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POWER PLANT PRODUCTION OF INERTIAL CONFINEMENT FUSION TARGETS

C. D. Hendricks
W. L. Johnson

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ABSTRACT

Many of the current techniques for fabricating experimental targets appear to be directly extendable to the high-rate, low-cost production of reactor targets. This report describes several new techniques that, in conjunction with the expansion of existing techniques, can constitute a target factory. We have evaluated this concept on the basis of a generalized reactor target design and the projected specifications of reactor-grade targets.

INTRODUCTION

For the inertial confinement approach to fusion energy production to be economically feasible, we must be able to produce reactor-class targets in a completely automated system at rates of 1-10/s. This system must reliably produce a high-quality, well-controlled product.

Figure 1 illustrates the general concept of the targets under consideration. Although these targets are specific, the generalized concepts in automating the building of these targets will be useful in the production of other targets and will display one approach to the problem of a target factory.

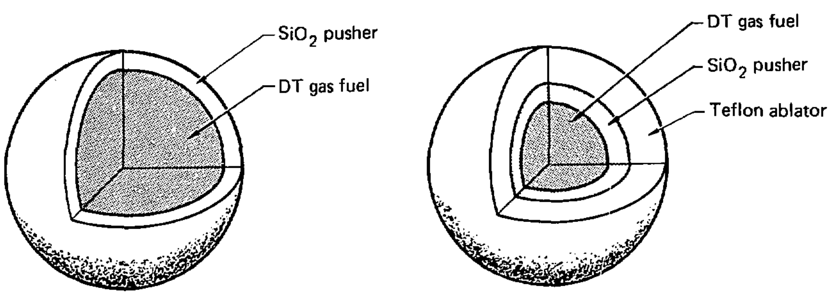
Present and near-future targets for inertial confinement fusion can be fabricated by techniques that currently exist or are in the development stage. Simple ball-on-stalk targets can be manufactured individually at a relatively large cost in manpower and time. Such targets cost several hundred dollars if they are very well characterized and made from high-quality components. The material cost of a ball is extremely small—as low as one microcent. The cost of the fuel in the glass ball is not quite as low—0.1 cent for 100 ng of tritium and a negligibly small amount for the deuterium. The material cost of the glass stem on which the ball is mounted is ~0.1 cent or less, and the cement to attach the ball to the stalk is worth $\sim 10^{-4}$ cents. Thus, we see that the cost of the material in this simple, but often-used, target is ~0.2 cent. It is obvious that the cost of such a target in a finished state is essentially the cost of the manpower to handle, select, fuel fill, measure, and assemble the parts.

As a reasonable figure for manpower cost, let us assume \$25/h. Since inertial confinement fusion is still in a research stage and every experimental target must be very well characterized on an individual basis (not statistically), several parameters must be measured to a high degree of accuracy. Table I lists some of the parameters we have examined and the limits on those parameters if a target is to be a high-quality part of the experiment.

Each hands-on operation for each of the parameters is expensive. If a target requires one man-day for parts selection, preparation, manu-

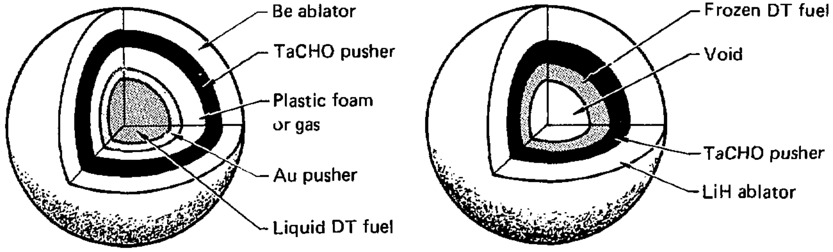
TABLE I. Summary of parameters and the degree of accuracy in their measurement.

