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Reducing the Costs of Targets for Inertial Fusion Energy

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The viability of economical target fabrication is a critical issue for the feasibility of future Inertial Fusion Energy (IFE) power plants. Current targets produced for inertial confinement fusion ignition experiments are estimated to cost about $2500 each. Design studies of cost-effective power production from IFE have found a cost requirement of about $0.25 each. While four orders of magnitude cost reduction may seem at first to be a significant challenge, there are many factors that suggest this is an achievable goal. This paper summarizes the major steps in cost reduction that will be taken to economically supply targets for IFE power plant fueling.

1. Introduction

A number of IFE power plant conceptual designs have been published over the past several decades [1,2]. IFE plants are pulsed power systems that typically will operate in the range of approximately 6 to 10 Hz. The basic requirement for the target supply system is to provide about 500,000 targets per day (at ~6 Hz) with precision geometry, and with precision cryogenic layered DT fuel. Target fabrication for inertial fusion is being investigated by a number of institutions throughout the world, including Russia [3,4], Japan [5–7], China [8,9], France [10], and the USA [11,12].

2. Target Cost Requirements for IFE

Cost requirements for an IFE power plant can be derived based on a number of assumptions including: selling price of electricity in a fusion economy, plant efficiency and availability, and fraction of income to fueling cost. The cost per target must include or provide for manufacture of the target capsules and other components (e.g., hohlraum materials), materials quality control (characterization and testing of the initial materials), filling with DT, layering (redistribution of the cryogenic fuel around the inside surface of the capsule), storage and handoff to the injection system, final quality control (characterization of the filled and layered targets), cost of money (initial capital outlay) for the Target Fabrication Facility (TFF), as well as maintenance, redundancy, and safety.

Based on the above considerations, it has been concluded [13] that a typical reactor will require targets at a total cost of about $0.25 each – delivered to the target chamber center for shots. In direct contrast to this, estimates of the average current “typical” cost per target are about $2500 each [14]. It must be emphasized that this estimate is based on the current requirements and methodologies for supplying targets to the on-going experimental programs. We maintain, and discuss below, that there are highly significant differences between current experimental target production and the eventual mass-production of targets for an IFE power plant. Given these differences, cost reductions of the four orders of magnitude required here are not only possible but clearly viable.

3. Large-Scale Cost Reduction Examples

Cost reductions of four orders of magnitude require considerable changes in production methodologies. One method that GA has used previously to reduce the costs of nuclear fuel particles[1] is fluidized bed technology. This technology is currently being explored experimentally for the production of targets [12]. Figure 1 illustrates the cost reductions obtained and projected for fuel particles compared to the reductions needed for IFE targets. Over 10^{11} fuel particles[2] were made in a production pilot-plant for the Fort St. Vrain Nuclear Generating Station in Colorado. Projected "nth-of-a-kind costs" were obtained by both actual equipment scaleup and further projections by serious commercial cost studies (dotted line in Fig. 1). Additional scaling and cost reduction examples abound in large industries such as computing and electronics — including Moore's Law — which notes that micro-processor power doubles about every 18 months. Moore's Law is an excellent example of major advances that can be made for a technologically complex product given sufficient motivation and funding.

While examples are useful to illustrate that such cost reductions are indeed feasible, the specific cost factors and the steps necessary to reduce the cost of IFE targets are discussed below.

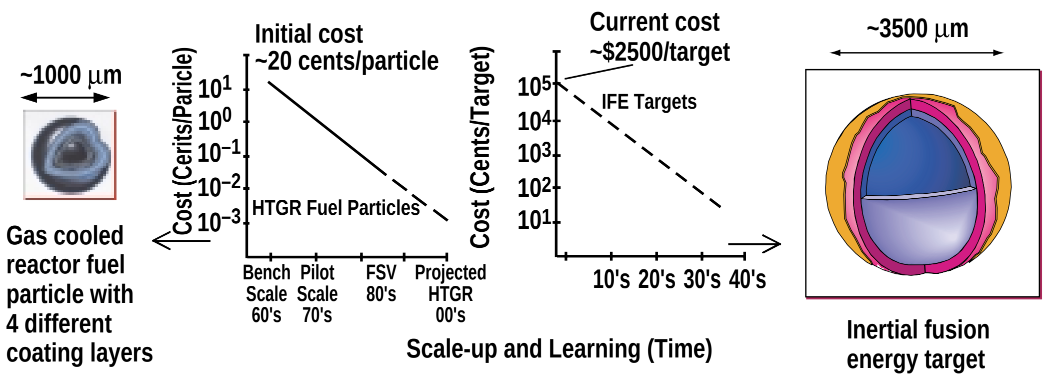

Fig. 1. The scaleup experience using fluidized beds for nuclear fuel particles is encouraging for IFE target production.

