

**SPACE
DIVISION**

ECONOMIC ANALYSIS OF CRYSTAL GROWTH IN SPACE

D. R. Ulrich, A. M. Chung, C. S. Yan and
L. R. McCreight

Final Report

July 1972

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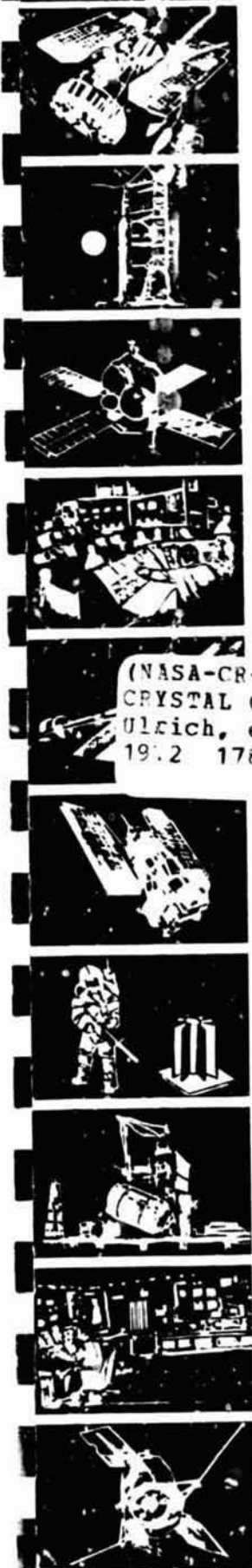
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Prepared for the
National Aeronautics and Space Administration
Marshall Space Flight Center
Huntsville, Alabama 35812

Prepared by
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GENERAL  ELECTRIC



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FOREWORD

This report was prepared by a team of Drexel University and General Electric Space Sciences Laboratory staff personnel. In general, the economics aspects were provided by Drs. Chung and Yan of Drexel University and the electronic materials and applications aspects by Space Sciences Laboratory personnel. The authors are respectively:

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CONCLUSIONS

1. The newer and more sophisticated compound single crystals, i.e. ceramic oxides and compound semiconductors, which now comprise about 20% of the electronic single crystal market, are the basis for many of the emerging and advanced electronic technologies and devices of the 1980's.
2. There is strong economic and technical justification for pursuing the preparation of these electronic crystals with maximum perfection, purity, and size to achieve high performance components and devices. Space processing appears to be the best way to achieve this, especially as the Space Shuttle with the expected lower transportation costs becomes available in the 1980's.
3. No economic or technical justification was found for the growth of silicon single crystals for solid state electronic devices in space. Silicon, which constitutes about 60-70% of the electronic single crystal market, already enjoys volume demand and commodity prices.

An exception may be the growth of very large area wafers of silicon for large power distribution devices by float zone refining; however, the costs will be high primarily due to the large power supply required.

4. Synthetic quartz, grown by a hydrothermal process, constitutes the remaining share of the electronic single crystal market. In addition to the fact that the growth process depends upon gravity induced convection, the low price and commodity nature of quartz and the massive processing equipment all mitigate against considering space processing for preparing quartz.

5. Magnetic bubble memories, which operate on rare earth iron garnet and rare earth garnet crystals, are expected to provide the single greatest demand for high quality single crystals by 1980. Electro-optic crystals will provide the second area of greatest demand. These consist of several unique compositions such as lithium niobate, lithium tantalate, bismuth germanate, lead germanate, bismuth titanate, gadolinium molybdate, lithium iodate and triglycine sulfate, which will be the basis for several advanced applications by 1980. The emerging technologies include optical storage media and page composers for holographic memories, light modulators for optical communication systems, pyroelectric detectors and thermal imaging systems for medical diagnostics, pollution monitoring and earth resources surveying, surface wave acoustic delay lines for navigation systems and radar, and electronic filters for the communications

industry. The third source of demand will be optoelectric crystals such as gallium phosphide and yttria aluminum garnet for light-emitting diode displays and high power crystalline lasers, respectively.

6. The demand, estimated cost savings, and anticipated improved yields of space processing economically justifies the planning and funding of research and development programs in preparation for the growth and processing of garnet crystals for magnetic bubble memories in space by the late 1970's or early 1980's. The anticipated expanded use, reduction in cost, and additional savings through the production in space of high-priced electro-optic crystals also economically justifies the planning and research for the processing of these crystals in space by 1980. In addition, the YAG crystals and gallium phosphide type of semiconducting crystals are of interest, although the latter crystals involve some high pressure equipment that will effect the economics.

RECOMMENDATIONS

1. Planning and research should be started as soon as possible for the processing of garnet and electro-optic crystals in space by 1980.
2. Planning and research for the growth of crystals in space should be supported in the encompassing areas of equipment, processes, compositions and characterization.
3. Process work should be directed toward growth from solution or the melt. The identified crystals which will potentially show improved yields and perfection and/or size are grown by techniques involving fluids or liquids; these include flux growth, Czochralski melt growth, aqueous solution growth and liquid phase epitaxy from fluxed melts. In addition, process work should include efforts to grow crystals in desired forms such as films which may be more feasible in space.
4. Research should initially be directed toward the compositions cited in this report; however, a survey for the reporting and discovery of new crystals of the compound oxide type should be periodically conducted and up-dated. It can be predicted with a high confidence level that any new crystal whose growth will benefit from space processing will be grown with a solution or melt technique. Conversely, the survey should also be directed toward the reporting of new applications which are dependent for operation on the aforementioned types of crystals.

5. Characterization research should be conducted and directed toward the determination of gravity dependent obstacles to growth and gravity controlled properties in specific crystals.
6. Potentially, large flawless optical quality crystals can be grown under micro-gravity conditions with natural flat perfect surfaces.
7. While the recently implemented plans for the Space Transportation System should provide markedly reduced costs for transportation, a parallel effort on space equipment, facilities and operations has great potential for reducing the costs and improving the efficiency of this part of the system. In particular, attention to space power and the operational aspects of crystal growing in space would offer great payoffs. In the latter area, emphasis on improving yields, including the growth of crystals into more optimum shapes, and the reuse of materials is recommended.
8. Some early space experiments are recommended to establish the technical validity of the expectations for improved crystals being obtainable in space.
9. Economic data on both the crystal industry and products in which they are used should be continually collected and assessed as a base for further projection. A diligent monitoring of relevant technical and economic developments is recommended.

SUMMARY

Background

The eventual processing of materials in space is likely to become the major economic exploitation of space technology. It holds great potential for technologically benefiting the preparation under microgravity conditions of numerous products through improvements in size, shape, purity or perfection, and the resulting properties. These are expected to markedly benefit man's material well being.

As contrasted to space exploration which also benefits man through mental stimulation, but for which the value is difficult to quantify, space processing will be expected to produce economically viable results. Thus the products must be of sufficient value as to warrant the extra costs of space transportation and processing compared to terrestrial processing. While it will be desirable to identify products which can uniquely and only be obtained under the microgravity of space, there seems to be few pure examples of this. Instead it appears that the removal of sedimentation and convection effects, for example, may markedly improve some products to the degree that they will be worth more to the users than it costs to provide them.

Numerous technologically sound ideas for materials science and manufacturing in space have been suggested over the past several years. It is timely however to project the costs and value of some of these ideas as a means of providing information on which to base research and development

programs in this field. The scarcity of space flights in the decade of the 70's prior to the availability of the space shuttle makes this approach desirable as a planning tool.

Among the ideas advanced for space processing consideration, the growth of electronic single crystals stands out for several reasons. Among them are that: the products are basic to several advanced technologies; they have high value, and they are likely to be used in quantities which can be met by the capacity of the space shuttle system.

The electronic single crystal field can be described in terms of two different product areas. First, there are the semiconductors which comprise 60-70% of the products and amount to some 28 tons primarily of silicon per year in the U.S. They are prepared by several processes but the one that gives the best results in terms of purity, perfection, and properties is Float Zone Refining (FZR). It is a process which is very distinctly affected by gravity that generally constrains the size of product boules to the 2-3" diameter range. This is sufficient for many uses but there are some potential future uses for which one might like to have up to 6-8" diameters available. These would be for preparing wafers for use in large D.C. power conditioning and handling devices, and for solar cells, for example, as well as for substrates in the preparation of integrated circuits.

The second product area is a very heterogeneous group of compound single crystals which comprise about 20% of the total field. They are the primary basis of many new products and consequently have high potential interest for the future. In general they are oxidic compositions grown from the melt or solution which implies imperfections due to gravity induced sedimentation and convection.

Finally, there is a related product area which is the hydrothermal preparation of quartz single crystals. These crystals and this process appears to be relatively unique but does not fit the space processing field except by analogy. The low value of the product (about \$20/lb.), the high weight of the thick walled pressure vessels used to grow quartz crystals, and the need for convection in the process all mitigate against considering it for space processing. In addition, the natural quartz crystals at \$3 per pound are an effective alternate or competitor to the synthetic crystals. They are often of higher perfection in certain respects but provide a lower yield of usable material which accounts for the large difference in price per pound. This process for growing quartz crystals is however apparently not applicable in general to the second product area in the single crystal field. Nevertheless, it was studied in this program as an analogy to the preparation of other crystals by solvent processes.

Study Approach

Starting from the above background, the study aimed at identifying the most likely technological area of crystal growth to be improved by production in space. The approach involved visits and discussions with experts as well as extensive examination of the literature in essentially a binary approach to the problem. On the one hand the technical aspects were examined with a view to identifying the valuable crystal compositions, processes to grow them, products which might use them, and some projections of the benefits to be expected by space processing. In parallel the economics of the crystal industry and of the user industries were examined by econometricians. These two approaches were then coupled into some properties of future space processing facilities.

Results - General

The study indicates that the compound type crystals for these emerging advanced technology products are the most likely to warrant space processing. These are generally the oxidic compound type crystals grown from melts or solutions. In general they are expected to be both benefitted technically by the minimization of gravity induced effects and to be of sufficient economic value as to warrant the costs of space processing.

The current R&D level of processing of these crystals often yields only a few per cent of usable material with a consequent high cost. For example, 25% yield and prices up to \$15,000/lb. are not uncommon. It is expected that both of these values will change markedly as production quantities are prepared.

This study contemplates therefore that prices may eventually drop by a factor of 5 or more to the \$1000-3000/lb. range while yields will approximately double.

Meanwhile, the more mature semiconductor industry from which float zone refined silicon is the principal product of interest to this study does not as clearly warrant space processing at the current diameter and price of silicon for use in integrated circuits. If large diameter wafers for D. C. power distribution equipment and solar cells require the purity and perfection of float zone refining and the value in these applications is high enough, this would be an excellent and perhaps unique product for space processing.

Results- Detailed Technical

The technical assessment indicates that there are six areas of advanced applications where systems performance is directly dependent on the quality of the ceramic oxide and non-silicon semiconducting compound electronic crystals used. These are computer memories, optical communications, optoelectronics, pyroelectric detection, surface acoustics and ultrasonics. Space processing has the potential of providing crystals with the required perfection, size and surface smoothness at high yields in production quantities to enable systems in each of the aforementioned areas to come close to their performance figures of merit.

Magnetic bubble memories, which operate on rare earth iron garnet crystals, is expected to provide the greatest demand for high quality single crystals. By the end of the decade they will fill the critical gap that exists between electronically and electromechanically addressable storage. They will complement semiconductor silicon crystal memories in computer structures since the former is used in the fast memory section and the latter for large storage in the bulk memory section.

The next highest demand appears to be for high quality electrooptic crystals such as lithium niobate, lithium tantalate, barium sodium niobate, bismuth germanate, lead germanate, bismuth titanate, gadolinium molybdate lithium iodate and triglycine sulfate. There are a wide range of compositions to process here since electrooptic phenomena are used across the total range of the cited applications. The crystals are used as optical storage media and page composers in holographic memories, light modulators in optical communication systems, pyroelectric detectors in infrared thermal imaging systems, surface wave acoustic delay lines in radar, navigation and communication systems, and ultrasonic filters in the communications industry. The third highest demand will be for optoelectronic crystals such as gallium phosphide and yttria aluminum garnet for light-emitting diode displays and high power crystalline lasers, respectively.

The holographic memories are destined to displace magnetic recording surface media and become the mass storage memories of the 1980's. Optical communications systems are in the research stages and will become the inter- and intra city systems for large volumes of traffic in the 1980's. Pyroelectric detection is becoming the standard infrared sensor for thermal imaging systems in medical diagnostics, pollution monitoring and earth resources surveying.

Surface acoustics is a very advanced technology whose exploratory research is opening the doors to hitherto unconceived applications. Quartz crystals no longer meet the rigid bandwidth and frequency requirements for new ultrasonic applications. Thus more sophisticated crystals are being identified and prepared for use in these applications.

These systems will benefit from the large, flawless optical quality crystals which potentially can be grown with natural, flat, perfect surfaces in space.

The results of the detailed technical assessment of electronic crystals and the market forecast for each application are summarized in Table 1. Crystals which have been identified as candidates for use in each and the terrestrial growth problems are listed. The benefits of space processing and the projected improvement in space grown versus terrestrial grown crystals are tabulated.

SUMMARY
TABLE 1
TECHNICAL ASSESSMENT AND MARKET FORECAST FOR ELECTRONIC SINGLE CRYSTALS AND PROJECTED IMPROVEMENTS BY SPACE PROCESSING

Application	Market Forecast	Type	Crystals Candidates	Terrestrial Growth Problems	Space Benefits		
					Crystal Perfection	Performance	Projected Improvement
Computer Memories Magnetic Bubbles	Magnetic bubbles by 1980 will fill intermediate gap in computer hierarchy. Bulk storage - high density storage.	Magnetic	Rare earth iron garnets	Gravity-induced convection. Growth Uncontrollable bubble size. Low yields.	Yes	Yes	Crystal perfection - Eliminate growth striations and thus control bubble size. High yield in production quantities.
Holographic Storage Media	By late 1970's, will replace magnetic surface recording. Mass storage.	Electro-optic	Lithium niobate Barium sodium niobate	Gravity-induced convection Compositional nonuniformity. Hologram distortion.	Yes	Yes	Crystal perfection - compositional uniformity. Optical quality - Eliminate hologram distortion.
Page Composer		Electro-optic	Bismuth titanate	Cutting and polishing causes surface defects and cracking.	Yes	Yes	Surface perfection - eliminate cutting and polishing through plate growth. Grow flat, natural surfaces. Reduces cost.
Surface Wave Delay Lines	Low Potential	Piezo-electric	Gadolinium molybdate Bismuth Germanate. Lithium Niobate	Gravity induced convection Strains causes switching fatigue.	Yes	Yes	Crystal perfection - eliminate strains. Permits indefinite switching with no fatigue.
Beam Addressable	Low Potential	Magneto-optic	Gadolinium iron garnet	Surface perfection - Ground ring causes wave distortions	Yes (?)	No	Surface perfection - grow platelet crystals. Flat, natural surfaces.
Optoelectronics LED's	By late 1970's dominant position for visual and alphanumeric displays. Competition is liquid crystals.	Semi-conducting	Gallium phosphide	Film crystal perfection. High defect density. Critical motion and system redesign problems.	Yes (?)	No	Crystal perfection - reduce defect density.
				Crystal perfection - Yes defect density high. Small size-gravity (convection) causes low growth rate.	Yes	Yes	Increase size - large area crystals for monolithic rather than individual displays. High growth rates. Crystal perfection - low defect density for increased efficiency.

Surface Wave Delay Lines	Low Potential	Piezoelectric	Bismuth Germanate, Lithium Niobate	Surface perfection-Yes (✓) No	Surface perfection - grow platelet crystals. Flat, natural surfaces.
Beam Addressable	Low Potential	Magneto-optic	Gadolinium iron garnet	Yes (✓) No	Crystal perfection - reduce defect density.
<u>Optoelectronics</u>	By late 1970's dominant position for visual and alphanumeric displays. Competition is liquid crystals.	Semi-conducting	Gallium phosphide	Yes Yes Yes	Increase size - large area crystals for monolithic rather than individual displays. High growth rates. Crystal perfection - low defect density for increased efficiency.
<u>LED's</u>					
<u>Laser</u>	Continuous demand in all sections for optical and high power sources.	Magnetic	Yttria aluminum garnet	Yes Yes Yes	Long crystals. Rod shapes. Crystal perfection. Production quantities.
<u>Optical Communications</u>	In research stage. In early 1970's, will become large capacity systems for inter-city systems. International demand.	Electro-optic	Lead germanate, Lithium iodate, Lithium niobate.	Yes Yes Yes	Crystal perfection - grow optical quality crystals. Large size.
<u>Pyroelectric Detectors</u>	Will attain dominant position in thermal imaging systems. Excellent potential for high value crystals. However, low volume demand.	Ferroelectric	Triglycine sulfate	Yes Yes Yes	Surface perfection - grow thin, flat plates. Surface imperfections and cracks. Increased cost.
<u>Acoustic Surface Waves</u>	New technology. Exploratory research finding many applications. Navigation, radar, communications. Advantage of matching microwave with semiconductor technology.	Piezoelectric	Bismuth germanate, Lithium niobate, Lithium tantalate, Aluminum nitride, Spinel	Yes Yes Yes	Surface perfection - grow flat, smooth natural surfaces. Rounded edges (waves travel around curves)
<u>Ultrasonic</u>	Good potential in communication industry. Quartz frequency bandwidth limited. Potential in high frequency filters.	Piezoelectric	Lithium tantalate	Yes Yes Yes	Surface perfection - grow large platelets with flat natural surfaces. Continuously drawn ribbon.