Ball diameter	**Selected to specified diameter ± 5 μm Measured to tolerances less than 1 μm**
Wall thickness	**Selected to specified thickness ± 0.2 μm Measured to tolerances less than ± 0.05 μm**
Sphericity	**Selected to be less than 1% of diameter Measured to tolerances less than 1% of diameter**
Surface finish	**Selected to be less than 1000 A Measured to tolerances less than 100 A (contour mapped over entire surface if necessary)**
Fuel fill	**Filled to specified value ± 20% Selected and measured to ± 10% (5% if necessary)**
Stalk	**Pulled from glass tube or rod or selected from Al_2O_3 or C fibers**
Cement	**Epoxy or other suitable bonding agent**
Assembly	**Under microscope by hand or with use of micromanipulators**



(a) Thermonuclear

(b) 100X liquid density



(c) Scientific breakeven

(d) High gain

FIG. 1. Four general designs of fusion targets: (a) thermonuclear, (b) 100× liquid density, (c) scientific breakeven, and (d) high gain.

facture, characterization, and assembly, the cost is approximately $200. it is difficult to conceive of a well-characterized target that would require less than one man-day of effort. However, when the research related to inertial confinement fusion is applied to power production, the resulting targets must be produced at high rates, they must be of high quality, and the cost of their production has to be less than 50 cents if such power production is to be economical.

To approach the problems of producing targets inexpensively, we must reconsider the following aspects of the fabrication processes:

- Fuel container production (glass, plastic, or metal shells, or the fuel itself as its own container)
- Layer coating
- Surface and interface characteristics
- Fuel state
- Required production rate.

REACTOR GRADE DESIGN AND REACTOR PRODUCTION OF TARGETS

We can learn much about reactor targets by first considering elementary ones such as a solid, cryogenic sphere of DT. Solid spheres of cryogenic materials, including hydrogen, have been produced at high rates. For example, Hendricks and his colleagues at the University of Illinois[1-3] have generated hydrogen spheres at rates up to 10^5/s and diameters >200 µm. Any spheres not used as targets can be recirculated and the fuel can be reused.

Because simple solid spheres are unlikely targets, we must consider modifications. Another target that is somewhat unlikely in its simplest form is the hollow spherical shell of frozen hydrogen (DT). Such hollow shells have been experimentally produced by Hendricks' group and generated at high rates at a very low cost per target.

Such unlikely targets are stepping stones to more realistic and more complicated targets. Consider a possible multishell target composed of a frozen core of fuel (DT) surrounded by several concentric shells of various materials, including neon, argon, and hydrogen. Studies that would lead to production of such multilayer cryogenic shells have been underway for some time and have been experimentally successful. Experimental and analytical research is being conducted on similar layered structures with a central hollow shell of DT. Such targets can be formed in a sequence of steps in a column or columns containing the coating materials. Each of the coatings is in an isolated chamber at a temperature that will allow condensation to form on the previous layer.

However, the layered structures may not be totally cryogenic; only the innermost layer of DT fuel may be at a low temperature. For such a target type, we must determine whether we can still deposit coatings and layers in a production-line mode. Consider a spherical, multilayer target in which the fuel is contained inside a thin, hollow shell of glass as it is with current targets. By perfecting and optimizing current techniques of glass-shell production, such as those used by Lawrence Livermore Laboratory (LLL), KMSF, Minnesota Mining and Manufacturing (3M), etc., a high yield of target-quality shells can be produced at high rates (about 10^3/s at LLL; similar rates are assumed for the KMSF processes).

CHARACTERIZATION AND QUALITY ASSURANCE OF TARGETS

In a production system, the glass shells must be characterized as they come from a generating unit. Computer-sensed, analyzed, and controlled techniques must be used to measure the appropriate parameters and either accept or reject the shells—all at a rate of $\sim10^3$/s. Current technology in computerized image dissection and analysis and optical matrix sensor methods are capable of performing such tasks. For example, a hologram of an ideal spherical shell can be stored in computer memory in digital form. As a real shell passes through a suitable optical system, a holographic image of that shell can be produced and projected onto a matrix of sensors. The output of the sensors can then be compared with the stored image elements of the ideal shell. If the two sets agree sufficiently well, the shell is accepted and passed to the next stage of the system. If the sets do not agree, the shell is rejected. Throughout the target production process, similar techniques will be used for characterization after every step. At no point in the process can we afford to pick up manually and examine or manipulate a single target. At $25/h, one second of manpower costs 0.69 cent. One minute of effort to "look at" or "pick up" a target costs about 42 cents.