4. Current Targets Costs and Major Steps for Cost Reduction

There are tremendous differences in the criteria and requirements for current-day targets and those anticipated for high-volume manufacturing of IFE targets (Table I). Given these differences, the major steps for cost reduction for IFE targets are given below:

Eliminating First-of-a-Kind (FOAK) Costs. Currently delivered targets are nearly always unique, with most of the labor going to development and trial runs. For example, experimentalists often specify production of a systematic series of targets, with varying layer thicknesses, dopant and dopant concentrations, and total target size. At times, trial runs are necessary to provide samples meeting the experimenter's requirements. Sometimes, even new methodologies must be developed and demonstrated to provide the requested samples. In fact, current day production essentially never manufactures more than one batch of any single target design. We estimate the average FOAK development

[1]Ceramic fuel particles have many similarities to the IFE targets. Fuel particles have multiple precision spherical layers of high and low density and require nuclear-level quality control. The precision for IFE target is estimated to be ~10 times greater than for fuel particles.

[2]This is a large quantity even by IFE power plant standards. If these fuel particles were targets they would supply a 1000 MW(e) power plant for more than 500 years!

Table I. Significant differences exist between the requirements for experimental target manufcturing (current day) and projected mass-production of IFE targets.

Item	Experimental Program	IFE Program
Production Rate	Relatively small (several thousand targets per year by GA)	500,000 per day
FOAK Costs	Very high – targets always vary	Essentially none
Characterization	Extensive – individual details needed	Statistical sampling
Product Yield	Low – product varies, small amounts needed	High
Batch Sizes	Small – small amounts needed (<100)	Large

cost now as hundreds of hours per batch of new targets. In contrast to this, the FOAK cost for IFE production will be almost non-existent (some small on-going process improvement cost can always be expected).

Reduction in Characterization Costs. Current experimental targets are supplied with what may be referred to as an individual "pedigree" (many pages of detailed characterization data that goes along with an individual target). While this data may be essential in understanding the detailed diagnostic results from an experiment, it is clearly something that will not be part of routine IFE target production. Instead, statistical process control will be employed based on a defined sampling plan. And, likely, rapid "quick-check" methods will be employed to ensure the validity of each target prior to injection. We estimate that the current pedigree, on average, also requires nearly ten hours per target. Between elimination of FOAK costs and elimination of the pedigree, we estimate cost reductions of about two orders of magnitude are readily achievable. This leaves only a factor of about 100 that requires true technical advances (discussed below).

Increasing Yields. Consistent with the constantly changing specifications for experimental targets discussed above, current yields are quite low. The best targets are often hand-picked to provide the optimum product for an experiment. Overall, average yields are estimated in the range of about 1% to 5% (this also reflects the fact that batches are fabricated and only a few samples may actually be selected, characterized, and delivered ready for use in an experiment). The goal of the IFE target fabrication programs must be to provide sufficient development to achieve product yields in the vicinity of 95% or greater. This increase in yield is a quantitative criteria to define the development program.

Batch Size Increases. Similar to increases in yield, a requirement for the target technology development program is to provide processes that can operate at large batch sizes (or continuous processes) with minimal labor. Between increased yields and batch size increases, two orders of magnitude cost reductions are clearly within the grasp of significant development programs.

5. Summary

The major steps for significant cost reductions of IFE targets are given. About two orders of magnitude cost reduction can be readily achieved by fixing the target requirements and adopting statistical sampling plans. An additional two orders of magnitude will require a significant target production development program. Adoption of industrial technologies and other mass-production techniques will make the economical production of IFE targets a reality.

Acknowledgment

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