Economic Analysis - Approach for Supply and Demand

In analyzing the economic feasibility of space processing versus earth processing, the supply and demand for terrestrially grown crystals has to first be considered. The demand for ceramic oxide and non-silicon single crystals is derived indirectly from the demand for their end products. Of the six applications identified during technical assessment, computer memories are potentially by far the most important end-product of the high valued crystals. Therefore, the analysis was focused on the demand for crystals derived from the demand for computer memories (demand from computer hardware) and the market share of various technologies.

In determining the demand for computer hardware, the lack of data on computers purchased by industry prevented the construction of a micro-model encompassing such variables as sales, growth in sales, profit and interest rate. As an alternative, macro-variables such as Gross National Product (GNP), Net National Product (NNP), growth in Gross National Product (Δ GNP) profit and sales of the private sector were related to the aggregate computer shipment. Computer hardware shipment was found to be closely correlated to NNP and GNP but not to growth in GNP. The acceleration principle and cash flow theory do not apply to computer hardware as much as to other capital equipment.

In determining the model of supply, crystal industry characteristics were analyzed. The crystal industry is highly diffuse and therefore industry statistics are hard to obtain. For the exotic crystals which have been identified as candidates for space processing, the production and supply data

are extremely difficult to collect for their growth processes are still highly experimental and their market has not yet formed a steady pattern. However, their production and supply data are indispensable for evaluating the potential of space processing. In the absence of these data, it was necessary to choose a proxy crystal and to infer from the data on this proxy crystal the cost and production of the exotic crystals. Since quartz has been grown commercially since 1958 and the data available are relatively abundant, its production and supply history was studied and used as the basis for analyzing the production and supply structure of the exotic crystals.

Results - Demand

Since NNP follows GNP and business sales are not as well correlated to hardware shipment as GNP or NNP, GNP was chosen as the independent variable in making the regression analysis. Estimates were made on computer hardware shipments to 1980 by applying GNP predictions to the regression equations. By 1980, assuming that, the value of memory systems accounts for 46% of total computer hardware sales, memory sales will be \$7,302 or \$8,124 million dollars, depending on the different regression equations employed.

In the projection of alternative memory technologies, price alone could be used to explain demand for a particular memory technology and can be taken as the dominant factor in the explanation of market share.

Assuming that memory technologies in the 1970's will be bubble, semi-conductor (MOS integrated circuit) and core, the market shares of these technologies were calculated to be:

	<u>1975</u>	<u>1980</u>		
	<u>Price/bit</u>	<u>Market Share</u>	<u>Price/Bit</u>	<u>Market Share</u>
Core	14	.97	0.54	0
Semi-conductor	0.94	.53	0.14	0
Bubbles	n/a	-	0.014	1

Applying the above market share estimates to the estimated memory sales, the following sales estimates were obtained:

	<u>1975</u>	<u>1980</u>
Core (billion)	\$2.1-\$2.2	0
Semiconductor (billion)	\$2.4-\$2.5	0
Bubbles (billion)	0	\$7.3-\$8.1

If past experience is any guide, however, the prediction that semiconductors will be completely replaced by 1980 by bubbles must be viewed with caution. Keeping in mind that bubbles and semiconductors will be complementary in the computer hierarchy, the above calculation indicates that bubbles will have the major market share by 1980.

From the past experience, however, the above prediction that MOS will be completely displaced in 1980 must be viewed with some caution; the regression equation results are meaningful when the results are considered in orders of magnitude. MOS memory may very well survive in some share by 1980, particularly if it is successfully introduced in the first half of the 1970's and keeping in mind that bubbles and semiconductors will be complementary in the computer hierarchical structure. Economic success of a particular memory generates financial means to breed further success by R & D or Marketing. At the same time, a new technology, however attractive, could not avoid the initial market resistance and may not achieve the market share predicted in time. But if past history is any guidance of future developments, bubbles will capture a dominant market share by 1980.

In determining the demand for single crystals in computer memories, unlike their end-products, it was postulated that the demand for crystals depends not so much on their prices, but mainly on demand for their end-products. Since a particular kind of crystal is indispensable for a particular memory technology, substitution by other inputs is virtually non-existent. The percentage values of crystals in semiconductor or bubble memories is difficult to estimate. However, based on the analysis of materials in computer memories, a rough estimate gives crystal value as 16% of memory value. Therefore, it can be asserted that the demand for crystals depends on the demand for crystal using technologies. On

this basis the demand model yields the result that silicon demand for semi-conductors will reach the range of \$380-400 millions by 1975 and the demand for garnet crystals for bubbles \$1,168-\$1,295 millions by 1980.

Results - Supply

The model of supply was based on the following observations from the analysis of the crystal industry characteristics: (1) crystal prices are closely related to production costs; (2) production costs depend on quantity produced; and (3) quantity produced in turn depends on market demand which, as shown in the demand analysis, can be expressed as a function of time. In considering the characteristics of the cost function, it was postulated that the optimum scale of production or minimum production cost can be easily reached as production volume increases. Furthermore, the competitive structure of the crystal industry tends to reduce crystal prices to the level of direct production cost, plus overhead and profit. From the data gathered, overhead cost and profit account for roughly 50 percent of the sales prices. Thus, as the volume increases, crystal prices will be normalized to about twice the production cost.

The demand model yielded the result that silicon demand for semiconductors (MOS integrated circuits) will reach the range of \$380-400 millions by 1975 and garnet crystal demand for magnetic bubbles \$1,168-\$1,295 millions by 1980.

Given such ample demand we can assert that normal crystal prices will prevail well before 1980. Since silicon already enjoys volume demand, further decline in its price from about \$450 per pound is unlikely save for major innovations in crystal growing technology. For the exotic crystals currently selling at high prices with negligible volume, it is generally expected that prices will be reduced to about 1/3 of the current levels as demand increases. For example, the price of gallium phosphide is expected to drop to \$8 per gram by 1980 from the current \$22 per gram (about \$3600 and \$9900/lb., respectively).

Results - Economic Feasibility of Space Processing

The economic feasibility of space crystal growth versus earth crystal growth was evaluated. Since the future production cost on earth is not available and the expected future prices of crystals can be more or less related to the future production costs, space processing was evaluated by comparing its products costs to the expected future prices of crystals. Space processing is advantageous if the expected future prices of crystals can cover the total cost, including direct production cost, overhead and normal profit.

The predicted space processing costs are presented in Table II which was constructed by taking silicon as a representative product from the float-zone refined process and gallium phosphide from the solvent growth process. For silicon, even at 80 percent yield, the price of \$450 per pound cannot cover overhead cost and normal profit. However, space processing of gallium phosphide or the other exotic crystals discussed for electrooptic, optoelectronic

TABLE II

PREDICTED SPACE PROCESSING COSTS AND PRICES FOR
SINGLE CRYSTALS - 1980

Silicon -- Float-Zone Refined Process

<u>Yield</u>	<u>Production Cost/Pound</u>	<u>Normal Price/Pound</u>	<u>Market Price/ Pound</u>
40 percent	\$784	\$1,568	\$450
80 percent	\$392	\$ 784	\$450

Gallium Phosphide -- Solvent Growth Process

25 percent	\$1,600	\$3,200	\$3,632
40 percent	\$1,306	\$2,612	\$3,632

and other applications looks promising from an economic viewpoint; even at a conservative 25 percent yield, the normal price, i.e. direct production cost plus overhead cost and normal profit is still less than the expected price from earth processing by \$432 per pound or 11 percent. Since the demand for garnet crystals in 1980 has been estimated at 115,000 to 130,000 pounds per year, this indicates that a total saving of over \$50 million per year could be predicted.

In several ways the aforementioned estimate is conservative. First, it is confined to only one important application of one type of high-priced crystal, viz., garnets in computer memories. There are many other areas of application of this and other types of high-priced crystals where a reduction in cost will lead to substantial increases in demand. Since no historical trends have yet been established by these new applications, it is considered ill-advised at this time to attempt any quantitative forecast of their demand. We are confident, however, that their expanded use will mean additional savings through the production in space of their high-priced crystal components.

Secondly, a conservative 25 percent yield has been assumed in the estimate of savings. This is the yield generally obtained in today's earth-bound processes, and is partially attributable to the gravitational pull and minute tremors inherent in the terrestrial production environment. With these obstructive forces removed in a space environment there seems to be good reasons to expect a higher yield with

consequent reduction in cost of production and concomitant rise in savings. If, for stance, a 40% yield were achieved (which is not impossible) the annual savings in the production of garnets for computer memory would increase from \$50 million to \$118 million. However, because of the lack of hard data we have elected not to use it as a basis for estimating potential benefits.

Third, there are increasing evidences that significant qualitative benefits may accrue to crystals grown in space with its attendant unique characteristics of zero gravity and freedom from vibrations. For example, we may expect space-grown crystals to have more regular shape thus permitting greater yield, or to have lower defect concentration making possible higher performance. There is also the prospect of growing substrate platelets with natural faces, which if successful will greatly reduce cost since the expensive wafering and polishing operations will no longer be necessary. There are important qualitative benefits of space production which will have far-reaching impact on the whole spectrum of crystal technology for a long time to come. It would be unfortunate to have them obscured by an overriding preoccupation with short-term cost considerations.

While the above discussion seems tinged with optimism, we wish to emphasize the restraints currently placed on the optimism. First, the cost of space-grown crystals is a preliminary estimate attempted before the concept of growing crystals has been tested in space and before the technical details of

the space factory has been completely worked out. Second, the projected maximum decline of earth-grown crystal prices in one example from \$22/gram to \$8/gram is based on the personal opinions of industrial experts. It presumably reflects to a large degree the industry's prevailing thinking. However, if either of these two estimates should prove to be incorrect the total amount of savings presented earlier would be significantly affected. Third, and finally, there is the question of whether the power plant required by the space factory would be ready by 1980; however, the motivation of the need for such a power system might serve to shorten the schedule to meet the demand.

Conclusions

In conclusion, there is sufficient economic justification to warrant the funding of planning and development studies which are essential to the growth of crystals in space by 1980. The demand by 1980 and estimated savings for high-valued garnet crystals as substrates and epitaxial films for magnetic bubble memories and of high-priced electro-optic crystals for a wide range of advanced applications economically justify the funding of studies directed toward the space processing of these compositions.

TECHNICAL ASSESSMENT

I. INTRODUCTION

The growth of electronic single crystals has been identified as one of the principal fields which may benefit from the microgravity of space. These high value crystals are the materials upon which the emerging technologies in the computer, communications, optoelectronic, acoustic and detection fields will depend. While some of the crystals can be grown in useable sizes and qualities in a terrestrial environment, they generally fall far short of their theoretical figures of merit due to the imperfections introduced during growth. Experimental evidence indicates that the primary sources of the imperfections are due to the convection and sedimentation present in the growth solutions.

The preparation and processing of crystals for the electronics industry is a multi-billion dollar industry in which many products are dependent directly on the quality of the single crystals. The preparation of crystals in space has intrigued man for over a decade at least since float zone refining and crystal growth in space was first suggested by Pfann in 1958⁽¹⁾. Other crystal growing processes which include vapor growth, solution or flux growth, Czochralski, and melt processes have since been considered.

An assessment of the present status of electronic single crystal production and industry requirements has been made. Using published articles, industry reports and interviews in the crystal growth industry (manufacturers and users), predictions and trends were made that indicate the need for electronic crystals. The market growth to 1980 and beyond has been forecast. In this section, the results are summarized with a detailed account reported in the Appendices.

Semiconductor crystals, especially silicon, represents some 60-70% of the single crystal electronic materials. These are used in integrated circuit solid state electronics and for low wattage power distribution and conversion. They are currently produced to very high quality standards so that space processing would primarily offer the possibility of preparing larger diameter float zone refined boules and possibly the preparation of ribbons drawn directly from the melt. The latter operation would be aimed at obtaining higher yields of product. Our analysis indicates that these operations would not be economically feasible at current prices for silicon. This is primarily because of the high cost of space power and transportation. On the other hand, there may be opportunities for further benefits from integrating the fabrication of integrated circuits with the preparation of wafers from melt drawn silicon ribbons. This may offer both technical and economical benefits sufficient to overcome the power and transportation costs. Although semiconductors represent a very large majority of the single crystal

electronic industry, other crystals, namely ceramic oxide and non-silicon semiconducting crystals are of disproportionately greater importance than their 10 to 20% share of the market would indicate. They play unique roles in electronic devices, are considerably higher priced, and appear to be the source of future innovations.

Six areas of application have been identified which will provide a substantial demand for high quality crystals in the 1980's and beyond. These are:

- 1) Computer memories
- 2) Optoelectronics
- 3) Optical communications
- 4) Piezoelectric detectors
- 5) Surface wave acoustics
- 6) Ultrasonics

The present and known future crystals have been identified and their terrestrial growth techniques analyzed. Potential improvements through space processing have been projected for each of the known crystals in light of their future needs.

The ceramic oxide and non-silicon semiconducting crystals that will benefit from space processing are those grown from a liquid or vapor phase. The majority are grown by liquid techniques which include the Czochralski or melt growth technique, solution or flux growth and the liquid phase epitaxial

growth of single crystal films. In this study, solution has been interpreted broadly to include melt grown crystals and liquid epitaxy from a flux.

The surface and bulk imperfections which are introduced in crystals during growth from solution are attributed to convection processes. Specific studies have been reported on high temperature solutions which show that gravity-related phenomena play a role. Temperature oscillations have been detected in calcium tungstate and calcium fluoride melts which can be directly correlated to the movement of convection patterns visible on the melt surface⁽²⁾. It has been shown that these oscillations cause growth striations in crystals grown from these melts; no evidence was found that the striations are related to the rotation of the crystal through a thermal field. Cellular patterns formed on the melt surfaces are similar to the patterns reported for the simpler problem of a semi-infinite fluid heated from the bottom so that a temperature gradient develops parallel to the gravitational axes⁽³⁾. Under highly stabilized growth conditions with constant power input to the melt and constant heat losses, fluctuations in temperature can arise which may account for the striated impurity distribution observed in doped oxide crystals such as rare earth aluminum garnets⁽⁴⁾. The growth of $\text{Pb}(\text{NO}_3)_2$ and KBr crystals from solution was studied under high force fields of up to 321,000 g by centrifugation⁽⁵⁾. Under high-g the crystals tend to get flattened by a minimum energy balance between the surface tension and the gravitational force. However, the experiments were inclusive relative to determining the effect of gravity on crystal perfection.

Several investigations have shown that imperfections are related to gravity induced convections in non-oxidic crystals. In metal and fused salt crystals, convections in the liquid phase cause temperature fluctuations leading to the well-known "impurity striations or banding" in these crystals⁽⁶⁻⁸⁾. It has also been reported that when temperature fluctuations are damped out by application of a magnetic field in conducting liquids, the impurity striations are eliminated and a fairly uniform distribution in the bulk of the crystal is achieved⁽⁶⁻⁸⁾.

Some very pertinent recent experiments employing the growth of Te doped indium antimonide from the melt showed that the melt successively exhibited turbulent convection, oscillatory instabilities and finally, thermal stability. During turbulent convection, the crystals underwent pronounced transient back-melting; the average microscopic rate of growth was found to be 20 times greater than the average macroscopic growth rate. The microscopic rate was controlled by the convection currents in the melt and the thermal gradients of the solid⁽⁹⁾.

It is generally agreed that there is a great likelihood of being able to prepare higher perfection crystals by solution type processes in the absence of gravity induced effects. If successful, the resulting more perfect crystals should be more valuable from either or both of two viewpoints. First, they should offer higher yields of usable crystals and secondly, the higher perfection should offer better performance in applications. The benefit of higher yield is quite directly translatable into economic terms and is considered in this study. However,

any potential benefit due to higher perfection is more difficult to predict and is therefore not explicitly considered in this economic study. It is however a principal reason for space processing experiments. Possible outcomes of such experiments include, (1) a general improvement of space processed crystals compared to the same compositions from terrestrial sources, and (2) a more intriguing possibility that some compositions will be improved more than others and thereby change the ranking of crystals being considered for an application.

