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INERTIAL-CONFINEMENT-FUSION TARGETS*

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ABSTRACT

Inertial confinement fusion (ICF) targets are made as simple flat discs, as hollow shells or as complicated multilayer structures. Many techniques have been devised for producing the targets. Glass and metal shells are made by using drop and bubble techniques. Solid hydrogen shells are also produced by adapting old methods to the solution of modern problems. Some of these techniques, problems and solutions are discussed. In addition, the applications of many of the techniques to fabrication of ICF targets is presented.

DISCLAIMER

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INTRODUCTION

In the most simple, straight forward direct driven case, an ICF target may be a simple ball on a stalk, fiber network, or film support as shown in Figure 1. In a more complicated case the fuel is inside a nonlinear designed to contain thermal x-rays produced by interaction of the driver beam with the outer shell. To simplify the presentation, in the remainder of this paper I will only discuss direct driven ICF targets.

The fabrication of laser fusion targets presents a set of unique problems in material science, chemistry, physics, optics and microscopic mechanical techniques. As target designs have evolved from simple disks of plastic, metals or glass to multilayer spherical shells, our techniques for glass sphere production, polymer and metallic layer deposition, mechanical assembly and characterization have also evolved.

Our early metallic disk targets were prepared by means of two primary techniques. Some of the disks were deposited on thin plastic films by evaporation through a small (100-150 μm) hole in a mask. Others were made by a cookie cutter technique, punching the disks from a thin metal foil. More recently we have made disks by masking and etching a silicon wafer to leave a flat topped, circular set of posts onto which is evaporated a metal layer of correct thickness. The disks are then removed from the top of the clylindrical posts by using a microscopic vacuum chuck. Disks have also been made of a low density (ρ = 0.05-0.07 gm/cc) cellulose acetate foam by slicing from an extruded foam cylinder. For use as a target, a disk is mounted on edge on the tip of a few micrometer

diameter drawn glass fiber whose base fits in a holder for insertion into the laser target chamber.

ICF targets consisting of hollow-spherical glass shells have been used extensively at many laboratories. Initially the shells were obtained commerically in batches which were produced primarily for plastic fillers and other industrial uses. Even with the relaxed specifications of early targets, it was a difficult and time consuming task to find one which was good enough to use.

Quite naturally, the manufacturers were not particularly interested in surface quality or uniformity of the sphere walls. To find a suitable target, we often sorted through 10^9-10^{11} glass shells! Because of the inefficiency of the sorting techniques and lack of availability of spheres which met our stringent specifications even after the sorting process, we decided to make our own high quality glass shells.

A liquid drop method developed at Lawrence Livermore National Laboratory (LLNL) has allowed us to improve the quality and yield of glass shells until we find that 90 to 99 out of 100 meet the much more severe requirements of todays targets instead of the 1 in 10^9 to 10^{11} which satisfied some of our earlier less critical needs. To achieve such phenomenal yields, very uniform liquid drops of an aqueous solution of glass forming chemicals are generated and introduced into a vertical tube furnace as shown in Figure 2.

The aqueous solution of glass forming chemicals (e.g. sodium silicate, boric acid, sodium hydroxide, potassium hydroxide, etc.) is forced through an orifice to form a cylindrical jet. A capillary wave launched onto the jet by means of a piezo-electric transducer induces the jet to break up into a series of uniform drops. The solvent (water) is evaporated from the drops in a vertical column at about 350°C, leaving dry particles which continue into a higher temperature region of the furnace to form glass spheres. Water of hydration and gases evolved from the chemical constituents expand in the molten glass spheres and form the glass into very uniform hollow shells. Instead of a yield of one in 10^9 or 10^{11}, our process yields the 99 out of 100 which meet the criteria for target use. This means a surface which is smooth to 100 Å and a wall thickness which does not vary by more than 1% of its average value. Surface tension of the glass in the low viscosity state makes the liquid into essentially perfect spheres.

The uniformity and reproducibility of the initial droplets are important to the process from several points of view.

Some of these are:

1. Equal mass of glass in every shell.
2. Repeatability allows variation of parameters to experimentally optimize the process.
3. Reproducible injection into furnace.