Assume the characterization is accomplished and we have 10^3 high-quality, empty, hollow shells arriving per second at some point in the production line. If they accumulate for more than one day, we would have enough spheres to sustain a one-shot-per-second power plant for one year, if every process in the production line were perfect. Because the various steps are not perfect, however, we must produce enough shells so that we can discard the unsatisfactory targets and still have sufficient targets remaining for power plant operation. The shell generation system must run almost continuously to allow for some rejection of some targets at each coating step. After $\sim10^6$ satisfactory shells have accumulated, a DT batch-fill process may be performed. The time constant for DT filling is a few hours; to ensure uniform results, a 24-h period should be satisfactory. Following the DT batch-fill process, the shells again enter the production line individually to be coated with the required layers of various material. Coating processes under development should enable us to deposit many micrometres of polymers on glass shells in a short time; in addition, coating processes used by the chemical industry can be adapted to our needs. However, coating materials, their properties, and the methods by which they can be deposited will require creative research and development before we can produce targets for a few cents, but we should be able to do so.

REACTOR RATE CONSTRAINTS ON TARGET PRODUCTION

The successful development of inertial confinement fusion for power production depends critically on the feasibility of high-rate, high-yield target production. The production rates and allowable cost-per-target increase with the power yield of the target. Target yields of 0.01, 0.1, and 1.0 t (a 1-t yield is ~4 X 10^9J) require production rates of 10.1 and 0.1/s, respectively; these rates provide economic power production in projected power plant designs with a cost-per-target of 0.01, 0.10 and 1.00 dollars, respectively. A recent conceptual design of 1200-MW laser fusion power plants identifies an operating point of 2700 MJ/l H_3 as attractive from an overall system viewpoint.[4] These estimates are based on the current assumptions of driver and target performance scaled to a power-producing target. In view of these rate and allowable-cost requirements, as well as the delicate nature of the product, this process system probably must be completely automated.

Each process will occur in a controlled environment in which several constraints can be monitored. The overall production yield of the process must exceed 95%; otherwise much of the output power would be used to drive defective targets. Also, the inventory of tritium must be low. The largest part of the inventory exists in the form of targets, and the total inventory increases proportionally with process time for a target. The absolute value of the inventory is also critically dependent on target concept and the processing step at which the fill occurs.

DESIGN FEATURES OF POWER PRODUCTION-CLASS TARGETS

Production-class targets, shown in Fig. 1, consist of multilayered concentric shells. The outside surfaces of these shells and the interfaces between the layers must be smooth enough to satisfy Rayleigh-Taylor stability requirements. At the outside surface of the target, which has a diameter of 1-10 mm, the most unstable spatial wavelength is approximately 50 μm with an allowable defect height of 100 Å. (Other wavelength defects have allowable defect heights similar to those shown in Fig. 2.) The successive layers of the target must be concentric with tolerances of 1-3 μm. In multishell targets, one or more of the layers can be voids,

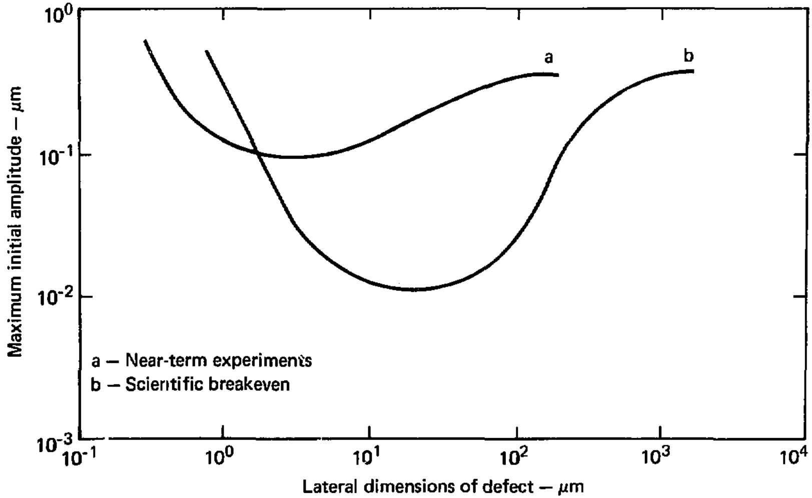


FIG. 2. Specifications for maximum defect dimension in amplitude vs lateral dimension; (a) and (b) show the shift in specification for higher-yield targets.

thus creating the need for levitation of shells. The concentricity of levitated shells is the same as for the layers, 1-3 μm.

