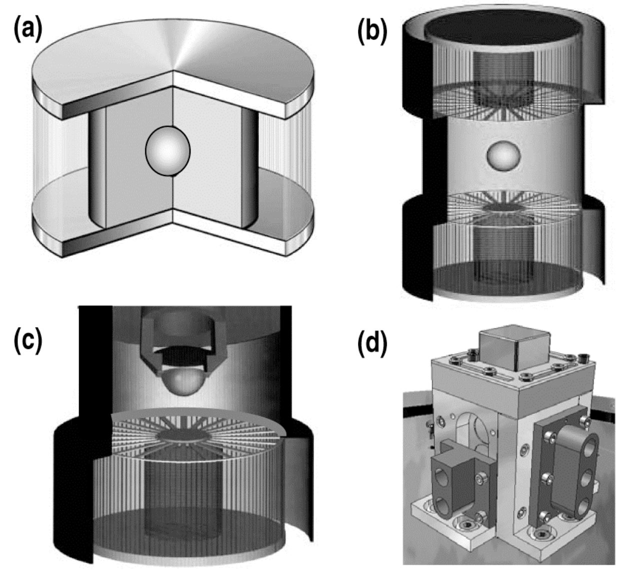

Figure 1. These are four target types typical for Z. The first three are wire array type targets, the fourth is an EOS type. They are: (a) dynamic hohlraum, (b) double pinch hohlraum, (c) fast igniter, and (d) EOS.

The requirements of the targets pushed the Target Fabrication laboratory to acquire a unique suite of assembly and characterization equipment. For example, there are two types of assembly stations, see Fig. 2. The first type incorporates a Nikon measuring microscope (with calibrated x and y movement), two digital cameras (for orthogonal views), and a geometric analysis tool. The second station has two cameras fixed in space for defined alignment. It has calibrated x, y, z and rotational movement and is capable of doing characterization analysis as the target is being built. For characterization tasks there are four microscopes. The simplest microscope is a Nikon CFH200-Z confocal microscope that can be operated in confocal mode, interference mode or in combined confocal interference mode. It is a manual microscope fitted with an interference probe to measure distances in the Z direction. A VEECO NT3300 interferometer is used for surface finish analysis. A Nikon VMR-3020 laser focus microscope is used for step height, complicated surface analyses and repetitive analyses. A confocal Nikon VMR-3040 can characterize the most difficult (least reflective) samples.

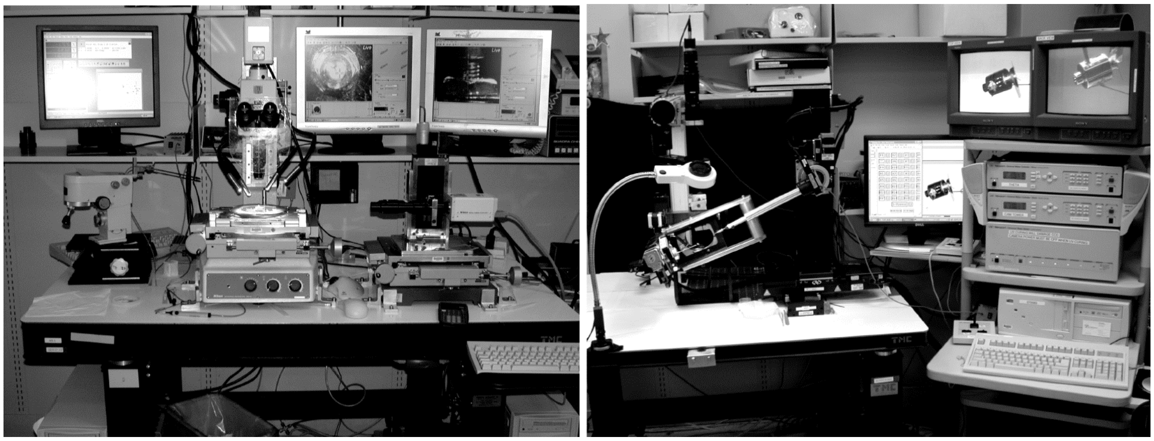

Figure 2. These are the two target fabrication assembly stations. The station on the left has two camerss, a measuring x and y stage and a x measurement on the side camera. The station on the right has the cameras fixed in space to define a cartesian space. The target can move in x, y, z and rotate.