The droplet process allows us some optimization of a slightly different process for producing the glass spheres. One of the earliest processes for producing hollow glass spheres commerically involved introducing dry particles of mixed glass materials into a gas flame. As the material fused in the flame, gases evolved from the components formed small bubbles whose walls became thin as expansion occurred. The internal bubble walls perforated and after a few milliseconds or less, one relatively internal large bubble was formed of all the smaller bubbles. The single bubble continued to expand and a hollow shell was formed. The glass flame was short and the glass shells cooled quickly on emerging from the flame and were literally scooped off the chamber floor, bagged and marketed in large quantities.

Preparation of the dry particles to be put into the flame (or other high temperature device, e.g. vertical tube furnace) varied with particular manufacturers. The glass forming materials could be mixed into a slurry, dried, pulverized, sieved and otherwise manipulated to gain some uniformity of size. Another method involved dissolving the chemicals in water (and often included a decomposible gas former such as urea) and spray drying to form the dry particles which were then put into a flame or furnace for sphere production.

The liquid drop generation technique allows us to produce first a set of <u>uniform</u> dry particles which can subsequently be introduced into a furnace or flame for fusing and forming into glass shells. Many

variations of the basic theme are possible and are useful in specific circumstances.

The reasons for the almost perfect centering of inner and outer surfaces, i.e. uniform wall thickness, are not completely clear for any of these techniques. The most probable mechanism is that variations in the temperature profile seen by the glass shells during the forming process provide variations in internal pressure in the shells which tend to pump the walls and induce flow in the glass which leads to centering. That pressure variations may indeed lead to the centering mechanism, is substantiated to some extent by the work of Taylor Wang, Dan Elleman, and their colleagues on bubble centering in liquid shells.

It should be pointed out that a large fraction of the fly-ash from large coal fired power plants consists of small, hollow glassy shells.

Experimental results indicate that for shell sizes up to about 3 mm, gravitational and aerodynamical forces do not appear to cause asphericity or decentering of inner and outer surfaces in vertical tube furnaces. Some analyses predict problems from these forces at even smaller sizes. A possible explanation of the absence of irregularities in the spheres may be that the spheres rotate and, indeed, may move up, down and sideways as well in the turbulent atmosphere of the furnace. Our observations extend only to spheres up to 3 mm size range. Larger shells may also not be disturbed by asphericity or decentering. At this time we have no data for larger sizes.

After the spheres are collected from the furnace, they are washed and filled with a mixture of deuterium and tritium (DT). These gases diffuse rapidly through the glass walls if the spheres are at a temperature of a few hundred degrees Celsius (e.g. 350°C). At lower temperatures the gas will not diffuse back out of the spheres over periods of several months to several years.

Spheres whose walls vary in thickness by more than 1-2% and whose surfaces have peak-to-valley roughness variations of more than a few hundred (100-300) Angstroms are of little interest for use as targets. Targets which are simple bare balls can sometimes be lower quality spheres than our canonical high quality shells.

Other direct driven targets are also of interest and require other techniques for production. Multiple layer coatings of various materials must be applied to the surface of gas or metal spheres to produce a complete target. We must produce metal shells which have the same high quality walls and surfaces as our present glass shells. The coatings, which may be CH or CF polymers, polymers with a few atomic percent of a high atomic number material distributed molecularly throughout the polymer, or layers of copper or beryllium or other materials should be very high quality. Layer thickness variation and surface irregularities should be kept to the few hundred to the thousand Angstrom range.

Some of our targets are glass shells coated with fluorocarbon polymers (like Teflon) or hydrocarbon polymers (like polyethylene) or metallic layers such as copper, gold, silver or platinum. After the glass shells are filled with DT, the coatings are applied by sputtering, plasma activated polymerization, chemical vapor deposition, electrodeposition or other suitable processes. Specks of dust, surface weathering, or other irregularities as small a few tens of Ångstroms initiate or seed irregular growth patterns in the coatings during the deposition processes. Unless the substrate spheres are virtually perfect and absolutely clean, it is very difficult to produce high quality coated shells. Figure 3 shows coating irregularity which originated on a defect or microscopic dirt speck on the surface of the glass sphere.

Of course, we must maintain the surface quality of the coatings at the 100 Å smoothness level for thin coatings and at about 1% of the thickness for thick coatings.