Finally, only rudimentary consideration has been given to the manufacturing engineering aspects of techniques for crystal growing in space. This situation along with the lack of data on the potential crystal perfection benefits of space processing described previously combine to produce an overly conservative economic outlook for the field. These aspects need considerably greater attention in the future. In the meantime, the following technical assessment and discussions of supply and demand are based on terrestrial experience and strongly suggests great economic benefit from at least the space processing of solution grown crystals.

II. COMPUTER MEMORIES

A. Perspective - Current and Advanced Technologies

Since the beginning of the modern computer era about 20 years ago, the size of memory directly accessed from a computing system has increased from a few thousand words (typically 10 to 36 bits or binary digits of stored information per word) in the early and mid-1950's to well over several million bytes (8 bits per byte) currently in use on many systems today. Numerous physical mechanisms and devices have been proposed for memory storage systems; however, most technologies have fallen by the wayside as a result of inherent materials and device fabrication problems, and therefore uncompetitive costs. In the meantime, the magnetic core, introduced in the mid-1950's and digital drums, and eventually discs, became the dominant technologies for direct access storage. As the need for additional storage arose, cores and discs were capable of providing increased size and speed at a reduced cost per bit of stored information. The alternative technologies of the 1960's could not easily challenge the potential improvements of cores and discs.

In the 1970's, however, cores and discs will no longer be the dominant technologies. Their ensuing limitations and the appearance of numerous diverse applications permitting special purpose tailored systems have resulted in the emergence of a wide range of advanced technologies as alternatives or supplements. Some of the more notable currently receiving considerable attention are listed

TABLE 3

ADVANCED MEMORY TECHNOLOGIES

1. Semiconductor integrated circuit memories
 - a) Bipolar
 - b) MOS (Metal-Oxide-Semiconductor)
 - c) Charge coupled (or charge transfer) devices
2. Magnetic domain memories
 - a) Magnetic bubble
 - b) Domain tip (DOT)
3. Holographic systems
4. Magneto optic beam addressable storage
5. Surface wave acoustic delay lines
6. Switchable resistances
7. Strain-biased electronic ceramics

in Table 3. The trends of the advanced technologies are toward media with increased storage density and read/write capabilities and toward memory systems with increased speed of the electronic scanning type.

The pacesetters for meeting future memory requirements are those of the circulating information and beam addressable types. Those with the most potential utilize electronic single crystals characterized by a wide range of solid state phenomena which include:

1. Semiconductors
2. Ferroelectrics
3. Ferromagnetics
4. Piezoelectrics
5. Electrooptics
6. Magnetooptics

The advanced technologies based on single crystals can be broadly classified into integrated circuit memories based on silicon single crystals and the memory systems based on ceramic oxide single crystals.

The current technologies include cores, magnetic discs and plated wire. Cores are tiny ring-shaped magnetic ceramics (polycrystals called ferrites) which are strung on a mesh of fine wires. Their advantage is low cost, but this mounts rapidly with increased capacity. Magnetic disc memory systems depend on the mechanical movement of a storage medium below a "head" that can read out data that were previously entered, or write in fresh data. While mechanical motion has brought simplicity and low cost into storage technology

in the past, it is now becoming one of the major problems because of slower access times and reliability as compared to all - electronic systems. Plated wire is an electronically addressable memory technology. Because of the small volume usage in comparison to cores and discs, it will not be considered relative to advanced technologies.

Non-single crystal advanced technologies are being investigated in which storage media consist of glass (amorphous) or polycrystalline materials. These include switchable resistance, strain-biased PLZT, and domain tip (DOT) memories. DOT, a moveable domain memory using polycrystalline films as storage media, is in current use, but will not compete in cost performance with the magnetic bubble movable domain concept. Switchable resistance devices are those capable of exhibiting a variable resistance with a threshold in voltage or current. These have been known for many years and have fallen by the wayside from the lack of understanding of the switching mechanisms and a demonstration of device capability. Strain biased PLZT are transparent, ferroelectric polycrystalline ceramics of hot pressed lead lanthanum zirconate titanate and have the potential for high density storage and a variety of readout applications. However, their use in memories from a cost/performance standpoint remains to be seen.

Integrated transistor memories are fabricated on or within single crystal semiconducting silicon. While a mature technology, they are a major contender for future memories because of cost reduction and advances in

fabrication technology. Space processing will not make viable contributions to the manufacturing, cost reduction, or perfection of the silicon crystal used in integrated circuit fabrication.

By definition an integrated circuit is an interconnected array of active (transistor) and passive elements (conductors, resistors and capacitors) inseparably associated on or within a single crystal silicon substrate. The two types referred to here are bipolar and MOSFETS (metal-oxide-semiconductor field effect transistors). A new type of semiconductor is the charge-coupled device, a surface charge transistor technology. Basically it is the electrical equivalent of the magnetic bubble memory discussed in B.1.

B. Single Crystal Advanced Technologies

1. Magnetic Bubble Memories

Magnetic bubbles are a new technology wherein a magnetic material is divided into regions called domains that are magnetized in different directions. Data bits of information are stored in cylindrical domains or bubbles which can be moved from point to point at high velocity in thin single crystal films of magnetic material.

Oxide single crystals with unique magnetic properties are the key element of a magnetic bubble device. Recent work indicates that single crystal rare-earth iron garnets come closest to having the preferred set of

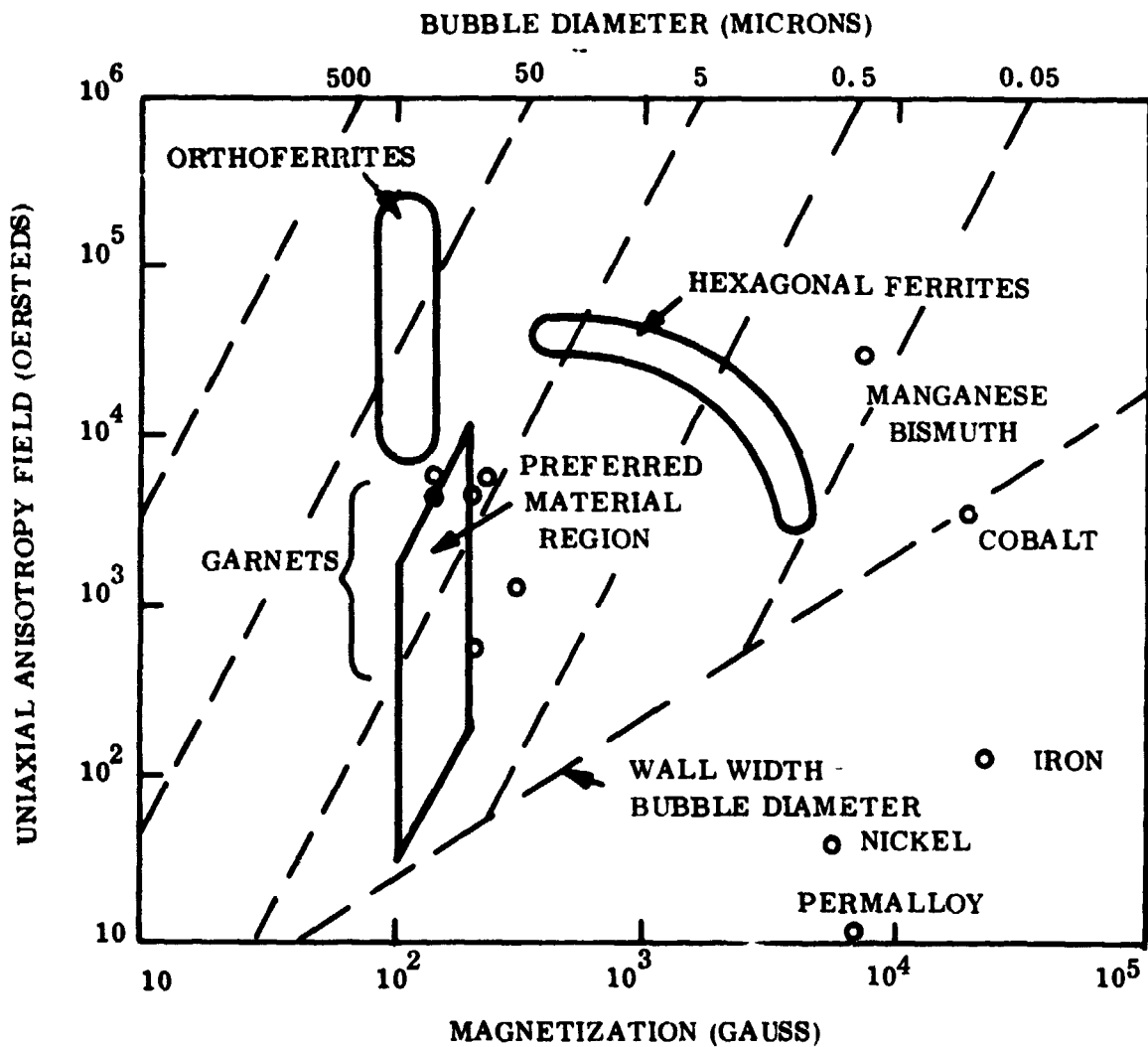


Figure 1. Properties of Magnetic Bubble Crystals. Uniaxial Anisotropy vs. Magnetization and Bubble Diameter (10)

properties (Figure 1). Crystal boules for substrates of rare earth gallium garnets are grown from the melt. The substrates are cut, wafered and polished from the boules. Rare earth and yttrium iron garnet single crystals are deposited on the substrates by liquid phase epitaxy (LPE) from fluxed melts.

The potential importance of space processing for the growth of more perfect platelets and films with high yields in quantities required for further development and production cannot be overstressed. Microgravity growth techniques hold the potential for controlling the perfection and uniaxial anisotropy which is the key to bubble size and bubble movement, and therefore information storage and transfer efficiency. The regions of uniaxial anisotropy are growth bands which result from temperature fluctuations during the growth process. The fluctuations are caused by thermal convection currents which are driven by the force of gravity. Thus if growth striations are responsible for bubble size, space processing is of interest to develop crystal growth techniques which will allow this effect to be controlled. Space processing also provides for the control of the formation of material facets by the advancement of a flat solid-liquid interface and for the growth of substrate platelets with natural faces thus eliminating the wafering and polishing operations and the accompanying mechanical cracking.

The most commonly identified hardware problem is that of the gap that exists between electronically and electromechanically addressable storage. With all the levels in a memory hierarchy, there is still a difference in access time of three to four orders of magnitude (10^{-6} to 10^{-2} seconds) between the electronic bulk memory and the electromechanical peripheral storage unit. Bubbles are an excellent candidate as an intermediate memory to fill the gap if the costs can be reduced. This is very likely.

During the next decade integrated circuit and magnetic domain technologies will complement one another in hierarchical computer structures. By 1975 semiconductor bipolar and MOS integrated circuits will be used in computer mainframes. These will be capable of submicrosecond speeds in the fast memory section. In the rest of the computer section where bulk storage is important memory blocks of magnetic bubbles will be used. They will provide high density storage with microsecond access times at speeds competitive with current core, disc and drum memories.

The relative merits and costs of bubbles, cores, integrated circuits and charge coupled devices are compared in Table 4. CCD's and bubbles will cost less than integrated circuits; bubbles will probably have a lower cost than CCD's, but will be slower. Bubbles cannot fill the 10-20 MHz regime and be competitive. All three of the advanced technologies exhibit the adaptability which may overcome the size and access limitations of cores.

TABLE 4 (11)

RELATIVE MERITS OF MEMORY TECHNOLOGIES

<u>Simultaneous RAM Spec.</u>	CORE		IC		BUBBLE		CCD's	
	Now	Future	Now	Future	Now	Future	Now	Future
Components per bit (#)	1	1	4	1-2	n/a	n/a	n/a	n/a
Bit density (bits/inch ²)	3x10 ³	10 ⁴	5x10 ⁴	10 ⁶	1.5x10 ⁶	10 ⁷	5x10 ⁵	4x10 ⁶
Maximum block (or chip) size (bits)	1	1	10 ² -10 ³	2x10 ⁴	10 ⁴	10 ⁵ -10 ⁶	10 ³	4x10 ⁴
Power per bit (microwatts)	100	50	3x10 ² -10 ⁴	10	0.5	0.2	n/a	1.5
Cost (cents per bit)	1	0.5	1-10	40.1	n/2	40.01	n/a	40.01
<u>Technology Quality</u>	CORE	IC	BUBBLE	CCD's				
Process Simplicity	good	complex	good	good				
Reliability	good	low-good	good	good				
Cost/Performance Trade-offs	limited	good	good	good				
Partitionability and Architecture Flexibility	limited	good	best	good				

Note: n/a = not applicable

2. Holographic Memories

Holograms are photographic records made through a form of lensless photography. They are best known for their ability to produce 3D images; however, equally important is their potential to store an enormous amount of information. Theoretically the information packing density is limited only by the wavelength of light; a theoretical limit of 10^{12} bits per cubic centimeter of medium can be created. In a stationary media holographic schemes can circumvent the mechanical motion of the rotating disc and provide large storage capacity at reduced cost. By the late 1970's, the trend will be to replace memories using magnetic surface recording rather than the internal memory such as core or semiconductors.

In holographic memory systems, electronic single crystals are serious contenders for dynamic storage and read/write memory applications. In addition to the optical storage media, they are also essential to the other system components such as lasers, digit deflectors and page composers. These are schematically shown in Figure 2. Of these components, crystals for the optical storage media and page composers will benefit most from space processing.

Storage media and page composers suitable for hologram recording are the most important components in need of further development. Both use ceramic oxide single crystals. Many different types of holographic storage media have been investigated in the past ranging from dichromated gelatin to magnetic optic manganese bismuth films. However, electrooptic crystals represent

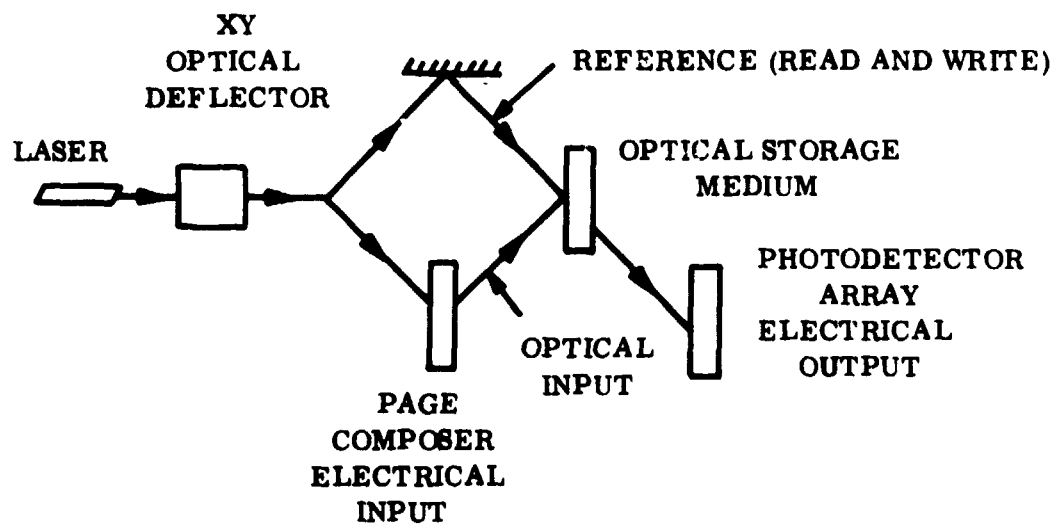


Figure 2. Holographic Optical Memory (Schematic) ⁽¹²⁾

the only type of holographic storage media to combine very high efficiency with the important feature of reversibility.

The most promising crystals are lithium niobate (LiNbO_3), undoped or doped with iron, and barium sodium niobate ($\text{Ba}_2\text{NaNb}_5\text{O}$), doped with iron or molybdenum. Lithium tantalate, barium titanate, and bismuth titanate are also capable of recording volume holograms.

The use of lithium niobate for holograms storage media would be enhanced by the growth of large, high purity crystals under microgravity conditions. Although crystals as large as one inch in diameter and six inches in length can be grown directly from the melt, dynamic growth at elevated temperatures introduces compositional nonuniformity. This causes variations in the index of refraction and other properties which are essential to electrooptic applications; distortion of the holographic patterns arise from long range refractive index variations.

In addition, perfect surfaces are required. Polishing of terrestrial grown crystals introduces scattering centers causing short-range refractive index variations. Microgravity growth offers the fascinating possibility of growing material faces along a preferred crystal plane.