The materials of the outermost layer are low-Z, low-density materials that perform efficiently as ablators, e.g., Be, LiH, or frozen H_2. Intermediate pusher layers are mostly low-atomic-number materials seeded with a small atomic fraction of high-Z material. The inner pusher alone may require high-atomic-number, high-density materials. The performance of these targets improves significantly with the addition of transitional layers to decrease abrupt material changes.

The pressure of total fuel fill, at room temperature, will probably exceed the material strengths of the shells. In the double-shell target, most of the fuel is contained in the region just inside the intermediate pusher. The inner fuel capsule requires a lower fuel fill and may not require a cryogenic fuel. Although fill-tube fueling techniques may be acceptable for the outer fuel region, they are much less likely to be applicable for the inner shell.

DEVELOPMENT TASKS IN TARGET FABRICATION

Several approaches can be taken to produce a target fabrication system, but the most direct one is to transport the target carefully and controllably through a series of well-characterized coating and fuel-filling processes. Such approach can be used on a wide variety of target fabrication systems, allowing them to develop from largely independent, but coupled, systems. A target can be fabricated through a series of cryogenic condensations (see Fig. 3) on a frozen DT shell to produce the layered structure, or through the use of more conventional processing steps (see Fig. 4), that parallel current

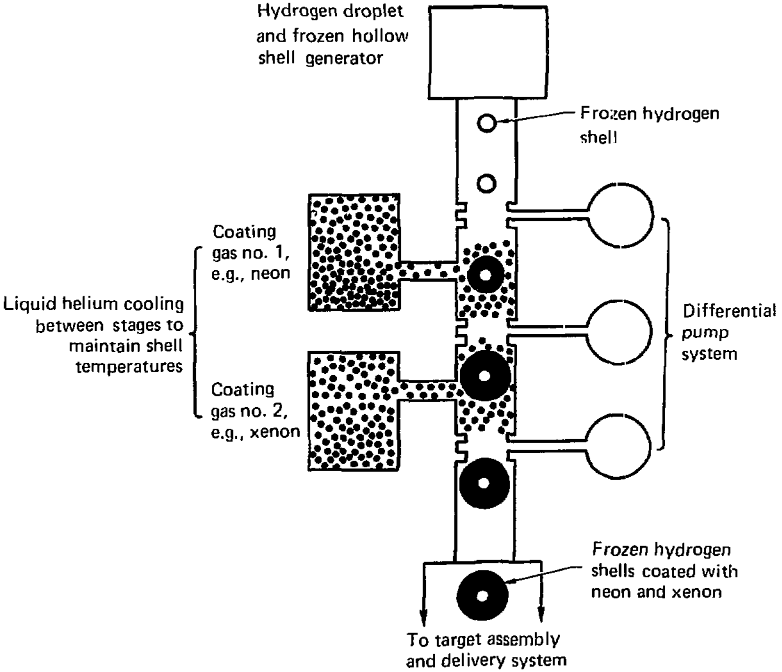


FIG. 3. Schematic of target production via a multilayer cryogenic reactor.