To avoid introducing damage sites by contact with supporting surfaces during the coating processes, we have developed a molecular beam levitation (MBL) technology which uses gas at very low pressure flowing through a collimated hole structure. The spheres are placed above the structure and the impact of the molecules on the spheres transfer sufficient momentum to levitate a steel sphere as large as a 3/8 inch diameter. The system is operated at a pressure low enough that sputtering and various beam coating processes can be accomplished. The levitation process is

sufficiently gentle that multishell assemblies in which inner spheres are suspended concentrically by means of a thin web (≈ 200 Å thick Formvar) can be overcoated to produce a seamless outer shell. A levitated sphere is shown in the MBL in Figure 4.

A second technique for producing the outer shell is that of assembling two hemishells around the inner sphere (Figure 5). Techniques for making and assembling hemishells into spherical shells have been developed to a relatively successful state. Utilizing single-point diamond tools and high precision air-bearing spindle lathes, we make machined hemishells with 250-300 Å surface finishes. To avoid assembly problems, we have also machined step joints into the edges of the shells as shown in Figure 6. The spheres are assembled around DT filled, coated glass shells to form double shell targets.

A number of directly driven targets for future reactor applications require metal spheres as containers for the DT fuel. Metal spheres have been produced by a number of techniques including annular jet techniques (e.g. copper, woods alloy, tin) and by deposition on and leaching out of spherical mandrels, and by machine lapping methods. It is not anticipated that fusion targets will become less difficult to produce or that the critical parameters will be relaxed in the near future. The techniques used to characterize the targets (optical interferometry, microradiography, electron and ion beam techniques) are, in some cases, in the development stages. A great deal of research remains to be done just on measurement techniques.

Some target designs contain one or more layers of solid DT fuel. Conceptually, in a paper design, such layers are easy to put in a target. Experimentally it may be very difficult to produce such targets. Many of the details of cryogenic targets we have down cold. However, there are still many problems to be solved before high quality cryogenic targets can be irradiated in the laser target chamber.

At each step of the target fabrication process it is imperative to have accurate data on the geometry of the spheres, the coatings, supporting films, DT fill, hemishells and the assembled target. To make all these measurements we have developed a highly sophisticated set of characterization systems and analytical techniques and apparatus.

Transparent shells, walls and surfaces are measured to a few hundred Angstroms accuracy with lateral resolution of about 2 micrometers or better. Transmission interferometry provides an excellent tool for characterization of transparent spheres and shells. Total 4π characterization of a glass shell can take up to 5 hours if done manually looking through an interference microscope. To reduce the time necessary for a complete 4π characterization of a sphere, we have developed an automated sphere characterization system which measures the sphere and plots a contour map to a height accuracy of about 200 Å with a lateral resolution of about 2 micrometers in about 5 minutes.

For detailed surface analysis and analytical studies we rely heavily on Scanning Electron Microscopy and Auger microprobes. Information on chemical composition of surfaces as well as on surface contours is thus made available to material scientists who are concerned with coating, sphere formation, and other materials problems.

Targets for economical energy production in the future are yet to be fully developed. However, in several areas we have made significant progress toward high rate, low cost production of reactor class targets.

Techniques for producing fully cryogenic targets and for levitating and transporting targets of all types have been developed. We are continuing our efforts toward determining the building blocks for a target factory (Figure 7).

As new target designs are generated and more powerful and energetic lasers are built, new targets must be produced. We are continuing the research and development which will allow us to respond to the continuing challenges in the field of target fabrication in inertial confinement fusion.

As further experiments are done with more energetic and powerful driver beams, our understanding of target designs should improve and our target fabrication tasks will change -- but they are not likely to become easier!