An important component of a holographic, optical memory is a page composer. This is an optical pattern generator for converting electrical signals into an optical pattern (representing a page of information) of the type required to write into the memory. Growth under microgravity in space would greatly benefit crystals such as gadolinium molybdate and bismuth titanate which are showing

promise for page composers. Gadolinium molybdate, $Gd_2(MoO_4)_3$, a ferroelectric-ferroelastic crystal, must be defect free so that it can be switched an indefinitely large number of times without fatigue. Zero-gravity growth offers the prospects for providing the conditions for the advancement of a smooth planar solid-liquid interface during growth and the elimination of the turbulent convection which gives rise to temperature fluctuations. These cause subsequent strain and defects which influence the threshold field.

Bismuth titanate is a ferroelectric crystal whose optical behavior has provided nearly maximum transmission in the intensity of transmitted light and is the most attractive material for a high-speed page composer. However, laminar crystals of $Bi_4Ti_3O_{12}$ grown by the terrestrial flux methods are at most about 1 mm thick and possess a face area which is too small for practical display purposes. Efforts to grow them by other techniques have proven unsuccessful. The growth of large, flat platelets with a crystal area suitable for display is a unique application for space processing.

3. Surface Wave Acoustic Devices

Surface waves represent one of the most recent technological candidates for bulk memory where moderately fast access and very high data are desirable. Whether or not it becomes a potential candidate for mass storage remains to be demonstrated. Surface waves are generated and propagated along the surface of a piezoelectric crystal. Both the internal and surface condition of the crystal are important. Lithium niobate and bismuth germanate ($Bi_{12}GeO_{20}$) are good candidate single crystal materials for analog operations.

The major technical problem where space processing has potential is in obtaining high quality crystals with low acoustic attenuation for high frequency operation such as spinel ($MgAl_2O_3$) or yttrium aluminum garnet and crystals with high velocity of propagation such as sapphire, rutile and aluminum nitride.

4. Magneto optic Beam Addressable Memories

Beam addressable memories are considered as another technology which could fill the access gap in the memory hierarchy between electronically addressable and electromechanical storage systems. Magneto optic beam addressed memories consist of a magneto optic sensitive storage medium illuminated by a laser.

The major technical problem is centered in the magneto optic material. Single crystal ferromagnetic films of gadolinium iron garnet or yttrium iron garnet have been built into a memory configuration for high density reading. While space processing will probably improve the quality and performance of the crystals by decreasing the defect concentration, the economic viability cannot be determined until the problems of slow mechanical mechanisms to address large arrays and density restrictions due to laser beam wavelength are resolved.

III OPTOELECTRONICS

A. Perspective

After computer memories, optoelectronics will have the greatest demand for electronic single crystals. Optoelectronics is the implementation

of electronic functions by optical means and is that branch of electronics which incorporates optical technology in all types of equipment. Crystals for storage media and page composers in holographic memories have been discussed. Crystals for optical sources, modulation and harmonic oscillation used in large scale communication systems are discussed in Section IV. Crystals for infrared pyroelectric detection are discussed in Section V.

In this section our attention is directed toward three other areas of optoelectronics:

- 1) Light-emitting diodes (LED's) and LED displays
- 2) Lasers
- 3) Ferroelectric Graphic Display

communication systems and optical memories, their roles as components related to crystals and space processing are discussed here. Optoelectronic detectors based on silicon crystals, are also discussed briefly in the Appendix.

B. Advanced Technologies

1. Light Emitting Diodes

The light emitting diode is an optoelectronic device of increasing importance with a variety of applications which are based upon the display of information from instruments to people. They can efficiently convert electrical energy into electromagnetic radiation most of which is visible to the human eye.

LED's are fabricated from material consisting of single crystal films which have been deposited on single crystal substrates. At present

gallium arsenide phosphide diodes, which emit red light, have gained widespread attention since manufacturing costs per crystal have been substantially reduced.

However, new crystals such as gallium phosphide (GaP) for green emission, indium gallium phosphide (InGaP) for yellow, and gallium nitride (GaN) for blue are being developed. In fact, GaP is the only source of three-color displays: red and amber as well as green. Poor quality substrate crystals and the introduction of imperfections during deposition of the film crystals are limiting the fabrication and performance of diodes.

It appears that the space processing would benefit from the growth of these crystals. For example, the liquid-encapsulation pulling of GaP substrates under microgravity conditions would potentially decrease their high defect density and increase efficiency. Further, large area GaP crystals could probably be grown in space for large monolithic displays which might reduce cost and make them economically viable with individual segment displays.

Space growth could decide the future for other new crystals. Aluminum gallium phosphide has the highest brightness of all known LED crystals. The electroluminescence potential of InGaP is very high, but problems in crystal growth have prevented its full scale exploitations. Zero-gravity processing may help in reducing the defect concentration of AlGaP and in growing reasonably sized InGaP.

2. Lasers

The laser is probably the single most important optoelectronic device. It is central to almost every new industrial, communication, and scientific system application which relies on optical techniques. Laser devices are finding applications in materials processing, instrumentation and measurement, optical, communication, medicine, holography, data processing and storage, displays and safety. The use of lasers in computer memory systems and optical communications is discussed in Sections II and IV.

Solid state lasers use oxide single crystals such as yttria aluminum garnet (YAG) or yttria aluminate doped with trivalent neodymium to produce the specific wavelength. The crystalline lasers are producing new material problems. They are well suited for continuous power applications. However, the crystals are limited to size and homogeneity and high average pulsed power cannot be produced. The demand for crystals appears to be large enough for space processing to be considered from both manufacturing and the cost view points. Other applications for lasers and the beneficial aspects of laser crystal growth are discussed in the Appendix.

3. Ferroelectric Graphic Displays

While there are some areas in displays where ferroelectric crystals seem to hold promise, their application does not appear to be imminent because of economic and technological factors. In addition, while space growth of these crystals does not appear to offer any economic advantage now, it may by 1980 if size becomes an important consideration.

IV. OPTICAL COMMUNICATIONS SYSTEM

Optical communication systems are still in the research stages and will be introduced in the 1980's. Since the first demonstration of a laser in 1960, much work has been directed toward the potentially very high number of channels of transmission made possible by the coherence of laser radiation. Recent technological advances in low-loss glass fibers for optical guiding structures are making optical-fiber transmission in communication systems a reality.

In order to regenerate and process the optical signals which have experienced transmission loss and distortion, solid state optical sources, modulators and harmonic generators are required. Solid state optical sources use electronic crystals in light-emitting diodes, gallium arsenide injection lasers and neodymium doped yttrium aluminum garnet (Nd:YAG) lasers pumped by LED's. Modulation and harmonic generators consist of nonlinear optical crystals, the most common being electrooptic. Modulators are required to impress the communications information on the optical carrier from YAG lasers or self-pulsating injection lasers. Harmonic generators are devices which can double the frequency of laser light and provide coherent light at many more frequencies.

The growth of electrooptic crystals is an area of high potential for space processing. Compositional nonuniformity along the length of the lithium niobate crystal can limit nonlinear optical activity. The optical quality of barium sodium niobate and potassium lithium niobate is degraded by a high

density of artifacts. Lead germanate ($5\text{Pb}0.3\text{Ge}0_2$) is a new ferroelectric crystal having switchable optical rotary power which is strongly dependent on crystal inhomogeneities.

Aqueous solution grown crystals such as potassium dihydrogen phosphate (KDP) are used in spite of their low electrooptic figures of merit because of the ease of growing large crystals. Lithium iodate (LiIO_3) has a figure of merit which is four times that of KDP; however, with increasing size, haze and growth striations caused by gravity-related thermal convection occur. Space growth should show significant improvements in both perfection and yield.

V. PYROELECTRIC SENSORS

The application of the pyroelectric effect to the detection of thermal radiation was first suggested some thirty years ago. Because of the development of new pyroelectric single crystals such as triglycine sulfate and barium strontium niobate, it is competing with established methods of thermal detection in thermal imaging and advanced sensor systems.

Pyroelectric crystals are high value crystals whose quality, size, thickness and surface condition should be markedly improved by the microgravity peculiar to space growth. Very thin lamellar sheets of highly perfect crystals are required. Growth in space should yield crystals which are tens of microns thick with the correct orientation and eliminate the strains and defects caused by cutting, lapping and polishing.

VI. ACOUSTIC SURFACE WAVE DEVICES

Acoustic surface wave devices are a new field of advanced technology. It makes use of the many theoretical techniques already developed for the microwave field and the experimental techniques developed for semiconductor integrated circuits. Practical devices are beginning to be used in radar and communications systems and studies of new concepts are being carried out.

Surface acoustic devices depend on vibrations on the surface of a crystal. Single crystals of bismuth germanate, lithium niobate, lithium tantalate, quartz and potassium sodium niobate are being used in the exploratory studies of new devices. It should be stressed that crystal surface perfection is as important as perfection within the crystal itself. The growth of surface acoustic

crystals with flat, perfect surfaces in a micro-gravity environment is believed to be one of the unique areas in space processing. For high frequency operation, size becomes important concurrent with surface roughness. Since surface waves can travel around curvatures, the space growth of crystals may be a means for obtaining not only high quality piezoelectric crystals with natural flat perfect surfaces, but also smaller crystals of high perfection with rounded edges for dispersive delay lines with long delays. In addition, at Gigahertz frequencies the linewidths of surface electrodes deposited in the crystals are in the range of the surface roughness dimensions of earth grown crystals. High frequency operation would benefit from the potentially smooth surface of space growth.

VII. ULTRASONICS

Piezoelectric crystals are the fundamental materials for electronic delay lines and filters in the communications industry. In an ultrasonic device acoustic waves confined within a crystal are used to produce an electronic result. While monolithic quartz crystals do some jobs extremely well, the frequency and bandwidth requirement of other applications exceed the capabilities of quartz. Lithium tantalate is an oxide single crystal with all the desirable features of quartz, but stronger piezoelectric coupling and wider bandwidth.

Filters are fabricated from flat plates. This is an area which should benefit from space processing since surface tension forces may be utilized for preparing thin, flat uniform sheets or the continuous drawing of ribbon.

VIII. SUMMARY

The results of the technical assessment are summarized in Table V. The largest demand for crystals appears to be in magnetic bubble memories. As a result of this conclusion the major emphasis of the econometric modeling was directed at rare earth iron garnet crystal production.

Electrooptic crystals are used in a wide variety of applications including holographic memories, optical communication systems, pyroelectric detectors, and surface wave acoustics. They are the second area of single crystal demand. However, as will be discussed in the later sections, the fragmented structure of the crystal growth industry resulted in the lack of production and cost data.

The third area of demand will be for optoelectronic crystals such as gallium phosphide. As a result, emphasis was also directed toward this family of materials.

EOLDOUT FRAME

TABLE 5
SUMMARY OF TECHNICAL ASSESSMENT OF TERRESTRIAL AND
SPACE CRYSTAL GROWTH

Applications	Crystals	Terrestrial Growth Method	Terrestrial Growth Problems	Surface	Size	Perfection	Economic	Space Growth Improvements
Computer Memories								
Magnetic Bubbles								
	Rare earth iron garnets or rare earth gallium iron garnet films	Liquid phase epitaxy from fluxed melts	Growth bands gravity related. Control bubble size. Natural facets control uniaxial regions.	Yes	Yes	Yes	Yes	Gravity-related turbulence and growth striations controlled.
	Rare earth gallium garnet substrate	Cochraleski melt growth	Substrate defects and scratches increasing faceting and hillock concentrations. Cutting polishing, grinding, mechanical cracking. Cut wafer parallel to plane-growth induced magnetic alignment relative to natural face.	Yes	Yes	Yes	Yes	Flat solid-liquid interface to control facets. Growth of platelets with smooth flat perfect surfaces along specific crystallographic axis.
Heliosaphic								
Optical Storage Media	Lithium niobate Barium sodium niobate Lithium tantalate Bismuth titanate	Cochraleski melt growth. Flux growth.	Compositional nonuniformity variations in E-O properties. Surface polishing-scratches, defects, holographic pattern distortion.	Yes	Yes	Yes	Yes	High quality. Large size.
Page Composer	Gadolinium Molybdate	Cochraleski melt growth	Temp. fluctuation cause boule D to change discontinuously. Severe strain changes threshold field. Stochiometry problems.	Yes	Yes	Yes	Yes	Eliminate turbulent convection. Advance of flat liquid-solid interface.
	Bismuth titanate	Flux	Face area too small. Cut and stack plate.	Yes	Yes	Yes	Yes	Growth of large flat platelets.
Surface Wave Acoustic Delay Lines	Lithium niobate. Bismuth germanate Lithium germanate Lithium tantalate YIG, YAG Spinel Aluminum nitride	Cochraleski melt growth, flux	Poor quality. Machine surface-defects.	Yes	Yes	Yes	No	High quality crystals. Natural, flat perfect surfaces.
Magnetoopic Beam Addressable	Gadolinium iron garnet films. YIG films.	Deposition	High defect concentration.	Yes	Yes	Yes	No	Reduced defect density.
Optoelectronics								
	Gallium phosphide	Melt grown, liquid encapsulation	Substrate-poor quality. Epitaxial layer - high defect density. Stochiometry division. Difficult to grow substrate. defect density	Yes	Yes	Yes	Yes	Decrease high defect density. Large area. Reduce defects Size Same
	Indium gallium phosphide Aluminum gallium arsenide Gallium nitride Indium aluminum phosphide	Melt, liquid phase epitaxy Liquid phase epitaxy Unexplored	----- Growth difficulties	----- -----	----- -----	----- -----	----- -----	----- -----

Material	Process	Surface Defects	High Defect Concentration	Yes	Yes	No	Reduced Defect Density	Natural, flat perfect surfaces
Acoustic Delay Lines	Bismuth germanate	growth, flux		Yes	Yes	Yes	No	Natural, flat perfect surfaces
	Lithium germanate			Yes	Yes	Yes	No	Natural, flat perfect surfaces
Magneto-optic Beam Addressable	YAG, YAC	Deposition	High defect concentration	Yes	Yes	Yes	No	Reduced defect density
	Spatial Aluminum nitride			Yes	Yes	Yes	Yes	Decreased high defect density
Optoelectronics	Gadolinium iron garnet films, YIG			Yes	Yes	Yes	Yes	Decreased high defect density
	Gallium phosphide	Melt grown, liquid encapsulation	Substrate-poor quality. Epitaxial layer - high defect density. Stochastic phase epitaxy	Yes	Yes	Yes	Yes	Decreased high defect density
Lasers	Indium gallium phosphide	Melt, liquid phase epitaxy		Yes	Yes	Yes	Yes	Decreased high defect density
	Aluminum gallium arsenide	Liquid phase epitaxy		Yes	Yes	Yes	Yes	Decreased high defect density
Ferroelectric Graphic Display	Gallium nitride	Unexplored		Yes	Yes	Yes	Yes	Decreased high defect density
	Iron aluminum phosphide			Yes	Yes	Yes	Yes	Decreased high defect density
Optical Communications System	Ruby (Ni ²⁺)	Cochraleski melt growth, flux	Size, imperfections	Yes	Yes	Yes	Yes	High quality Large size
	YAG (Ni ³⁺)			Yes	Yes	Yes	Yes	High quality Large size
Pyroelectric Sensors	Lead telluride phosphide	Epitaxy Bridgman	Cellular substructure, voids	?	?	?	?	Further decrease defect density - marginal unknown
	Bismuth titanate	Flux	Composition inhomogeneity	Yes	Yes	Yes	No	Unknown
Surface Wave Acoustics	Lithium niobate		Composition inhomogeneity, plates	Yes	Yes	Yes	No	Large platelet face growth
	Barium sodium niobate	Melt	Compositional nonuniformity	Yes	Yes	Yes	Yes	Improved optical quality
Ultrasonic	Potassium lithium niobate	Cochraleski melt	Variation in nonlinear optical activity	Yes	Yes	Yes	Yes	Improved optical quality
	Lead germanate		Artifacts	Yes	Yes	Yes	Yes	Improved optical quality
Pyroelectric Sensors	Lithium iodate	Aqueous	Switching time depends on inhomogeneities - small size	Yes	Yes	Yes	Yes	Decreased defect density
	Potassium iodate	Aqueous	Size, base, growth striations	Yes	Yes	Yes	Yes	Decreased defect density
Surface Wave Acoustics	Sodium iodate	Aqueous	Growth striation Hopper growth	Yes	Yes	Yes	Yes	Decreased defect density
	Triglycine sulfate	Aqueous	Flaws	Yes	Yes	Yes	Yes	Thin lamellar sheets
Ultrasonic	Barium sodium niobate		Solvent inclusions	Yes	Yes	Yes	Yes	Large, flawless crystals
	Sapphire	Melt	Polishing - surface imperfections	Yes	Yes	Yes	Yes	Natural faces perpendicular to polar axis
Surface Wave Acoustics	Spatial Lithium niobate		Orientation	Yes	Yes	Yes	Yes	High quality
	Bismuth germanate		Cutting-strains	Yes	Yes	Yes	Yes	Perfect, flat natural surfaces
Ultrasonic	Lithium tantalate	Melt	Length, Chemical inhomogeneity	Yes	Yes	Yes	Yes	Surface smoothness, rounded edges
	Lithium niobate	Melt	Surface perfection	Yes	Yes	Yes	Yes	Flat crystals
Ultrasonic	Lithium niobate	Melt	Surface roughness	Yes	Yes	Yes	Yes	Zero Temperature
	Lithium tantalate	Melt	Thin sheets	Yes	Yes	Yes	Yes	Coefficient of delay orientations

DEMAND FOR ELECTRONIC SINGLE CRYSTALS

I. INTRODUCTION

Whether efforts and resources should be expended to grow electronic single crystals in space depends on three factors:

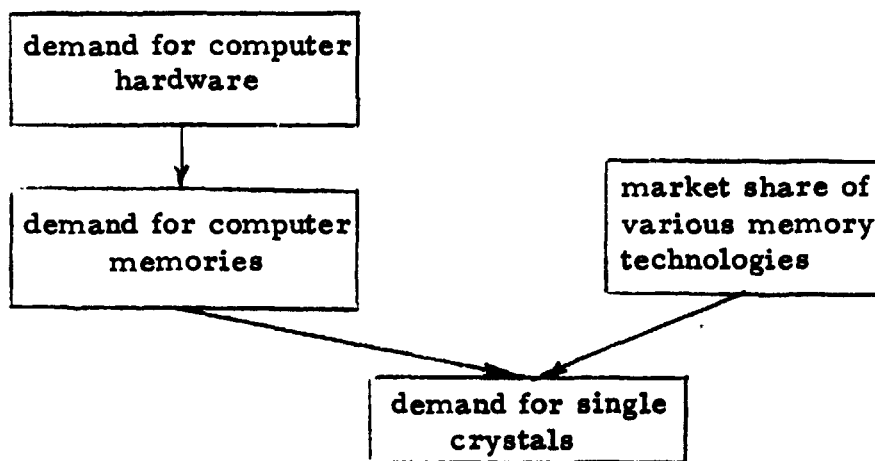
- 1) potential demand or volume for the crystals
- 2) potential cost saving from space processing
- 3) potential quality improvement or expansion of technical frontier from space processing.