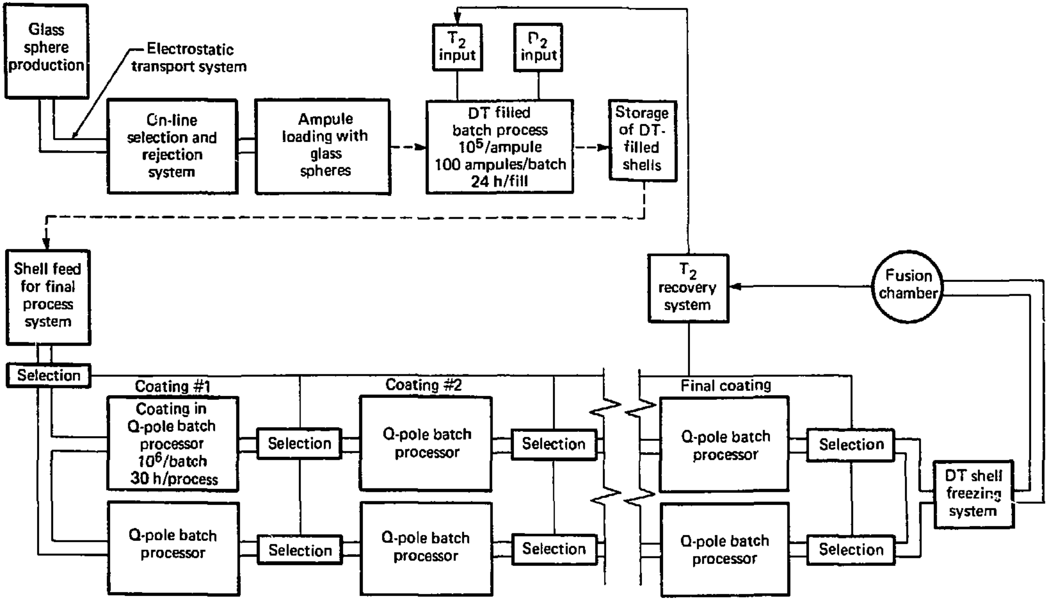


FIG. 4. Flow of processes in a target production system using inertial confinement fusion.

target fabrication. Each process must be sufficiently well developed to obviate the sorting of targets with respect to more than one or two easily detectable defects per process; that is, the yield must be high in each step. Although they are interdependent in the final system, the processing steps can be developed independently, except for the target transport and manipulation system.

The developmental tasks that must be accomplished to determine the feasibility of target production are centered in several areas discussed below.

Layered-Shell Fabrication

In a double-shell target, the inner shell is up to several hundred micrometres in diameter with a diameter-to-wall ratio of ~5:1. This shell is the inner pusher and can be made of high-atomic-number materials. It may consist of a thin mandrel, coated with the appropriate shell material. Processes currently used to generate glass shells and subsequently to coat them with polymerized fluorocarbon must be greatly refined until only a few easily detectable defects limit the yield of these processes.

In a single-shell target, the diameter of the shell must be ~1-10 mm. Shells of this size have been made of glass and plastics, but production techniques must be extended to materials of low atomic number and perhaps seeded with high-atomic-number elements. Techniques must be developed also to construct the shells with a fuel fill-tube attached, or to join a fill-tube to the separately fabricated shell on a production basis without degrading the surface finish.

Although coating of the shells preserves the surface finish, the coating process requires much development. We must further study grain-boundary growths, stoichiometry of materials, and coating conditions to ensure amorphous material deposition. We must also develop methods to adapt the atmosphere of the production coating processes to the target transport and manipulation system. If the option of coating fuel-filled shells is required, we must further develop those systems by which surfaces can be coated at cryogenic temperatures. If the condensation of layers on a cryogenic mandrel is used for target production, we must determine the nature of materials coated below the freezing point of DT (20 K).

Therefore, to produce an inner or single-shell target we must develop processes to fabricate shells of various materials within design specifications. We must also generate new techniques to coat shells and to make these coating processes compatible with the transport and manipulation systems.

Layered-Hemishell Fabrication

In double-shell targets, the outer shell may be constructed from hemishells. Micromachined mandrels that are coated in layers may have the hemishell mating edge machined before the mandrel is etched away. This fabrication method, like shell coating, requires the development of advanced coating techniques and etching methods.

DT Fill

In reactor targets the fuel must be at high density in the single shell. The filled shell must be coated to form a layered structure that meets the design constraints to avoid Rayleigh-Taylor instability during implosion.