LIQUID DROPLET MICROSPHERE GENERATOR

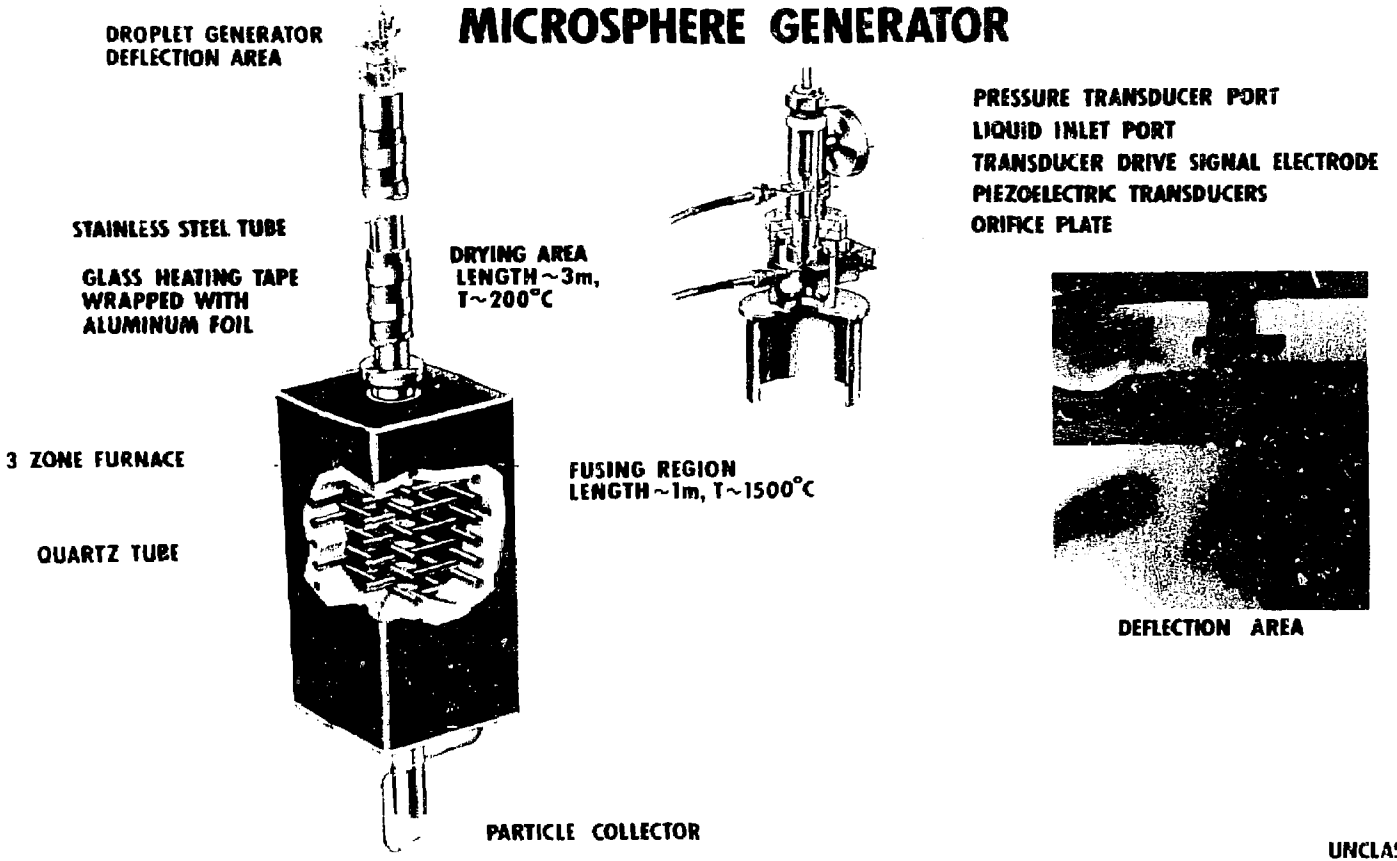

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Fig. 2

ORIGIN OF DEFECTS IN THICK $CH_{1.3}$ COATINGS

Viewed by SEM

20 μm

Viewed by Transmitted Light

100 μm

- Overall surface smoothness better than 0.3 μm
- Defect originates at a surface irregularity