Since demand for the product is the prerequisite of any economically feasible project, we will first study the potential demand for the electronic single crystals. However, due to substantial transportation cost incurred in space processing, only those with high value, e.g. currently in excess of \$10,000 per pound, have potential cost saving from space processing. The following crystals have been identified as the candidates for space processing:

rare earth gallium iron garnet, rare earth iron garnet,
lithium niobate, lithium tantalate, gallium phosphide,
bismuth germanate, lead germanate, yttrium iron
garnet, triglycine sulfate and lithium iodate.

Those crystals are almost exclusively purchased by electronic manufacturers as components of various electronic products, many of which are still in the

R&D stage. The demand for them is thus derived indirectly from the demand for their end products. The potential end products for those crystals are computer memories, alphanumeric display devices and communication devices. As new technologies develop, it is expected that electronic single crystals will become the major critical material for the above electronic products. Of the three products, expert opinion indicates that computer memories will become by far the most important end-product of the high valued crystals. Thus our analysis will be focused on the demand for crystals derived from computer memories. The analytical framework is depicted in the following flow diagram.



II. DEMAND FOR COMPUTER HARDWARE

Considering computers as one kind of capital equipment, the theory of investment leads us to relate demand for computers to such variables as sales, growth in sales, profit and interest rate. Unfortunately, lack of data on computers purchased by industry or by firms prevents us from building a

micro-model encompassing these variables. As an alternative, macro-variables, such as Gross National Product (GNP), Net National Product (NNP) and growth in Gross National Product (GNP) profit and sales of private sector are related to the aggregate computer equipment shipment compiled by McGraw-Hill and published annually in the January issue of Electronics. As shown in Figure 3 (with relevant data tabulated in Table 6), computer hardware shipment is closely correlated to GNP and NNP but not to growth in GNP. Also, hardware shipment is somewhat correlated to business sales but not business profit. These relationships are illustrated in Figure 4 with data points listed in Table 7. We may thus assert that acceleration principle and cash flow theory do not apply to computer hardware as much as other capital equipment.

Since NNP follows GNP and business sales are not as well correlated to hardware shipment as GNP or NNP, GNP is chosen as the independent variable in the regression analysis. In order to account for any possible time trend, another independent variable, time is also included in the regression study. Of the various functional forms tried, linear form fits best and hence only the results of linear equations are reported in Table 8, together with the standard errors of coefficients in parentheses. Since multiple correlation coefficient, R^2 , of Equation 3 (Table 8), is significantly lower than Equations 1 and 2, it will not be considered any further. Equation 2 is a slightly better fit than Equation 1 in spite of the fact that the latter has two independent variables. However, since the difference in fit is insignificant, both equations will be retained as the basis for estimating future shipment of computer hardware.

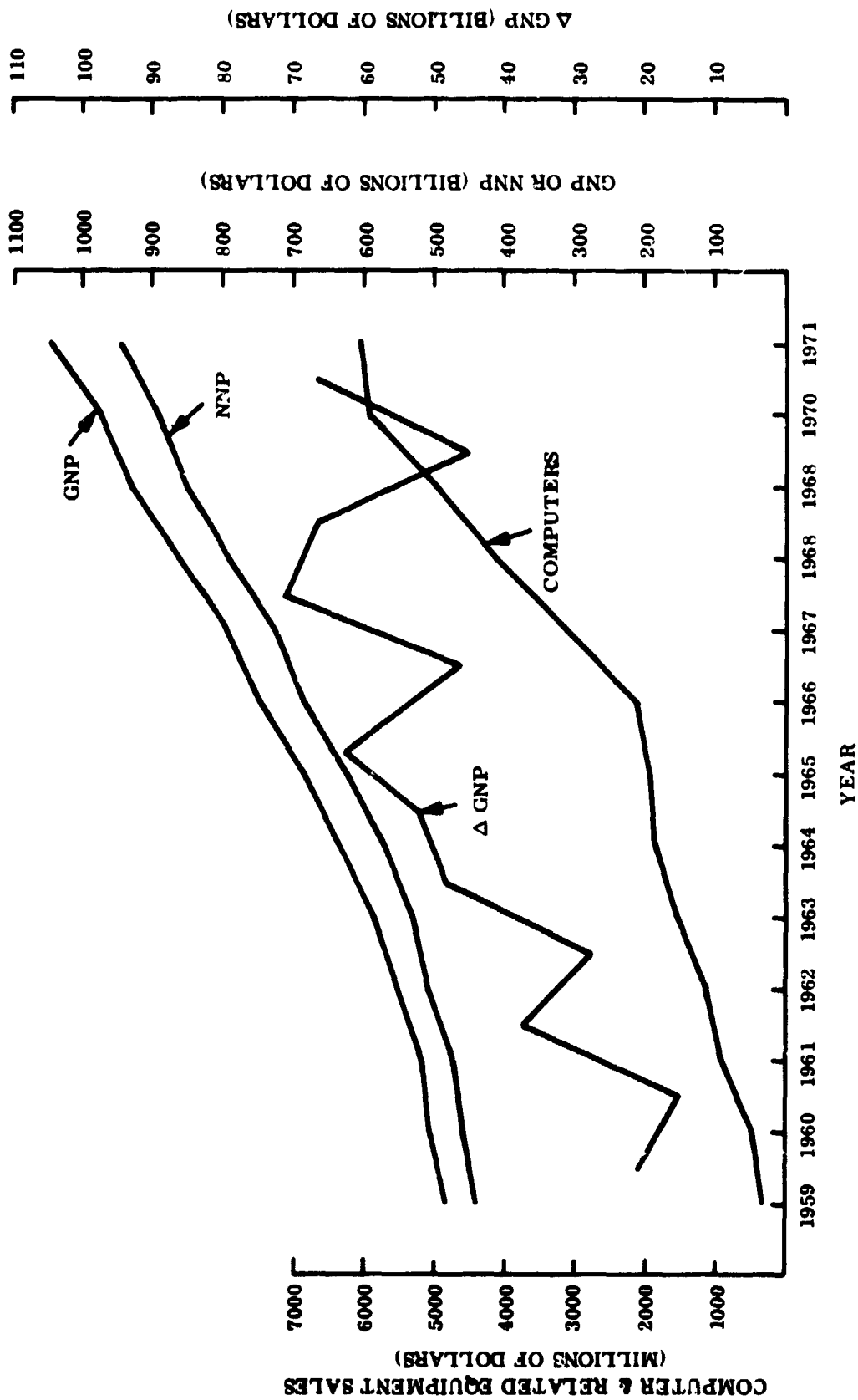


Figure 3. Trends of GNP, NNP, Δ GNP, Computer and Related Equipment Sales

TABLE 6

RELEVANT DATA FOR FIGURE 3

YEAR	COMPUTERS AND RELATED EQUIPMENT SALES ¹ (Millions of Dollars)	GROSS NATIONAL PRODUCT (Billions of Dollars)	NET NATIONAL PRODUCT (Billions of Dollars)
1959	350	483	443
1960	500	504	460
1961	964	519	473
1962	1,150	556	508
1963	1,570	584	533
1964	1,850	632	576
1965	1,946	683	625
1966	2,145	748	684
1967	3,120	794	725
1968	4,134	865	791
1969	4,943	931	853
1970	5,971	977	892
1971	6,012	1,043	946

¹ Electronics, McGraw-Hill Publication, January Edition 1960-1972.

² Statistical Abstract of the United States

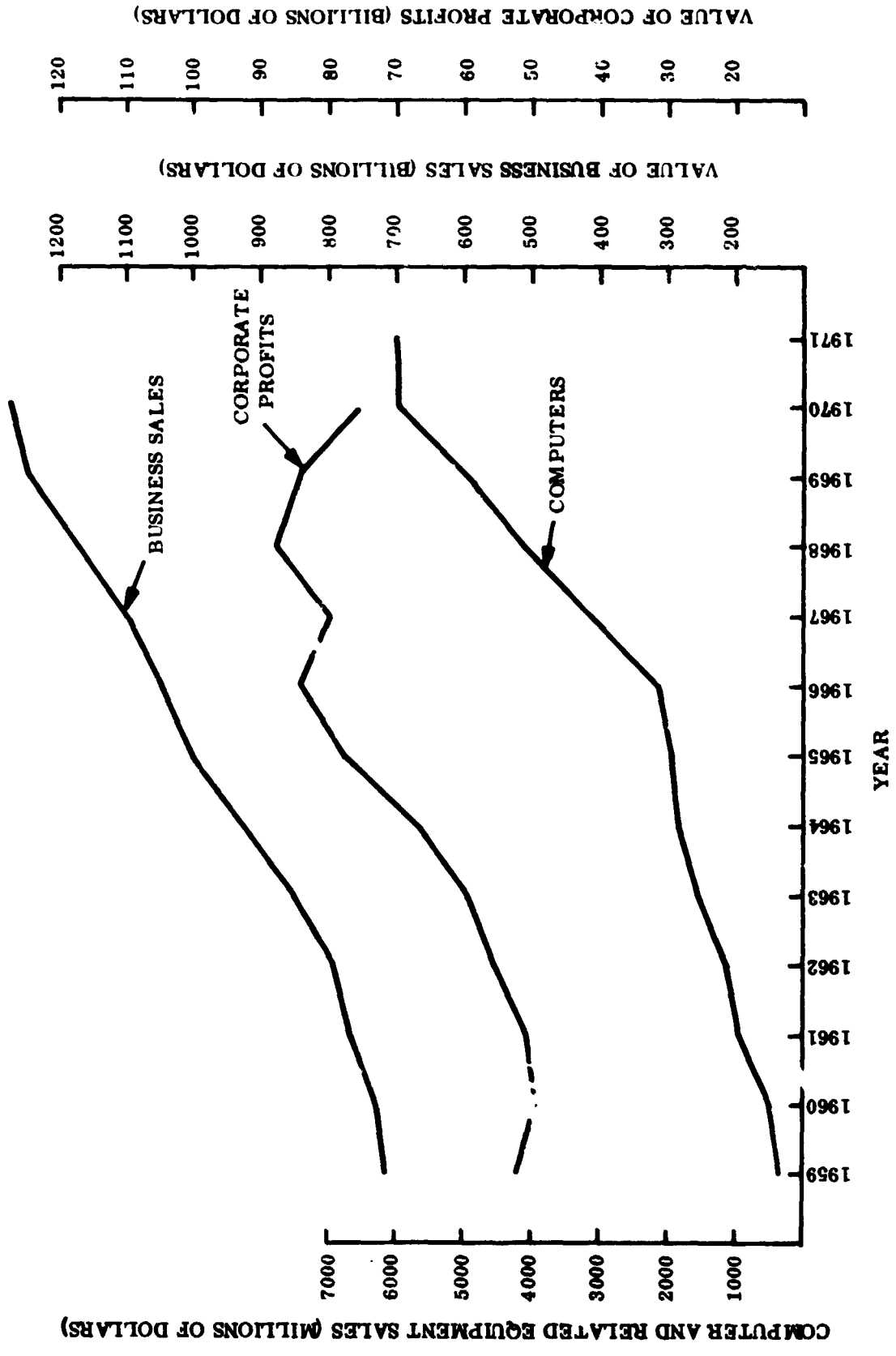


Figure 4. Trends Of Business Sales, Corporate Profits, Computer and Related Equipment Sales

TABLE 7

RELEVANT DATA FOR FIGURE 4

<u>YEAR</u>	<u>Computers and Related Equipment Sales³</u> (Millions of Dollars)	<u>Value of Business Sales¹</u> (Millions of \$'s)	<u>Value of Corporate Profits²</u> (Millions of Dollars)
1959	350	714,993	52,141
1960	500	726,365	49,712
1961	964	767,904	50,349
1962	1,150	792,480	55,408
1963	1,570	851,508	59,401
1964	1,850	924,516	66,789
1965	1,946	1,005	77,787
1966	2,145	1,046,058	84,224
1967	3,120	1,096,495	79,815
1968	4,134	1,165,258	87,636
1969	4,943	1,243,188	84,191
1970	5,971	1,275,315	75,362
1971	6,012	1,371,002	NOT AVAILABLE

1. The Handbook of Basic Economic Statistics, Economics Statistics Bureau of Washington, D.C., Volume XXVI, Number 1, January 1972. Total business sales includes: manufacturing (durable and nondurable goods); retail trade (durable and nondurable goods); and merchant wholesales (durable and nondurable goods).
2. Ibid. Corporate profits for all industries before Federal and State Income and Excess Profits Taxes.
3. Electronics, McGraw-Hill Publications, January Editions 1960-1972.

TABLE 8

	REGRESSION EQUATIONS	R ²
(1)	Y = 4136.17 - 173x ₁ + 13.723x ₂ (.05) (26) (.53)	.96298
(2)	Y = -4666.41 + 10.262x ₂ (468.95) (1.26696)	.966469
(3)	Y = -29330.7 + 492.2x ₁ (2990.25) (45.928)	.927035
Notation	Y = computer hardware shipment	
	x ₁ = time	
	x ₂ = GNP	

Applying the prediction of GNP by the Department of Commerce to Regression Equations 1 and 2, the following estimates of computer hardware shipments are obtained:

	<u>1975</u>	<u>1980</u>
GNP (billions)	\$1400	\$2000
Computer Hardware Shipment: (billions)		
by Regression Equation 1	\$10.3	\$17.7
by Regression Equation 2	\$ 9.7	\$15.9

III. MEMORY MARKET PROJECTION

As can be seen from Table 9, the value of main frame memory system ranges from 7 to 15 percent of total computer equipment sales.

TABLE 9

MAIN FRAME MEMORY VALUES

	<u>1960</u>	<u>1965</u>	<u>1967</u>	<u>1970</u>
Main frame memory system sales (millions)	\$ 35	\$ 280	\$ 680	\$887.3
Computer and related equipment sales (millions)	\$500	\$1946	\$4000	\$5971
Main frame memory system sales as percentage of total hardware shipment	7%	14%	15%	15%

The percentage is expected to increase to 25-30 percent by 1972 for the following reason:

"The cost effects of demands for more capacity and more speed had been largely offset, in the calculating sections of the computer, by improved design and lower prices in electronic components. This is not so in memories. Cost reduction in core memory system had not kept pace, and increasing premiums had to be paid for advance in memory size and cycle time."⁽¹³⁾

This assertion is subject to qualification when emerging memory technologies are expected to cut the memory price to less than 0.01¢/bit by 1980 as discussed in the next section. However, there is another powerful reason for memory value to account for larger percentage of total hardware sales:

"The emphasis in the memory industry during the period 1965-1970 has been primarily in the area of increasing production capacity to satisfy the rapidly growing demand. Memories are not used in a number of different applications that were either not considered in earlier years to be the province of memories, or were not considered at all." "The annual growth rate in each application has been running from 20 to 30 percent in terms of value. - - -' and every piece of equipment tends to use an increasing amount of memory." (14)

Table 10 indicates the changing nature of memory markets.