Filling a target with fuel after much of the processing has been completed is particularly advantageous. In the double-shell target, most of the tritium is contained in the outer shells. Thus, the hemishells can be made with reasonably standard, noncryogenic techniques, so the frozen fuel can be added just before the hemishell is sealed. The amount of tritum in inventory is dependent primarily on the time the tritium spends in targets being processed. By filling targets after they are assembled, we could reduce, by as much as a factor of five, the tritium inventory needed if the fill remains with the target throughout processing.

Assembly

To produce reactor targets, methods are needed to assemble hemishells with internal concentric shells to the required high accuracy at production rates. If a fill-tube is not feasible, assembly and bonding must be accomplished at < 20 K to avoid excessively high pressures and retain the fuel. We must also find methods to support concentric shells with minimal material. Polymeric films as thin as 100 Å support spherical shells in a concentric configuration. Other support techniques, e.g., those using gas jets or electric or magnetic fields, represent the next level of development. Since small-scale defects can be allowed (a wavelength of 1-5 μm with a height of 1-5 μm) in the regime of production targets, the seam and some minor surface damage can be tolerated if relatively long wavelength tolerances (~50 μm) are met.

Characterization

The defect that is of most concern in production targets has an extremely low aspect ratio, defect height/spatial wavelength ~10^{-4}. Many of the materials suggested for these layered shells or hemishells are opaque to visible light, precluding the use of highly developed optical techniques. The lack of intense, coherent radiation sources at short wavelengths makes thickness resolutions as low as 100 Å very difficult to attain.

Assembled targets or subassemblies are difficult to characterize quickly and efficiently. The ρR-type defects in seams of hemishells and pieces damaged during assembly are particularly difficult to measure. The production processes must be developed to the point that monitoring, at most, only one or two easily detected types of defect per process step will assure quality control. Occasional (perhaps one out of a thousand) targets can be withdrawn and completely characterized for statistical monitoring of the processes.

Transport and Manipulation

The surface-finish requirement makes the transport and manipulation of the shells, hemishells, and partially or totally assembled targets difficult. Support and transport methods include electrostatic, electrodynamic, gas jet, acoustic, magnetic, and focused laser light-beam levitation. Of these, the electrostatic or electrodynamic techniques currently appear to be most useful. Other methods must be developed to ensure reliable containment and manipulation of small parts without damage.

Figure 4 is a schematic of a target factory. The glass shells are produced by means of a droplet generator that delivers droplets of glass solution into vertical furnaces. Axial airflow centers the glass solution droplets and particles in the drying and blowing sections of the heating cycle. Vertical airflow and gravity move the particles through the furnaces. These furnaces can be made in sections, so any required length can be obtained. An electrostatic transport system can be used to transport particles between furnace sections and into and through subsequent portions of the system. The electrostatic transport and control system consists of quadrupole rails, as shown in Fig. 5. Electrodes, placed in the rail, sense the particle charge and velocity, while other stations adjust the charge and velocity to the required values. Transport of systems of particles has been given attention by Masuda.[5,6]

The transport system receives the particles from the furnace section and delivers them to a series of selection units, which accept or reject the particles according to preset values of parameters such as mass, surface finish, wall characteristics, and diameter.

The selection units may be based on the electrostatic levitator.[7] Each levitator station will be able to do one specific task of processing. For example, after selection for sphericity, the concentricity of the inner and outer walls may be determined by spinning the particle in the quadrupole levitator and observing the super position of the visual-image axis on the axis of rotation. The noncoincidence of the two axes is a measure of the nonuniformity of the particle wall.

After some preselection, the glass spheres are loaded into ampules for the DT batch-filling process. The cycle time is approximately 24 h; after that, the shells may be stored for future use. The ampules for storage are then fed into the final system for coating, cooling, and firing. Throughout the entire coating process, the shells are kept separated and are not touched to prevent surface damage.