II. WIRE ARRAY TARGETS

There are three main types of wire array targets: the dynamic hohlraum, the double pinch hohlraum, and the fast igniter. The terms hohlraum and fast igniter are familiar to an experimenter who uses laser drivers such as Omega, Gekko XII, NIF and LMJ, but Z targets may not look familiar. The first difference is size, the typical Omega hohlraum is 1.6x2.4 mm; a Z hohlraum can be 6x15 mm. (A size comparison is shown in Fig. 3.) A fast igniter target for FIREX-I is based on a 0.5 mm shell, the Z fast igniter target is based upon a hemisphere 3 mm in diameter. Other differences are caused by the Z driver being a pulsed power source, not a laser. Three categories of wire array targets are outlined below.

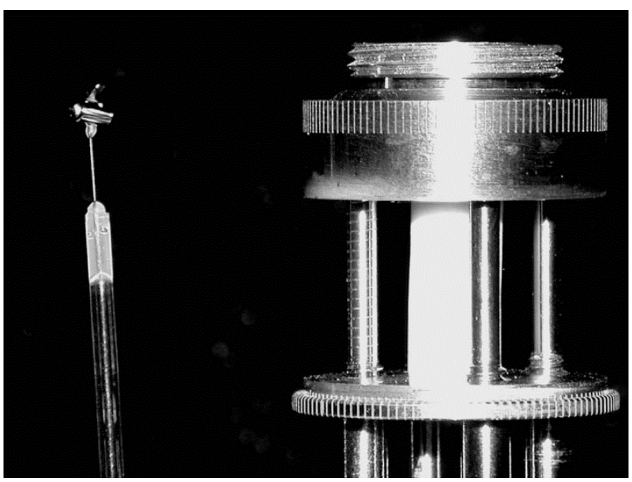

Figure 3. The hohlraum on the left is a full scale Omega target: the hohlraum on the right is a typical dynamic hohlraum without wires. The wires would run through the slots on the top and the bottom of the assembly.

A. *Dynamic Hohlraum*

In the Z-pinch dynamic hohlraum a wire array is turned to plasma and stagnates on an inner cylinder of low-density foam. The impact of the plasma on the foam launches a shock that propagates toward the cylindrical axis of symmetry. The high-opacity pinch plasma traps the radiation and serves as the hohlraum wall. Obviously the success of this target depends upon the foam. SNL requested that the foam be TPX [poly(4methyl-1-pentene)] whose simplified chemical structure was CH_2. This foam had been developed by Los Alamos and Oak Ridge as a machinable low-density foam. We adapted the foam fabrication so that foams could be cast to net shape. In the new process the foam is created by dissolving the polymer in cyclohexane, pouring the solution into a mold, degassing the solution, freezing the solution, trimming of any excess solution from the mold, and lastly, removing the cyclohexane by freeze drying. When requested, doping of the foam was done by the addition of either nanopowders or organo-metallic molecules to the cyclohexane solution. The casting process reduced labor cost, shortened processing time, improved the uniformity of the foam structure, and reduced the lowest density to 2 mg/cm^3. Casting also allowed for precise placement of objects within the foam. Foams were made with embedded foils (whose spectral lines indicated temperature [3]), beryllium markers (that diagnosed the movement of the shock front) and gas filled capsules (that demonstrated the potential to use this target as an ICF target when experiments resulted in thermonuclear neutrons [4,5]). For each of these embedded components, techniques had to be developed to precisely place the object and to characterize completed foam for uniformity and object placement. For placement of objects such as capsules we used an assembly station composed of x, y and z Metronics micromanipulators that could position capsules to within 10 microns in a foam solution. For characterization we used a low energy radiography system designed by Larry Ruggles (SNL). The source is a Manson source that produces broadband x-rays by striking a Molybdenum anode with electrons. The x-rays then travel through an aluminized Mylar filter producing 5 keV broadband energies. The sample chamber contains a 25 cm rotating disk that has 9 rotating sub-stages. This allows 9 samples to be characterized at multiple angles without having to break vacuum. X-ray collection is done on a 2048x2048 pixel cryogenically cooled CCD. With typical sample placement the field of view is 20 mm on a side. Some interesting examples of dynamic hohlraum targets included shaped foams, shimmed capsule foams and foams containing beryllium capsules. Sample radiographs of these foams are shown in Fig. 4.

