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SPACE PROCESSING - A PROJECTION

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This paper contains estimates concerning space manufacturing, which might well become the largest and most specific application of space technology by the end of the century. It does not say, however, that these projections will happen, only that they can happen if nurtured and developed. The plan for nurturing and developing space manufacturing is very preliminary, although more detailed plans for some small-scale research and development activities have been drafted.

Recent analysis [1] of various ideas for space manufacturing indicates technical benefits which may result from preparing many materials and products in space. All of these ideas merit further exploration. At this time, however, two classes of materials do appear to satisfy the technical and economic constraints that must be considered before actual space manufacturing can be seriously contemplated. These two classes of materials and some products are:

1. Electronic crystals
   a. Float-zone-refined semiconductors
   b. Solution-grown crystals,

2. Biologicals
   a. Vaccines for human usage
   b. Cells for human usage
   c. Viral insecticides and pesticides.

We estimate that some 30-50 Space Shuttle payloads might be generated from these product areas by the end of the century. The total value of a payload with this type of product could range from \$10 million to \$1.5 billion. However, some of this value would be attributed to ground-based pre- and postflight operations. More detailed estimates are shown in Table 1. In addition, several more payloads may be required to provide logistic support as well as the several research and development (R&D) payloads that will be needed before actual manufacturing can proceed.

Each of these products is briefly described and the production calculation outlined in the following pages. Many details might refine the calculations and even greatly change the products or quantities, but we strongly feel that other products in other quantities will replace them. We firmly believe this because the basis for space manufacturing ideas is using the zero gravity, which is available only in space. As long as we have gravity, we will have some of its detrimental effects when we process materials on earth. So the basic idea of space manufacturing is both simple and elegant, but much R&D will be needed to prove the ideas and to plan the experiments and missions in detail.

Electronic Crystals

Float-Zone-Refined (FZR) Semiconductors

Small boules of silicon (1.5-2 in. diam). Present applications for float-zone-refined silicon range from integrated circuits to rectifiers, diodes, and similar electronic devices. Space processing of this material would primarily be warranted for the economies of making larger diameter boules and/ or wafers from them. Such boules or wafers might be diced into smaller pieces and more efficiently handled in manufacturing other items. Devices based on this single-crystal silicon are now valued at \$1.3 billion in the U.S. and \$2 billion worldwide, with a predicted increase to \$2 and \$3 billion respectively by 1980 [2]. Additional processing in space (if warranted technically and economically, such as by wire or ribbon drawing [3] or by using the space vacuum in vapor depositing films) would shift some of this potential market toward the space transportation business. Current production is about 28 tons per year in the U.S. and 45 tons total worldwide. This material is valued at about \$450 per pound or \$40 million worldwide.

Large Silicon Boules and Wafers (4-8 in. diam)

Float-zone-refining in space is the only apparent way to make large boules and wafers of high quality [4].

If these sizes were available, it would be more feasible to consider solid state control and direct current power transmission, enabling underground installation in densely populated areas, overhead installation from remote generating facilities, and as interties among systems. Since solid state rectifiers and other distribution and conversion equipment are highly reliable and more easily serviced, such equipment could easily boom into a tremendous market that would quite clearly depend upon large-diameter silicon.

A Federal Power Commission engineer [5] has reported estimates that in the U.S. alone, within two decades, there will be about 350 new generating plants needed to produce another million megawatts of electrical energy. This will require about 400 000 miles of high voltage transmission lines. These additional transmission lines are expected to require up to 4 million acres of land for right-of-way, beyond our present usage of 4 million acres. While these right-of-way acres potentially are also usable for industrial or commercial purposes, they are presently inefficiently used for these secondary purposes. In any case, the overhead right-of-way in densely populated areas is rapidly becoming so expensive that more cable is likely to go underground for the last 20-40 miles into a city [6]. Although this move to underground power cables generally costs about five times as much as overhead lines, applying cryogenic (low temperature) technology or perhaps even superconductor (ultralow temperature) technology may overcome this cost disadvantage. Such cables might require the purity and perfection that zone refining and space processing can probably provide; however, this is not sufficiently certain to warrant inclusion in this forecast. Therefore, only the related distribution equipment is included.

This expected trend toward High Voltage Direct Current (HVDC) [7] energy transmission and the related use of solid state conversion and distribution equipment would require many tons of semiconductors, such as silicon. Assuming that only half of the new distribution network were operated on direct current, but that a large number of substations and customized power conditioning equipment would also need solid state equipment, it is estimated that semiconductor requirements could total 200 to 400 tons per year for these applications. We have used the lower figure in our estimates.