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Fig. 3

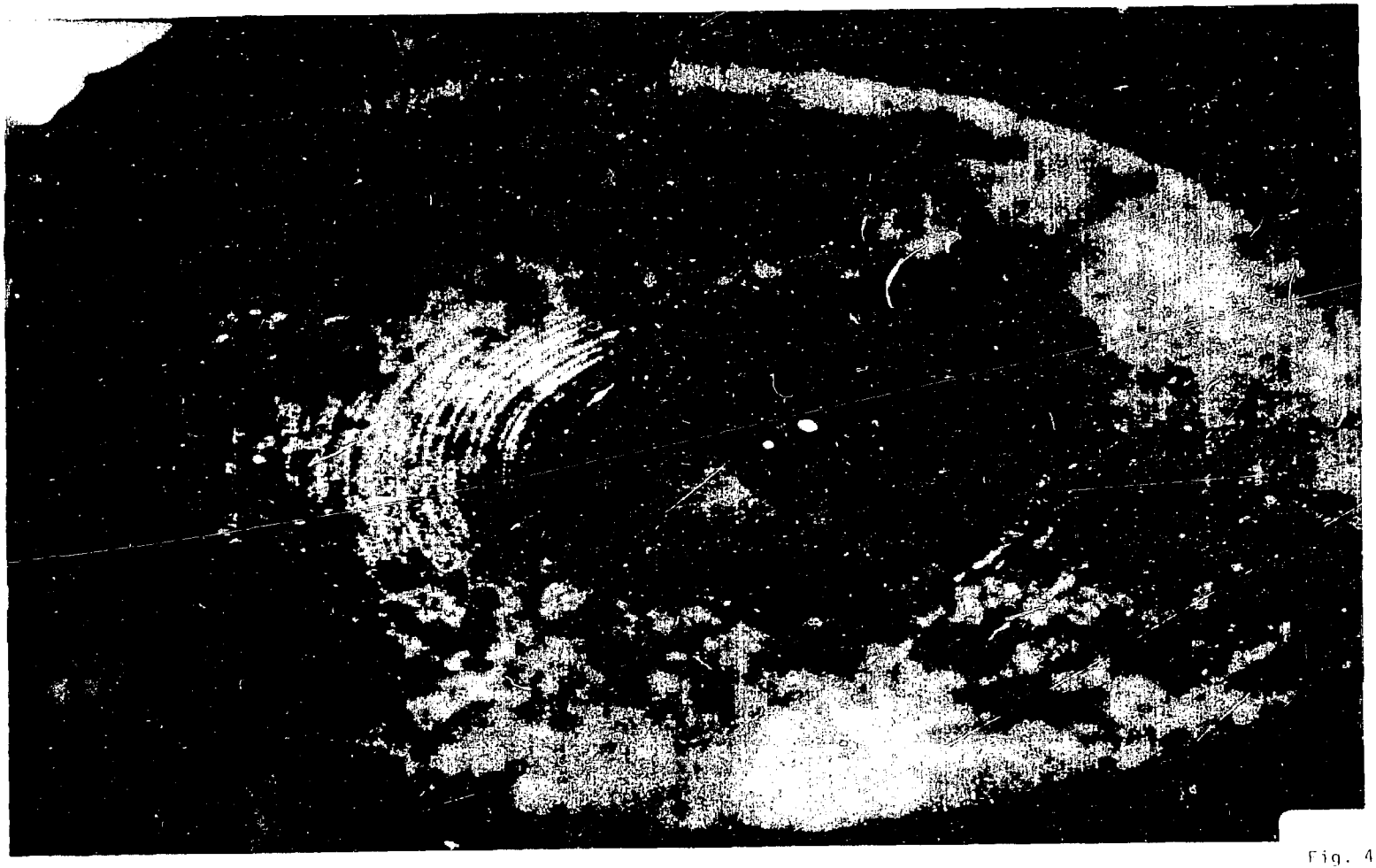

Fig. 4

DOUBLE SHELL TARGET

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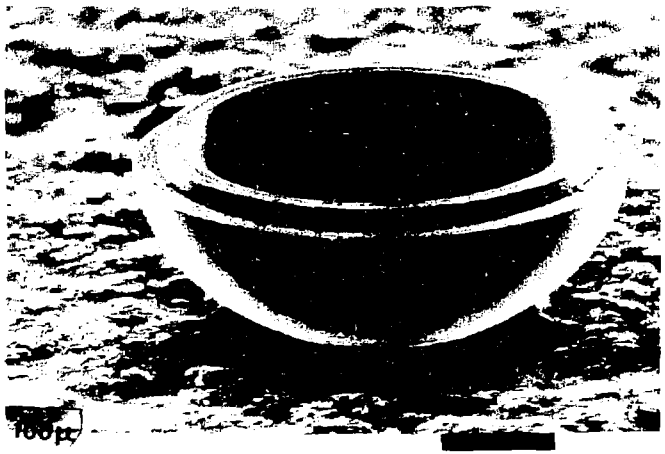
MATING POLYSTYRENE HEMISPHERES