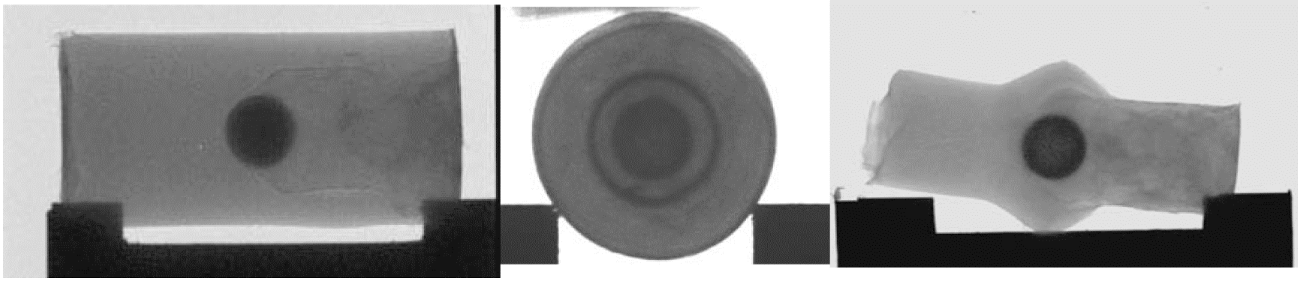

Figure 4. Theses three radiographs are the foams from three dynamic hohlraum experiments. The left radiograph shows a simple capsule in a cylindrical foam. This was the most common target type, but the capsule type varied from polymer to glass and beryllium and the placement was often better than 50 microns within the 6 mm diameter foam. The middle radiograph shows an end on view of 6 micron aluminum shim around a capsule in a cylindrical foam, and the right radiograph shows a capsule in a shaped foam.

TPX was the most commonly used foam on Z due to its ease of manufacture and good casting abilities, but there were times when its large cell size made it unsuitable. For those applications we also made polystyrene emulsion foam, divinyl benzene foam, and aerogels from resorcinol-formaldehyde and silica.

B. Double Pinch Hohlraum

The double pinch hohlraum has two wire array primary hohlraums above and below a secondary hohlraum that contains a capsule. Shielding between the primary hohlraums and the secondary hohlraum and the diameter and length of the secondary hohlraum are designed to produce an x-ray flux that uniformly compresses the capsule [6]. The capsule is precisely placed in the secondary hohlraum by sandwiching the capsule between two sheets of sub-micron thick Formvar film.

Two of the more interesting double pinch targets used modifications to the capsule. To improve the uniformity of compression capsules were made with gold bands of radially varying thickness. These shells required precise rotational alignment within the hohlraum to match the greater shim thickness to the areas of higher x-ray flux. Another interesting capsule design had tubes attached to simulate the instabilities caused by a fill tube on a cryofilled capsule. Due to the multiple fill tubes on a single capsule, one of the Formvar films had to have a hole placed to permit penetration by a fill tube. This is shown in Fig. 5.