Near zero gravity processing in space might achieve a potential refinement of these estimates, because of a process improvement of great significance to the semiconductor, as well as to some related fields. This would be the drawing of wires and controlled-thickness ribbons directly from the melt. Although extensively studied, this operation is not possible on earth in the case of materials having sharp melting points [3]. If this then were accomplished in space, it could markedly increase the yield of silicon from boules into devices, thereby reducing the total requirements. It could also permit preparing the FZR boules here on earth, and only require space processing for the ribbon drawing. This would not change the weight of material to process, but would probably simplify the space processing operations.

Other Single-Crystal Electronic Materials [8]. Although silicon and germanium account for nearly 90 percent of the electronic single-crystal materials production, several other materials are used in single-crystal form in electronic devices and have an even higher value per pound than silicon. Such materials currently average $5000-10 000 per pound. They could account for about 5 tons now, and could increase to 10 tons by 1980, if one extrapolates the present rate of growth. However, the "technical action" for new electronic materials is in this field. It is therefore quite possible that the field could grow to the point of equaling the present production of float-zone-refined silicon or about 50 tons per year of materials. This would then lead to a potential of $80-100 million.

Biologicals

Many feel that higher purity biologicals are generally desirable and urgently required in some specific cases [9, 10, 11]. The higher purity is required to reduce undesirable side effects and to permit applying stronger, more effective doses [9]. This had been demonstrated here on earth in the case of the Hong Kong flu vaccine [12], but it appears possible to further improve this product significantly through space processing.

Basically, the idea of space processing the three classes of biological products discussed in this section would be to purify them primarily by fluid electrophoresis. This process is nearly unusable for large-scale preparative work here on earth because of convection and sedimentation problems. On a very small scale as an analytical technique, however, it is unsurpassed and is, therefore, widely used. We have concentrated on this process, although space processing of biologicals may also require some related processes, such as freeze drying, to preserve the purified products.

Viral Insecticides [13]. Viral insecticides may replace persistent chemical insecticides (e.g., DDT), during the next decade or two, for protecting forests and agricultural crops because the viral material offers specificity without side effects. This is particularly true for certain highly destructive insects, such as the tussock moth, eastern tent caterpillar, European pine sawfly, and the cotton bollworm (alias corn ear worm or tomato worm). Each of these insects does $50-100 million damage per year in the U.S. alone, in spite of the widespread use of chemical insecticides. Recent reductions in the use of chemical pesticides, such as DDT, have been accompanied by alarming increases in destructive insect populations. In the currently available form, the viral insecticides cost about $45 000-50 000 per pound. About 1 ton of virus for each of the above insects would be required per year in the U.S.; about four times that amount worldwide. The annual market would, therefore, be about $500 million in the U.S. and $2 billion worldwide. It is assumed that the FDA and counterpart organizations in other countries would not sanction widespread use of the present relatively crude or impure material, which is contaminated with bacteria. Current preparation methods depend upon various purification processes, including centrifugation, but large-scale preparative electrophoresis may be the only way of isolating some of these viruses in an ultrapure state and with a high degree of viability [9]. Preparative electrophoresis on earth is, of course, severely hampered by convection and sedimentation. Electrophoretic purification of the world's supply of five viral insecticides would require the use of about 150 tons of supplies (principally electrolyte) per year.

Vaccines. While we cannot predict exactly which vaccines will be in widespread use 10 to 20 years from now, we generally can predict what the total usage of vaccines in the U.S. and worldwide may be. Present U.S. consumption of the 10 most common vaccines amounts to about 60 million doses per year [10].

If we accept the World Health Organization's prediction of a world population, in 1990, of 5 billion people, and a public health level equivalent to the present-day U.S., world consumption of these vaccines should be 1.5 billion doses per year.

Normally, 1 g of active ingredient contains enough vaccine for 100 000 people, although it is administered in more dilute form. Therefore, processing any one (typical) vaccine in space will require transporting about 10 000 grams of active ingredients per year (22 lb per year) [10]. Using the same assumptions about electrophoretic purification as are used elsewhere, this corresponds to 4400 lb of water per year per vaccine purified. Vaccine production rules and regulations, however, would probably require a dedicated module for each vaccine [11]. Therefore, in effect we will have 10 loads per year if we assume the preparation of a year's supply of each of 10 vaccines. This may permit the use of excess weight capacity for carrying some inert payload, or perhaps an arrangement could be made to carry several compatible vaccine production units at the same time, but only one could operate at a time.

Cells and Other Biologicals. Many biologicals are separated and analyzed by electrophoresis. However, very few preparative operations are performed. It is quite clear, however, that it would be desirable to conduct preparative electrophoresis, especially of the cells and of products larger than can even be analyzed now in gels or on paper [14]. The current research on cells in connection with cancer research [15], for example, would suggest the future need for a considerable quantity of blood separation work. This has been roughly estimated at 10 Shuttle loads per year at about the end of the century.

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