TABLE 10
MEMORY MARKETS (14)

1945	Experimental digital computers
1950	Developmental digital computers
1955	Production computers
1960	Buffer stores
1965	Process controllers
	Telephone switching equipment
1970	Desk calculators
	Radar scan converters
	Preprocessing equipment for large computers
	ECM data processing
	Data communication
	Peripheral equipment
	DRT display system

If peripheral memory is included, the value of memory system accounts for as much as 40 percent of total computer hardware sales and it is predicted to reach 46 percent by 1975 with peripheral memories increasingly becoming more important than mainframe memories. If this prediction materializes, the memory system sales in 1975 will reach \$4,737 million by Regression Equation 1 and \$4,468 million by Regression Equation 2. For 1980, assuming the percentage stays at 46 percent, the memory sales will be \$8,124 million and \$7,302 million by regression equations 1 and 2 respectively.

IV. PROJECTION OF ALTERNATIVE MEMORY TECHNOLOGIES

Memory technologies compete with one another on the basis of data handling capacity per dollar cost. The key factors considered in selecting a particular main frame memory technology are capacity, speed and price. These three factors are by no means independent of one another. Price is normally a

decreasing function of the memory size and cycle time. Therefore, price alone could be used to explain the success of a particular memory technology. Assuming the functional relationships among these factors are hyperbolic, we then have,

$$\left(\begin{array}{l} P \\ \\ \\ \end{array} \right) = \frac{a}{S} \quad (4)$$

$$\left(\begin{array}{l} P \\ \\ \\ \end{array} \right) = \frac{b}{C} \quad (5)$$

where P = price per bit

S = main frame memory size in bits

C = cycle time in seconds

a & b = parameters

Since demand for a particular memory technology should be inversely related to price and positively related to size and speed (inverse of cycle time), we postulate the following functional relationship:

$$\begin{aligned}
 D_i &= \phi (P_i S_i C_i) \\
 &= \frac{d}{P_i} + e S_i + \frac{1}{f C_i} + g \quad (6)
 \end{aligned}$$

where D_i = demand for a particular memory technology
 i (subscript i stands for a particular memory
 technology)

e, f, g = parameters

Substituting (4) and (5) into (6), we have

$$\begin{aligned}
 D_i &= \frac{d}{P_i} + e \frac{a}{P_i} + \frac{1}{f \frac{b}{P_i}} + g \\
 &= \frac{d}{P_i} + \frac{ae}{P_i} + \frac{1}{bf} P_i + g \quad (7) \\
 &= (d + ae) \frac{1}{P_i} + \frac{1}{bf} P_i + g \\
 &= \frac{A}{P_i} + B P_i + C
 \end{aligned}$$

where $A = d + ae$ $B = \frac{1}{bf}$ and $C = g$

Thus, price alone could be used to explain demand for a particular
 memory technology. Since we are working on the time-series data, in order
 to account for the ever changing memory technologies and computer market,
 is necessary that the variables in Equation 7 be in relative terms.

Thus, Equation 7 can be re-written as:

$$D_{it} = \frac{A}{P_{it}} + B P_{it} + C \quad (8)$$

where D_{it} = market share of technology i at time t

P_{it} = relative price of technology i at time t
(the price of the cheapest technology equals to 1).

Equation 8 is fitted to the data derived from computer census published in Computers & Automation and from Richard's paper on core memory ⁽¹⁴⁾.

$$D_{it} = -.133799 + 1.02809 \frac{1}{P_{it}} - 0.003127 P_{it} \quad (9)$$

(.074) (.08) (.015)

$$R^2 = .927342$$

Since the coefficient of the P_{it} term is rather insignificant and smaller than its standard error, a modified version of equation 9 is tried without the P_{it} term. Historical data points utilized are plotted in Figure 5 and listed in Table 11. The following regression equation is obtained:

$$D_{it} = -.15106 + 1.043 \frac{1}{P_{it}}, \quad P_{it} \geq 1 \quad (10)$$

(.07222) (.106243)

$$R^2 = .927291$$

The Regression Equation 10 is also plotted in Figure 5.

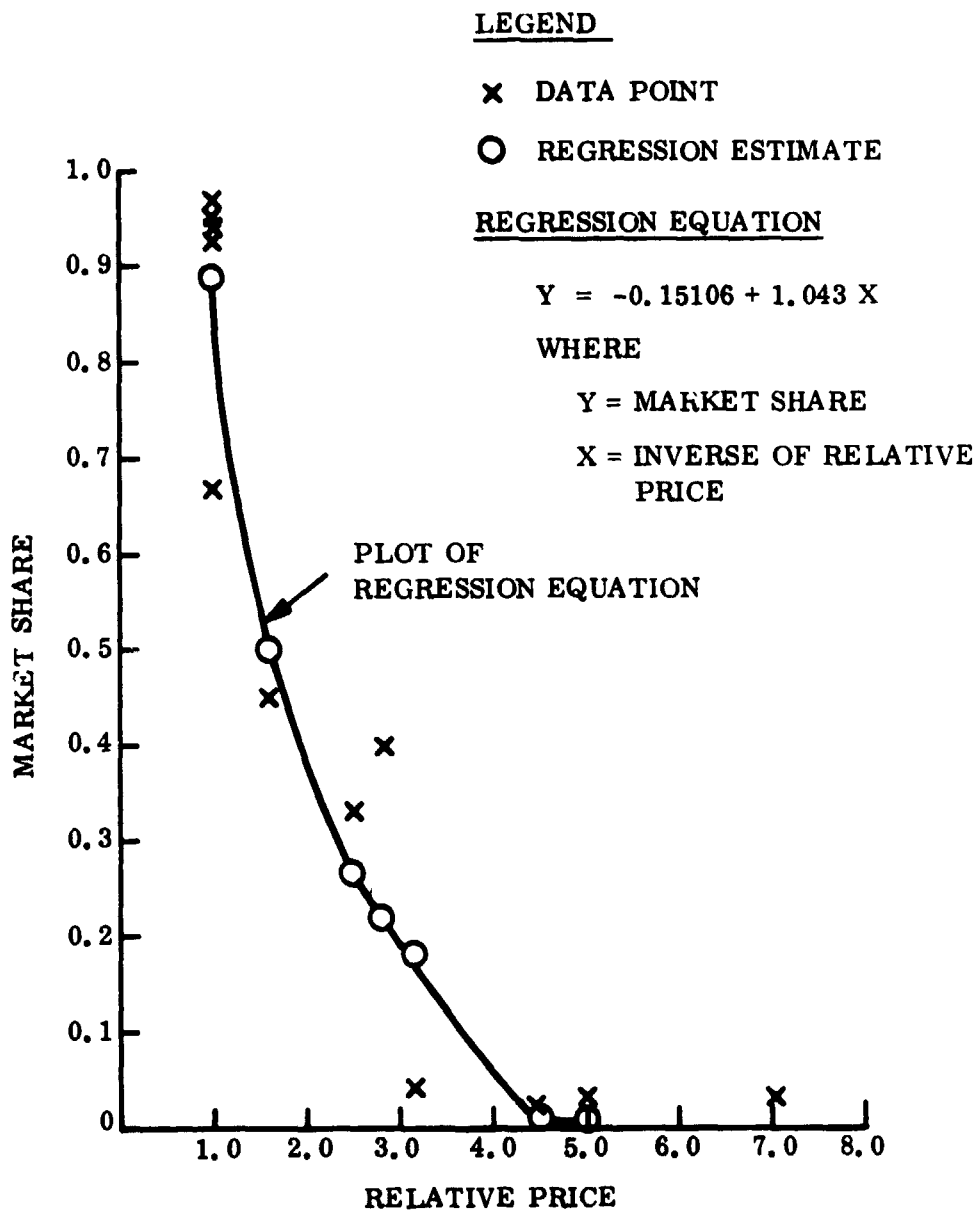


Figure 5. Relative Price Versus Market Share

Statistical fit of this equation is about as good as Equation 9, and hence it will be used in estimating the future market shares of memory technologies. The final selection of Equation 10 over Equation 9 for predictive purposes does not mean that speed is not an important determinant of market share in the normal relationship of competing memory technologies. Rather it underscores the underlying assumption that price is a direct function of speed (or inverse function of cycle time) so that the positive effect of higher speed is largely offset by the negative effect of the associated increase in price. Consequently, price alone can be taken as the dominant factor in the explanation of market share.

A closer examination of the above regression, however, reveals two obvious drawbacks, viz., (1) the estimated market shares of all technologies at any given time may not add up to one, and (2) the estimated market share of a particular technology may be negative. The difficulty arises partly because the Regression Equation 10 depicts a normal relation while in reality a new technology, in spite of its competitive price, often encounters some resistance in the market. To overcome these difficulties, the estimated market share D_{it} will be adjusted by the following two conditions:

$$D_{it} = 0 \quad \text{for } P_{it} \geq 6.9 \quad (10-1)$$

$$D_{it}' = \frac{D_{it}}{\sum_1 D_{it}} \quad \text{for } \sum D_{it} \neq 1 \quad (10-2)$$

TABLE 11

RELEVANT DATA FOR FIGURE 5

<u>Market Share</u>	<u>Relative Price</u>	<u>Inverse of Relative Price (X-Variable)</u>
0.02	4.46	0.2242
0.03	7.05	0.1418
0.03	5.00	0.2000
0.04	3.16	0.3165
0.33	2.51	0.3984
0.40	2.82	0.3546
0.45	1.60	0.6250
0.67	1.00	1.0000
0.93	1.00	1.0000
0.94	1.00	1.0000
0.95	1.00	1.0000
0.97	1.00	1.0000

Note: The above data was derived from information obtained from the following sources:

(1) Census of Computers, Computers and Automation

(2) B. W. Rickard, "Core Memories: The Perennial Leader"
IEEE Transactions on Magnetics, Vol. Mag-6, No. 4,
December 1970.

In this manner, future market shares of competing memory technologies (D_{it}) may be readily estimated with assurance of internal consistency.

Memory technologies in the 1970's are asserted to be core, plated wire, bipolar, MOS and bubble. Table 12 summarizes the various future cost-forecasts.

Although core memories have been in use for almost two decades and currently dominate the market, the general opinion is that they are approaching their operational limits and further significant improvement in the overall cost performance is unlikely. (As shown in Table 12, the optimistic estimate of the core cost is 0.5¢ per bit.) Many experts predict that core will be replaced by MOS as a dominant factor in the market by 1975.

Plated wire has been available for more than 10 years. However, due to its small memory size, only limited adoption is foreseen in the early 1970's.

On the other hand, semi conductor memories, particularly MOS, are expected to become a significant element in the memory market by 1975, due to their potential cost reduction and technical performance. However, silicon technology, though highly adaptive, requires complex processes to vary the homogeneous silicon structure so that it can perform different functions. Hence, its cost reduction potential is not as great as magnetic bubbles which use identical particles to do logic, memory and switching without change of material structure. The preparation of magnet bubble

memories from rare earth garnets is relatively very simple and may cost only a few
 (11)
 millicent per bit . Auerbach predicted that bubble memories would be seen
 (15)
 on the market in the second half of the 1970's .

Table 12
 Predicted Cost Of Materials

<u>Type of Memory</u>	<u>Cost of Memory (¢/bit)</u>		
	<u>1975</u>	<u>1980</u>	<u>Future</u>
Core	n/a	1¢ ⁽¹⁴⁾	0.5¢ ⁽¹¹⁾
Bipolar	1.2¢ ⁽¹⁶⁾	n/a	n/a
Static MOS	1.1¢ ⁽¹⁶⁾	n/a	0.1¢ ⁽¹¹⁾
Dynamic MOS	0.6¢ ⁽¹⁶⁾	n/a	n/a
Bubble	n/a	n/a	less than .01¢ ⁽¹¹⁾

Applying Equation 10, the market shares of new memories.

in 1975 and 1980 are estimated as follows:

	<u>1975</u>			<u>1980</u>		
	<u>price/bit</u>	<u>P_{it}</u>	<u>Market Share (D'_{it})</u>	<u>price/bit</u>	<u>P_{it}</u>	<u>Market Share (D'_{it})</u>
Core	1.0¢*	1.1	.47	0.5¢	50	*
MOS	0.9¢	1.0	.53	0.1¢	10	*
Bubbles	n/a			0.01¢	1	1

* New memory markets share will be insignificant.

* In the absence of specific forecast by experts, the 1980 estimate is used here. This, of course, tends to yield an optimistic forecast of market share for core.

Applying the above market share estimates to the estimated memory sales given in Section III, we obtain the following sales estimates of dominant memory types:

	<u>1975</u>	<u>1980</u>
Core (billion)	\$2.1 - \$2.2	*
MOS (billion)	\$2.4 - \$2.5	*
Bubbles (Billion)	0	\$7.3 - \$8.1

* New memory market start will be insignificant .

From the past experience, however, the above prediction that MOS will be completely displaced in 1980 must be viewed with some caution; the regression equation results are meaningful when the results are considered in order of magnitude. MOS memory may very well survive in some small share by 1980, particularly if it is successfully introduced in the first half of the 1970's and keeping in mind that bubbles and semiconductors will be complementary in the computer hierarchy. Economic success of a particular memory generates financial means to bread further success by R & D or marketing. At the same time, a new technology, however attractive, could not avoid the initial market resistance and may not achieve the market share predicted on time. But if the past history is any guidance of future development, bubbles will capture a dominant market share by 1980.

V. DEMAND FOR SINGLE CRYSTALS IN COMPUTER MEMORIES

We shall now estimate the value of single crystals used in MOS and bubble memories.

Unlike their end products, such as MOS and bubbles, we postulate that demand for crystals depends not so much on their prices but mainly on the demand for their end products. It is understood that price elasticity of intermediate goods depends on: a) possibility of substitution by other

competing inputs; b) percentage value of the intermediate good in the end product; and c) price elasticity of demand for the end product. Since a particular kind of crystal is indispensable for a particular memory technology, substitution by other inputs is virtually non-existent. The percentage value of crystals in MOS or bubbles is difficult to estimate and there are no published data available whatsoever. Nevertheless, the analysis of materials in computer memories for 1967 by Brown and Burkhart can be borrowed to obtain a rough estimate of crystal value in memories. The value of materials, such as core and plated wire, derived from Brown and Burkhart amounts to 16 percent of memory value. If we can assert that demand for crystals depends on the demand for crystal using technologies, i. e. MOS or bubbles, then,

$$E_g = f(T_B)$$

$$E_{si} = f(T_{MOS})$$

where

E_g = demand for garnet crystals used in bubble memories

E_{si} = demand for silicon crystals used in MOS memories

T_B = demand for bubble memories

T_{MOS} = demand for MOS memories

Furthermore, assuming a linear functional relationship, we have

$$E_g = \alpha T_B \quad (11)$$

$$E_{si} = \alpha T_{MOS} \quad (12)$$

where α = percentage value of crystals in bubbles and MOS, i. e. roughly 16 percent.

Substitute the values of MOS and bubbles in 1975 and 1980 into equations 11 and 12, the demands for silicon and garnet used in computer memories in 1975 and 1980 are \$380 - 400 million and \$1,168 - 1,296 million, respectively. At the predicted price of approximately \$1000/pound for garnets, this volume of demand indicates a need for 115,000 to 130,000 pounds of garnets by 1980.

VI. THE MODEL OF DEMAND

We shall now summarize the model of demand developed in the last four sections.