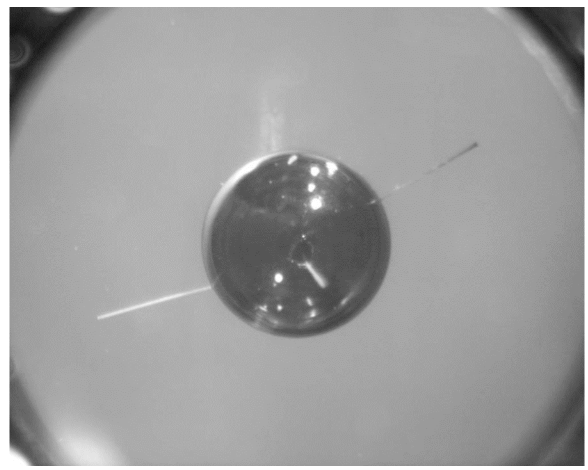

Figure 5. This is capsule with 3 fill tubes mounted in the secondary hohlraum of a double pinch target. The fill tube pointing towards the camera came through a hole in the Formvar film.

C. Fast Igniter

The fast igniter target is similar to the double pinch hohlraum in that the wire array is around the primary hohlraum, and the experiment is in the secondary hohlraum. The goal is to uniformly compress a hemisphere in a target design that permits access from above for a peta-watt laser to trigger ignition [7]. The prototype design used a 2 mm diameter hemisphere placed on a gold glide plane to within a 5 micron tolerance. A comparison of the target "as built" and during compression is shown in Fig. 6.

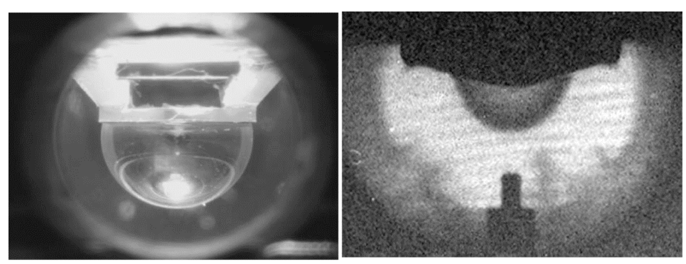

Figure 6. The photo on the left shows the hemisphere in a fast ignition target as built. The radiograph on the right shows the hemisphere compressing during an experiment.

D. EOS Targets

An EOS target on Z is a short circuit; there are no wires but rather four panels bolted directly to the machine. The current flowing through these panels create a very large magnetic force that can launch either an isentropic shock front or a flyer plate. Each panel is typically 20 mm by 50 mm but panels of various sizes and aspect ratios have been fielded. Each panel can have one to five separate experiments within a counter bores in the panel. The experiment is built from the counter bore and it can consist of a series of components including one or more samples, a reservoir for liquid, a gap for a flyer plate and usually a coated window. Each component is characterized for thickness and completed assemblies are characterized to ensure distances are known. Characterizations can be complicated by anti-reflective coatings on windows, the composition of the material (such as foams), or by the need to measure through components after assembly (to measure flyer plate distance for example).

The goal with EOS assemblies is to have minimal glue bond thicknesses, sub-micron if possible. To achieve this, samples are bonded in a clean room using presses, pressure gauges and digital readouts. This allows us to apply just enough force to compress the glue but not enough force to damage the components. In EOS experiments the goal has been to study heated or cooled samples so temperature control has also been required. To accomplish this heaters or cryo-assemblies and thermocouples are used, dramatically increasing the complexity of the target assembly (Fig. 7).

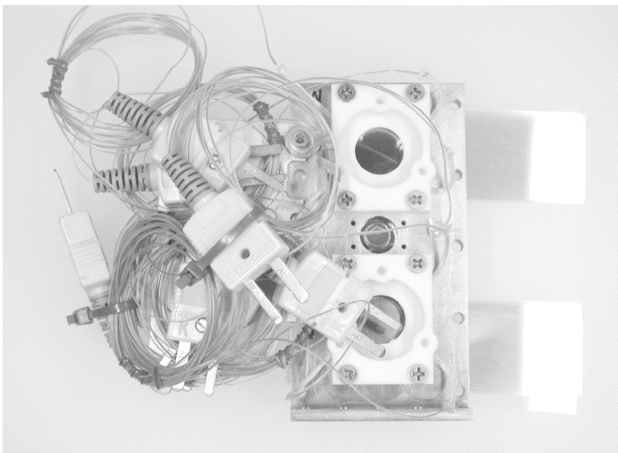

Figure 7. This is one panel of a four panel experiment that was shot on Z. It has two counter bores that have heaters and thermocouples and a center counter bore that has a simple coated window for a velocity measurement.