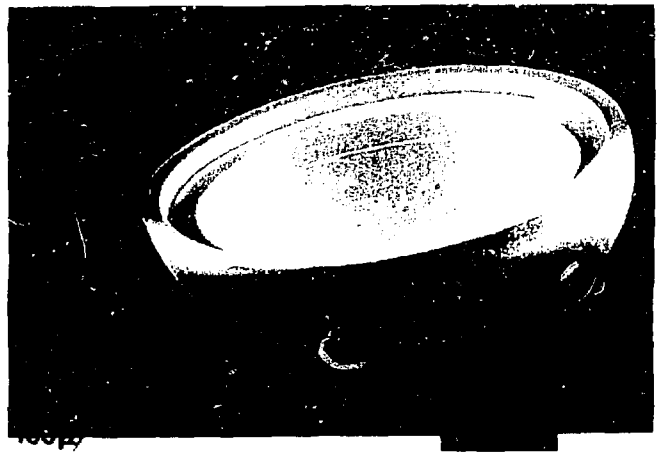


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Fig. 6

MULTILAYER CRYOGENIC REACTOR TARGET PRODUCTION

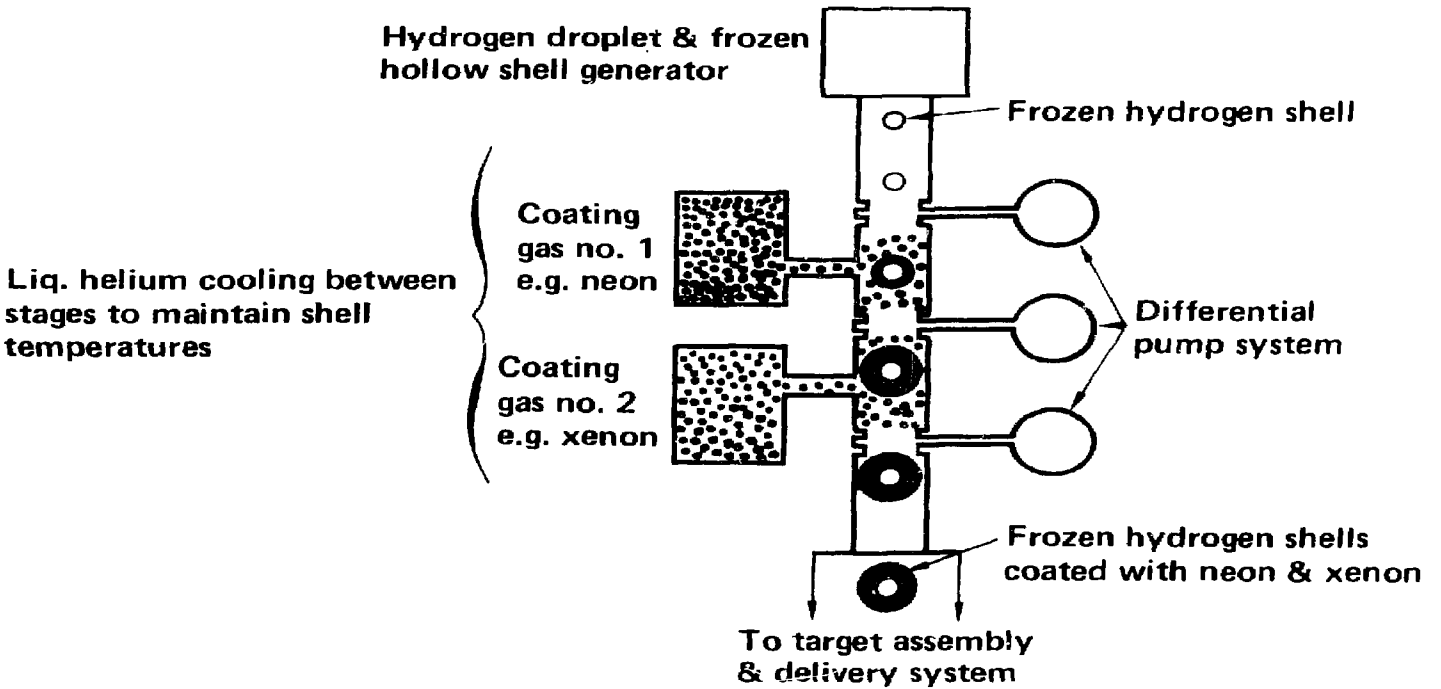

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Fig. 7