Notation:

Y_t	=	computer hardware shipment in year t (in millions of dollars)
X_1	=	time (1959 = 59)
$X_{2,t}$	=	Gross National Product (GNP) in year t (in billions of dollars)
M_t	=	memory sales in year t (in millions of dollars)
m_t	=	memory sales as percentage of computer hardware shipment in year t. ($m_{1970} = 40$ percent, $m_{1975} = 46$ percent, $m_{1980} = 4$ percent)
$D_{i,t}$	=	market share of memory technology i in year t
$\bar{D}_{i,t}$	=	market share of memory technology i in year t (adjusted)
$P_{i,t}$	=	relative price of memory technology i in year t (price of cheapest memory technology in year t = 1)
$T_{i,t}$	=	demand for memory technology i in year t (in millions of dollars)
C_{it}	=	demand for crystals used in memory technology i in the year t (in millions of dollars)
(I) Y_t	=	$4136.17 - 173X_1 + 13.723X_{2,t}$
OR		
Y_t	=	$466.41 + 10.262X_{2,t}$

$$(II) \quad M_t = m_t Y_t$$

$$(III) \quad D_{it} = -.15106 + 1.043 \frac{1}{P_{it}} \quad \text{for} \quad \begin{cases} 1 \leq P_{it} < 6.9 \\ \sum_i D_{it} = 1 \end{cases}$$

$$D_{it} = 0 \quad \text{for} \quad P_{it} \geq 6.9$$

$$D_{it} = \frac{D_{it}}{\sum_i D_{it}} \quad \text{for} \quad \sum_i D_{it} \geq 1$$

$$(IV) \quad T_{it} = D_{it} M_t \quad \text{for} \quad D_{it} = 1$$

or

$$T_{it} = D_{it} M_t \quad \text{for} \quad D_{it} < 1$$

$$(V) \quad E_{it} = .16 T_{it}$$

where X_1 , X_2 , t , m_t and P_{it} are exogenous variables. When these exogenous variables are expressed in terms of time, demand for a particular crystal incorporated in a particular memory technology can also be expressed as a function of time.

SUPPLY OF ELECTRONIC SINGLE CRYSTALS

I. CHARACTERISTICS OF THE CRYSTAL INDUSTRY

As crystals become one of the indispensable materials in the space age, the crystal industry has doubled its size during the 1960's and probably will continue the trend in the 1970's. The industry in 1971 grossed over \$1 billion of which 60-70 percent is accounted for by silicon and germanium single crystals used in semiconductors. The quartz crystals used in communication make up another 20 percent and the rest is accounted for by exotic crystals used in the fast growing technologies, such as optics, magnetics, ultrasonics and lasers. Although the volume of exotic crystals in which we are most interested is currently low, it is expected to grow at the fastest rate among all crystals in the 1970's as new devices continue to be developed based on them.

The crystal industry is highly diffuse and hence industry statistics are hard to come by. There is no trade organization to monitor production or sales and much of the information on the industry can only be inferred from the data on the crystal user industries.

Much of the crystals produced by the major electronic firms such as IBM, Texas Instrumen., Western Electric, Fairchild Camera, Motorola

and G.E. is for captive consumption. These companies, in the highly competitive electronic industry, have been spending large sums on the research and development of new exotic crystals, in the hope of securing a sizable market share in the new technology areas in the future.

There are also many firms growing crystals for sale. However, as the trend of vertical integration in production continues, these firms will be increasingly subject to the dominance of the user firms. Currently many small crystal growers are subordinated to large electronic firms which purchase their products as well as supplying them the technical know-how of crystal growing.

While crystal growing requires technical skill, it is basically a batch process with modest equipment and overhead requirements, and is consequently relatively easy to enter. This easy entry results in keen competition among the many producers. Most crystal growers are also engaged in cutting, polishing and mounting of crystals. The yield of usable crystals is extremely low; sometimes the scrappage rate is as high as 90 percent on new types of crystals. There is thus a great temptation to cut prices in anticipation of production improvements in order to generate volume and market share. This further intensifies the competition in the industry.

From the above analysis, the crystal industry possesses many characteristics of a competitive industry even though there exists

oligopolistic competition among a handful of firms. User firms dominate the market and price tends to move along with the cost in the long run.

II. SUPPLY STRUCTURE OF ELECTRONIC GRADE QUARTZ CRYSTALS

For the exotic crystals which we have identified as candidates for space processing, the production and supply data are extremely difficult to collect for their growth processes are still highly experimental and their market has not yet formed a steady pattern. However, their production and supply data are indispensable for evaluating the potential of space processing. In the near absence of these data, it is necessary to choose a proxy crystal and to infer from the data on this proxy crystal the cost and production structure of the exotic crystals. Since quartz has been grown commercially since 1958 and the data available are relatively abundant, its production and supply history will be studied and used as the basis for analyzing production and supply structure of the exotic crystals.* Much of the data and information on this subject were furnished by Mr. Bruce Mitchell of P. R. Hoffman Co. (17)

Although import prices of quartz fluctuate over time (Figure 6), the prices of manufactured quartz have shown only minor variation since

*This choice was suggested by Dr. Rastum Roy, Director of the Materials Research Laboratory at Pennsylvania State University.

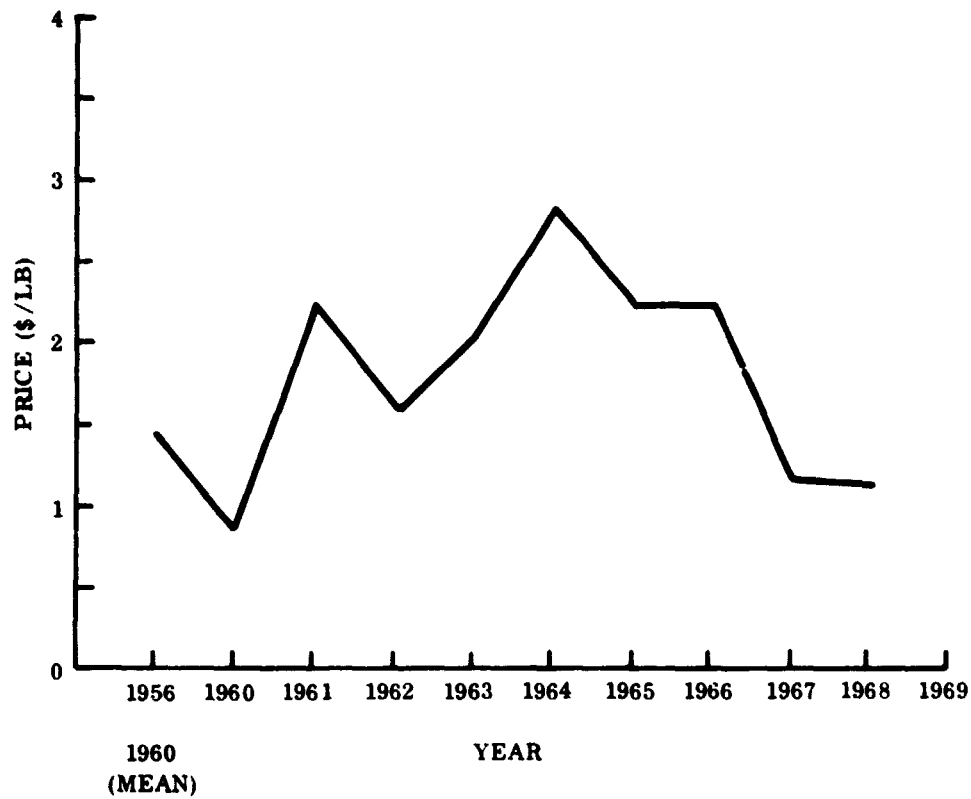


Figure 6. Import Prices of Quartz Crystals (Electronic Grade)
 Source: Mineral Facts and Problems, 1965 and 1970

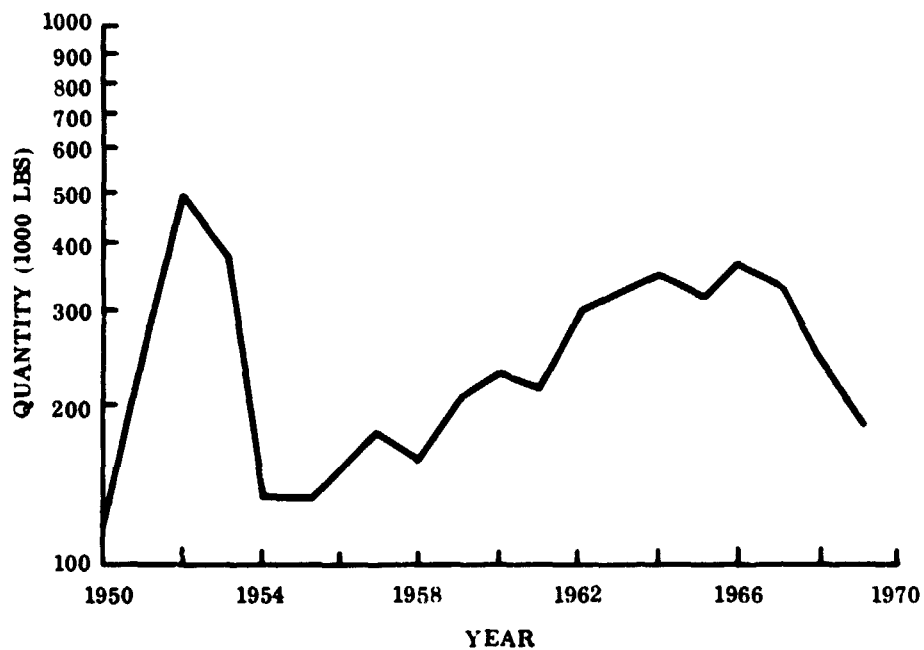


Figure 7. Consumption of Quartz Crystals (1000 Lb)
 Source: Mineral Facts and Problems, 1965 and 1970

Sawyer Research Products, Inc., Eastlake, Ohio, began commercial production in 1958.⁽¹⁶⁾ Consumption of quartz, however, shows wide variation over time (Figure 7). The relative independence of price from demand can be partially attributed to the competitive nature of the quartz industry. Currently, in addition to Sawyer Research Products, the major producers are P. R. Hoffman, Thermo Kinetics, Quality Crystals, and Motorola. With declining demand since 1967, the industry is currently experiencing over capacity which exerts downward pressure on prices.¹⁷

Since the price stability in the past is associated with the commercial production starting in 1958, it can be asserted that as demand developed to a sufficient volume to warrant commercial scale production the selling prices tended to closely adhere to the production cost which is relatively stable once the industry gained experience and technical know-how of volume production.

Stable prices in the period of rapid expansion in demand also indicate the possibility of constant returns to scale. As a matter of fact, quartz crystals are grown by batch process in vessels with limited optimum size. The vessels used by P. R. Hoffman today have output capacity of 2.5 - 3.00 pounds quartz crystals per vessel-day. As a result, to meet annual production of 16 - 20,000 pounds and allow room for expansion, P. R. Hoffman has a stock of 24 vessels. Unlike the steel or automobile industry where

heavy investment is required for efficient operation, the optimum scale of production in the crystal industry is quickly reached as volume picks up. Thus, there is no need to consolidate various production units and the industry is inherently composed of small competitive firms.

The input-output structure of quartz production is illustrated in Table 13 for the optimum growth period of 80 days per vessel. Only direct inputs are shown in the table. The difference between the total direct input cost and total output value is attributable to the overhead costs, such as selling expenses, administration, R&D, and profit. In relative terms, the overhead costs account for 38 percent and profit 20 percent of the total sales while direct input costs account for 42 percent.

The percentage of various costs can be broken down as follows:

Vessels and Control Units		
Depreciation	10%	
Maintenance	6%	
Labor	8%	
Materials	14%	
Power	4%	42%
Overhead		<u>38%</u>
Profit		<u>20%</u>
		100%

At P. R. Hoffman, there are \$400,000 assets of which \$100,000 are current assets, \$30,000 building and \$270,000 equipment. Total annual profit is \$60,000 and depreciation allowance \$30,000, assuming 10 year life

TABLE 13

INPUT-OUTPUT STRUCTURE-QUARTZ

<u>Input:</u>	Per vessel for 80 days	
	Vessel and Control Unit	
	depreciation	\$360-480
	maintenance	\$216-288
	Labor	\$288-384
	Materials	\$504-672
	Power	\$144-192
	<u>TOTAL DIRECT INPUT</u>	<u>\$1512-2016</u>
<u>Output:</u>		
	Output per day	2.5 - 3.00 lb.
	Total output (80 days)	200 - 240 lb.
	Price per pound	\$ 18-20
	<u>Value of Total Output*</u>	<u>\$3600-4800</u>
	Average size of single crystals	400 g.
	Number of single crystal bars	200 bars
	Average growth rate of a single crystal	5 g. per day

*The difference between value of total output and total direct cost is attributable to selling expenses, administration, research and development and other overhead cost and profit. At P. R. Hoffman, profit reportedly accounts for 20 percent and overhead 38 percent.

for fixed assets. The annual cash flow is then \$90,000. We can then calculate the various rates of return as follows:

$$\$40,000 = \$90,000 + \frac{\$90,000}{1 + r_1} + \dots + \frac{\$90,000}{(1 + r_1)^9}$$

$$r_1 = 25 \text{ percent}$$

$$\$300,000 = \$80,000 + \frac{\$80,000}{1 + r_2} + \dots + \frac{\$80,000}{(1 + r_2)^9}$$

$$r_2 = 34 \text{ percent}$$

$$\$270,000 = \$80,000 + \frac{\$80,000}{1 + r_3} + \dots + \frac{\$80,000}{(1 + r_3)^9}$$

$$r_3 = 40 \text{ percent}$$

where r_1 = rate of return on total assets

r_2 = rate of return on fixed assets assuming the opportunity cost of the \$100,000 current assets to be \$10,000

r_3 = rate of return on equipment assuming zero opportunity cost for building.

The pay-back period is: $\frac{400,000}{90,000} = 4.4 \text{ years}$

For the electronic industry as a whole, profit margin for the period 1961-70 averages 9.575 percent which is less than half the rate expected by the quartz industry.⁽¹⁹⁾ However, the fixed capital of the electronic industry as a whole is considerably lower. The annual depreciation for

the period 1961-70 averages only 2.5 percent of the sales versus 10 percent for the quartz industry. Therefore, the rates of return on total assets and fixed assets are more attractive in the electronic industry as a whole than the quartz industry.

III. GALLIUM PHOSPHIDE: GaP

The following data on GaP were collected in a visit to the General Electric Lamp Division, Miniature Lamp Department at Cleveland, Ohio.

	1971		1980	
		<u>As Percent of Total Cost</u>		<u>As Percent of Sales</u>
Cost:				
variable cost	\$ 200,000	4.54		35
depreciation	20,000	.45		15
overhead, other than R&D	180,000	4.09)	30
R&D	<u>4,000,000</u>	<u>90.92</u>)	
Total Cost	\$4,400,000	100.00		
Sales *	\$ 400,000	9.08	\$19,000,000	
Profit	-\$4,000,000	-90.92		20
Price (GaP)	\$22/gram		\$8/gram	
Price (lamp)	80¢/lamp		30¢/lamp	
Industry sales	\$ 600,000		\$40,000,000	

*Large proportion is attributable to GaP crystals.

Although the department presently has only \$400,000 annual sales in this area, its annual research and development expenditures amount to as much as \$4 million. The mass efforts on R&D are aimed at perfecting the product

lines of light-emitting diodes (LEDs) in order to capture a large market share in the estimated \$40 million a year market by 1980. In addition to G.E., other electronic firms such as Texas Instrument, Monsanto and Hewlett-Packard are also expending large amounts of money and manpower on LEDS and the related crystals.

As the market volume grows an expected 100-fold by 1980, it is estimated that the percentage overhead cost will decrease to 30 percent which is lower than the 38 percent for quartz reported by P. R. Hoffman. However, the 20 percent profit margin currently realized at P. R. Hoffman is also expected by the G. E. Lamp Division by 1980. Thus, the normal profit margin in the crystal industry may be considered as 20 percent. This margin is higher than the 10.69 percent earned by the electronic industry as a whole in 1970 and could be attributed to the fact that the ratio of fixed assets to sales is many times higher in the crystal industry than the electronic industry as a whole.⁽¹⁹⁾

As the volume picks up in the future, the price of GaP lamps is expected to drop from 80 cents to 30 cents by 1980. If the price history of quartz is applicable to GaP, when the overhead reduces to as low as 30 percent of sales, further decrease in price is unlikely save for major innovation in crystal growing. Although the competition is keen in the industry, in the long run, a normal profit rate of 20 percent is expected

and price is likely to be stabilized once the processes of commercial production are perfected and there is sufficient demand to utilize the optimum production scale.

IV. CHARACTERISTICS OF THE COST FUNCTION

Batch processes are used in growing crystals. After required materials and seeds are prepared in a vessel or furnace, a control unit is attached and crystals are grown in the vessel or furnace for a certain prescribed period. There is some degree of economy of scale in crystal growing. However, only for the crystals already enjoying volume market, such as quartz, are economies of scale fully exploited. For the exotic crystals in which we are interested the optimum scale of production has not yet been reached, due to a lack of volume demand.

Since batch processes are used and vessels (or furnaces) can be purchased individually, production increases in the short-run tend to be accomplished by multiplying the number of identical vessels, and hence, short-run production cost displays the character of a step-function with constant return to scale such as illustrated in Figure 8. In the long run, however, vessels of larger sizes and greater efficiency will become available as higher volume of demand and production can be expected on a sustained basis. Thus production increases in the long run will tend to be accomplished by adopting larger and more efficient vessels rather than

by adding to the number of identical vessels. As a result, long-run production cost will be as depicted in Figure 9 which shows a step-function with decreasing increases in overhead cost.