III. TARGETS AFTER Z REFURBISHMENT

Three targets types have been proposed for experiments after the refurbishment of Z, the double pinch hohlraum, the fast ignition and EOS.

A. Double Pinch Hohlraum

For the double pinch target we expect to test the theory that the Z-pinch machine can generate three shaped pulses appropriate for hot spot ignition of high yield inertial confinement fusion capsules [8]. Experiments have demonstrated a reproducible and tunable foot pulse (a first shock) is produced by the interaction of the outer and inner wire arrays. A second shock is produced by the inner array collision with a central foam annulus. The third shock is produced by stagnation of the inner array on axis. The second shock is expected to be tunable by adjusting the foam radius and density. This was tested on Z just prior to the refurbishment by using a foam annulus with two areas of different density. The densities requested were 8.9 and 13.4 mg/cc, with the tolerance of ±10%. In addition, the ratio of the two density regions had to be maintained (1:1.5). The two sections were to be joined without glue. The TPX foam was to be 11 mm tall, 7.2 mm in diameter with an inner diameter of 4 mm. A resultant target foam is shown in Fig. 8. This experiment was successful so a prototype three-density annulus was requested with the anticipated need being Z shots after refurbishment. We were successful creating this prototype and the density uniformity and attachment of sections are better than the previous target (Fig. 9). There is a slight shift to one side between the three foam sections, which we expect to correct by modifying the mold for better alignment. We will attempt to make the foam to the correct dimensions for the new Z target when they become known.

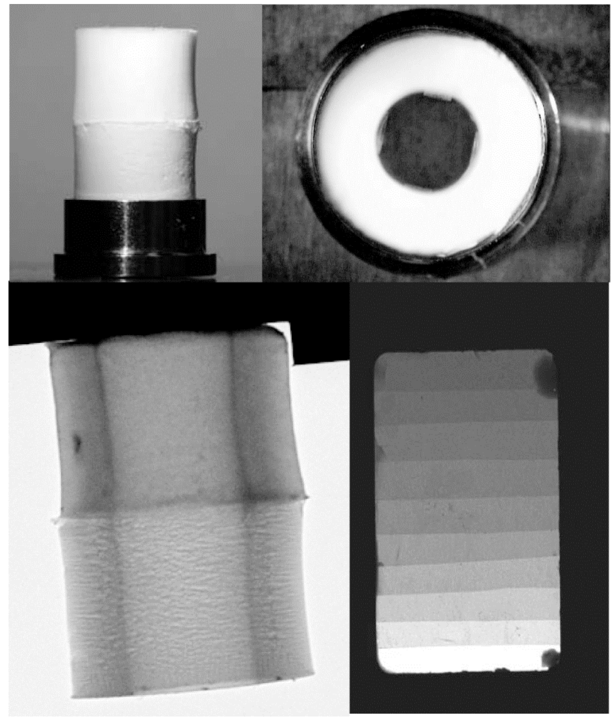

Figure 8. (a) The top left picture is a side view and the top right picture is a top view of the foam used in shot #1712 on the Z machine. The densities of the two sections were 14.2 and 9.9 mg/cm^3. Radiography was used to determine the densities of the two areas. A standard was created by layering of 10 steps of 11 micron thick polypropylene film obtained from Goodfellow. The image on the bottom left is the radiograph of the foam shown above. The image on the bottom right is a typical radiograph of the standard.