Figure 6 illustrates a proposed coating batch processor. In this unit the shells are circulated around the ring and rotated as they are being coated with the materials. Careful control of each process allows continuous variation in the materials composition rather than sharp changes at interfaces. After coating, further selection is based on the most probable defect of that process. Rejected targets from each process are recycled for tritium recovery. If a cryogenic target is required, the final process is the freezing of a uniform DT shell. This can be accomplished with the freezing-heating-freezing techniques developed by R. Woerner[8] and others.[9,10] After this process has been completed, the target is delivered and dropped into the target chamber where it is irradiated by the driver (laser, ion beam, or electron beam).

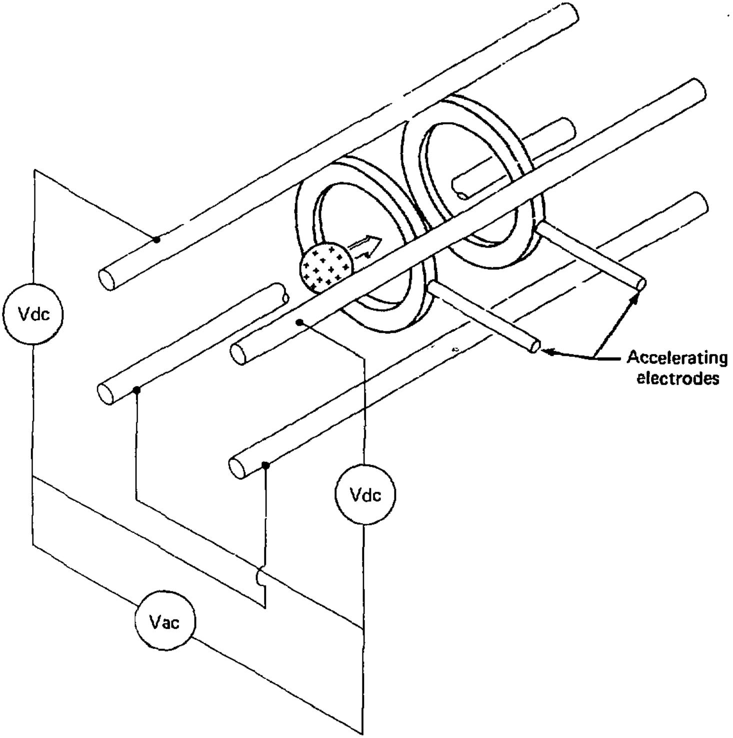


FIG. 5. Schematic of electrostatic target transport and control system used to transport particles between furnace sections.

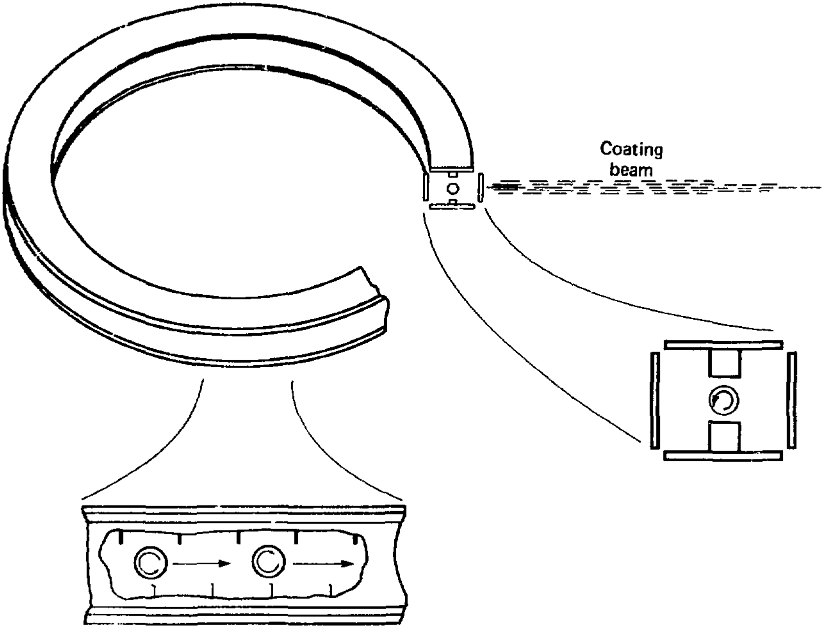


FIG. 6. Proposed electrostatic batch coating processor.

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