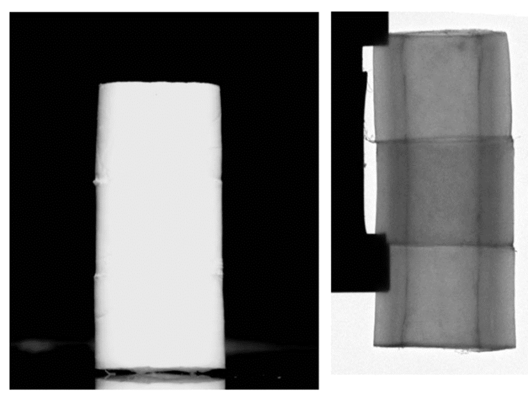

Figure 9. A side view optically and by radiograph of the three section foam annulus. The foam is 15.5 mm tall, 7 mm od, and 4 mm id.

B. Fast Ignitor

The fast igniter experiments on Z after the refurbishment will have two precisely aligned hemispheres (Fig. 10). This space between the hemispheres is to be filled with liquid deuterium. During the experiment the two hemispheres and the deuterium will be compressed and analyzed for uniformity. In later experiments the compressed target will be tested for fast ignition by striking with Z-Beamlet operating in the peta-watt laser mode. We are currently prototyping the assembly and are trying to overcome several challenges. The inner hemisphere is only 4 microns thick and ~2 mm in diameter. The alignment between hemispheres is requested to be ±5 microns and the seals around the hemispheres must be liquid tight at cryogenic temperatures. The fill tube for the liquid deuterium is only 150 micron in diameter and is prone to wicking up epoxy during assembly.

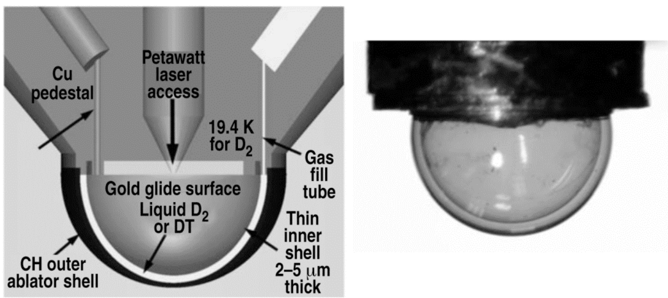

Figure 10. The drawing on the left shows the conceptual components required in the dual hemi cryogenic fast igniter design. The picture on the right shows the prototype target. It has the glide plane components and the two hemispheres.

C. EOS Targets

The future EOS targets will require greater precision especially in the area of measuring glue bond thickness. This is a complex problem as each component can have surface flaws, bowing or non-parallel surfaces, all of which effect final stack height. Fig. 11 is an analysis of an EOS panel showing that the "flat" power flow surface actually has a bow on the side opposite of the counter bore and that the surface of the counter bore has a ridge in the center of the diamond turned surface. This more complete analysis of the panels will become more commonplace in future experiments.

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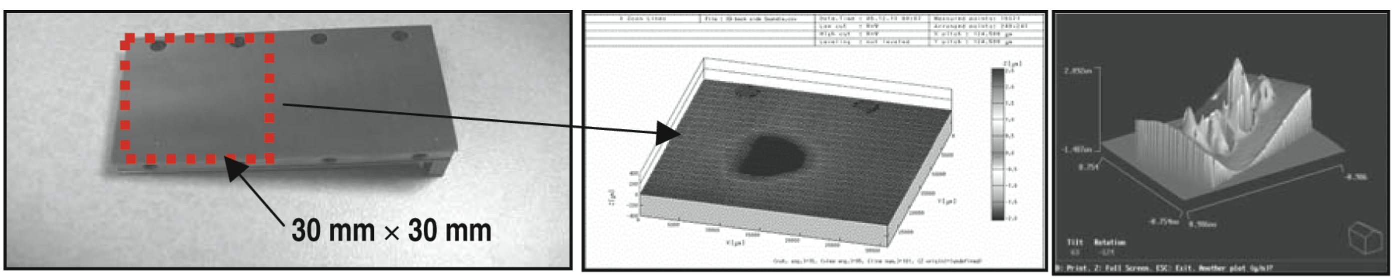

Figure 11. This is a sample analysis of an EOS panel. The power flow surface has a 2.5 micron bow and the counter bore has a ridge 4 microns high.

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