For various reasons, however, size efficiency of vessels is limited:

- (1) In hydrothermal crystallization, high temperature (about 400°C) is required for rapid crystal growth. The vapor pressure of water at such temperature exceeds 20,000 psi. The combined severe conditions of temperature and pressure make it necessary to have thick wall and heavy closure of vessels, which tends to restrict the size of vessels. In addition, it is difficult to maintain the desired temperature uniformly across the dissolving and crystallizing compartments as the size of vessels increases.
- (2) In solution growth, equipment cost for mounting and pulling seeds is high relative to the cost of vessels. Also the uniformity of temperature and concentration of nutrient required necessitates more elaborate arrangements for larger crystallizers, such as a rotary crystallizer. Therefore, economy of scale diminishes as the size of vessels increases.
- (3) In the strain-anneal or grain growth method of crystallization, a critical temperature gradient has to be maintained at the advancing front.

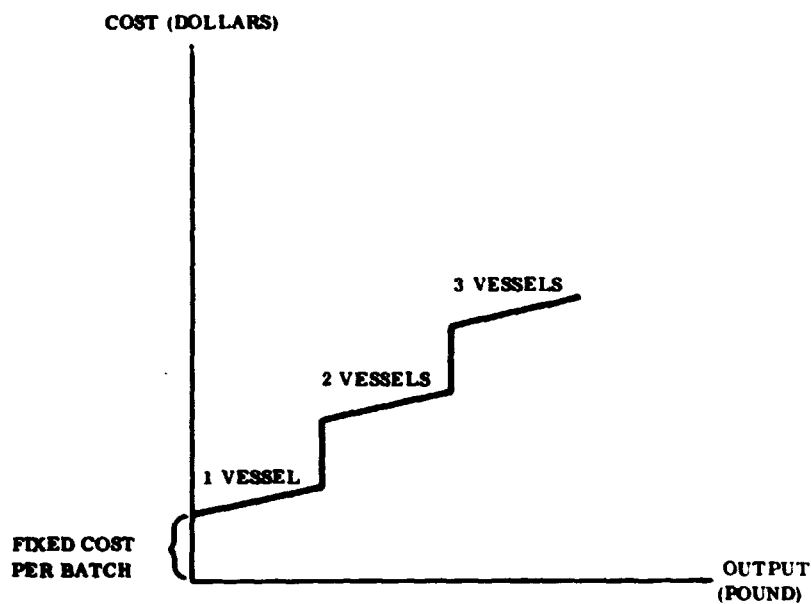


Figure 8. Short Run Cost Function (Single Vessel or Furnace Size)

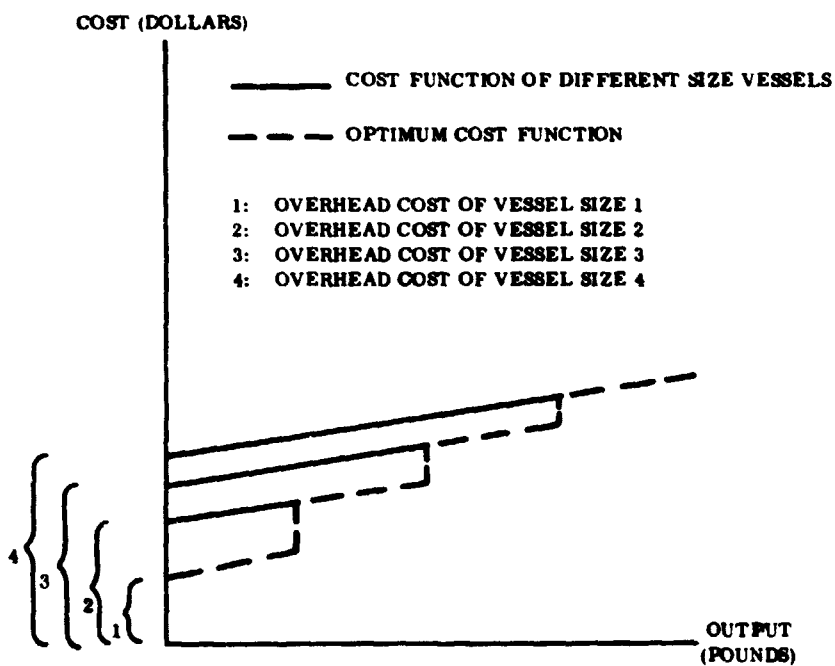


Figure 9. Long-Run Cost Function (Various Vessel Sizes)

It becomes difficult to obtain and maintain this gradient uniformly over the cross section when the bar becomes large.

The above limitations also hold true for the Czochralski Method. The maximum diameter of crystals is generally limited to the uniform temperature gradient achievable by cooling nitrogen stream. Since the controlling mechanisms for drawing and cooling are more elaborate and costly than the crucible, there appears to be little economy for big "multiple drawing" crucibles.

In addition to the above limitations, the risk of growing defective crystals multiplies as the size of the vessel increases. Therefore, the optimum size of vessels is limited.

We can thus postulate that as the market volume expands, the optimum scale of production is quickly reached and the minimum direct average cost is realized. Of course, total average cost, which includes the overhead cost such as administration, selling expenses, R&D etc., will not be minimized until there is a sufficient volume to reduce the percentage of overhead to about 30 percent of the sales. When the above percentage is realized, economy of scale is fully exploited and constant returns take over.

Based on the above assertion, the price of GaP will be reduced to about one-third of the present price as the volume picks up in the future. The

same view was also expressed by G. Lofacono of ISOMET, Oakland, New Jersey, who expected the prices of most exotic crystals to go down to about one-third of the present levels when the volume grows. Assuming the demand estimates in the last chapter materialize, the following price estimates for various exotic crystals are obtained.

TABLE 14
PRICES OF EXOTIC CRYSTALS
(\$/gram)

	<u>1971</u>	<u>1980</u>
GaAs	22	8
GaP (poly-dense crystal)	22	8
GaAntimonide	15	5
Indium Arsenide		
Single crystal	15	5
Poly crystalline	10	4
Indium phosphide		
Poly crystalline	15	5
Indium Antimonide		
Single crystal 5×10^5	15	5
Single crystal 5×10^5	20	7

V. THE MODEL OF SUPPLY

From the above analysis of the crystal industry characteristics, it can be asserted that: (1) crystal prices are closely related to production costs; (2) production costs depend on quantity produced; (3) quantity pro-

duced in turn depends on market demand which, as shown in the last section, can be expressed as a function of time. In mathematical notation,

$$(I) \quad p = f(AC)$$

$$(II) \quad AC = g(q)$$

$$(III) \quad q = h(t)$$

where p = normal price

AC = unit production cost

q = quantity produced

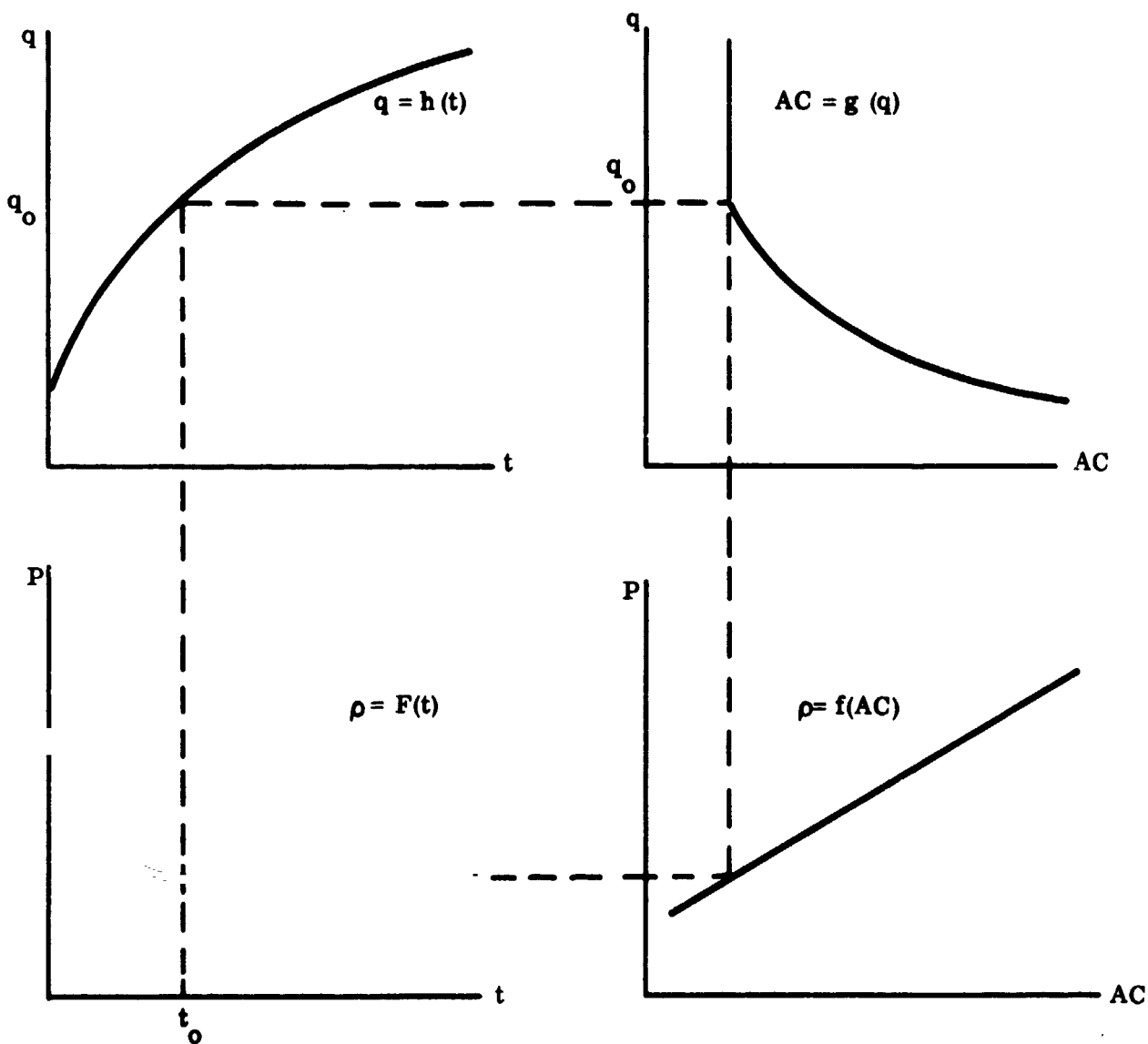
t = time

consequently,

$$(IV) \quad p = F(t)$$

The specific functional forms we postulate are depicted in Figure 10. When the optimum output level, q_0 , is reached, the unit cost is minimized and there is a tendency for it to remain constant regardless of the further expansion in output. Thus price will remain constant after t_0 when q is equal or greater than q_0 . If the normal profit margin is 20 percent and the overhead is 30%, it can further be asserted that

$$P = f(AC) = 2 AC \text{ for } q \geq q_0$$



q_0 = OPTIMUM OUTPUT LEVEL WHERE C IS MINIMUM

t_0 = YEAR WHEN q_0 IS REACHED

Figure 10. Model of Supply

It is difficult to say precisely when q_0 will be reached without adequate data. Nevertheless, from the result of demand analysis in the last section, we can contend that the optimum output level q_0 for garnet crystals will be reached before 1980.

ECONOMIC FEASIBILITY OF CRYSTAL GROWTH IN SPACE

I. INTRODUCTION

The growth or preparation of high value crystals for electronic applications may well become an important usage of the space environment. This prediction while still speculative, is based on very preliminary estimates that the size, shape, quality, or yield (or some combination of these parameters) of crystals grown in space may warrant space operations from a technological standpoint. Further, that the costs of obtaining these benefits may be sufficiently low by virtue of the availability of the space shuttle as to warrant the use of the space environment from an economic standpoint.

If these conditions can be met to a sufficient degree, it is possible then that by the end of the century, automated crystal growth factories could be orbiting the earth. They might supply at least the high value part of the spectrum of crystals needed for our highly technological society.

The compositions and usage have been discussed earlier in this report as well as elsewhere. This section will focus on some very preliminary conceptual ideas of what might constitute an early space factory for crystal growth, and includes some preliminary cost estimates on which to assess the feasibility of the project. Two types of crystal growth (Float Zone Refined and Solvent) are first discussed from a conceptual process and facility standpoint. Then a central power station is briefly described followed by some estimates of the economic aspects of crystal growing in space.

II. FLOAT ZONE REFINED CRYSTALS

One unit would be devoted to preparing Float Zone Refined (and perhaps Czochralski) boules and ribbons of semi-conductors such as silicon where the primary operations would be aimed at processing silicon into large diameter boules or perhaps wide ribbons from which 4-8" diameter wafers could be obtained. The quality of the present earth produced semiconductor materials is excellent. While the quality is not to be degraded by space processing, it is also not a prime reason for space processing as are some other proposed space operations.

This then leads to a conceptual design in which a space processing plant for FZR semiconductors would primarily consist of a single large induction heating station to which numerous pre-processed full size billets would be delivered sequentially at a rate of one or 2 per day by a conveyor system (or the induction coil moved). These billets would be brought in large numbers (e.g. 20) perhaps only every month or so by a space shuttle flight. The shuttle would then return to earth with either large single crystal boules or the wide ribbon drawn from them. Thus, it is assumed that all raw material would be returned to earth for final processing. It is conceivable however that other processing operations could be warranted. Metallurgically the billets would probably be of a poly crystalline high purity form prepared perhaps by powder

metallurgy methods and in need of only one heating pass to convert them to single crystal boules. This would be the prime purpose of the space processing, as a minimum. It is hoped however that the absence of gravity may permit drawing thin, full width ribbons from these boules without contamination. This would permit large savings in the preparation of wafers since the present practices waste about 60% of the material. These operations are depicted in Figure 11.

One can also speculate that the use of vacuum and the quiescence of space could be useful and economically justified for the preparation of integrated circuits and similar devices. The prime argument for this is based on obtaining better resolution of photographic imaging equipment in the vibrationless spacecraft. This might permit either the use of larger diameter wafers or the obtaining of a better yield from present sizes. This use of the space environment may indeed be achievable but is secondary to our purpose here since the large diameter wafers are principally thought to be for power distribution equipment.

III. SOLVENT CRYSTAL GROWTH

The second type of crystal growth operations proposed for space is based on preparing oxide or other compound crystals from solutions. Here indeed the quality is the principal reason for wishing to use space processing where convection and sedimentation are expected to be minimal. In addition, there may be some advantages in processing in space to yield desired shapes such as ribbons or films with high surface perfection. The compositions of interest in this



Figure 11. Space Processing Concept for Large Diameter Float Zone Semiconductors.

field, as previously discussed in Section II, are extremely numerous with the corresponding demand for any particular composition being very low compared to the many tons (25-30) of single crystal silicon used in the U.S. yearly. This then leads to a complex, multiproduct, facility where great care will need to be exercised to avoid cross-contamination while at the same time providing great flexibility in terms of time, temperature, solvent, etc.

Conceptually such a crystal processing facility might be operationally opposite to the previously outlined float zone processing system. Here the various containers of solvent would be mounted or reloaded (by materials handlers from the shuttle crew) in suitable furnaces or heating devices for processing over generally much longer periods of time than the float zone refined material experienced. For example, one to three months is a typical growth time for many crystals although there are numerous examples of both suitable growth in hours and some of up to a year. It is therefore envisioned that simultaneous operation of the furnaces will be most efficient. For these types of crystals, this usually requires an initial "high temperature" followed by a long slow controlled cool-down cycle. Thus the use of a multiplexed central power distribution system might be a useful concept.

Usually, the growth of oxide and other compound crystals utilize quantities of solvents weighing several times that of the crystals grown. These solvents are usually discarded after one use. It would appear to be desirable or necessary

however to provide for means of extracting the crystals from the solvents and reusing them in order to avoid the cost of space transportation even on the space shuttle. This would be relatively easily achievable in the case of aqueous growth processes where the shuttle crewman may only have to resupply some nutrients to the batch after harvesting the crystals if the same crystal composition is to be grown again or the solution could be reprocessed to obtain the water for reuse. In the case of fused solvents with high operating temperatures (up to 1500°C for example), however the operation would be considerably more difficult. Current typical operations in this case involve the cooling to room temperature then the dissolving of the flux or glass solvent such as in a suitable warm acid that would not attack the crystals. The crystals would then be harvested and the dissolved flux precipitated or concentrated from the acid solution. The artists concept of this system shown in Figure 12 also depicts some auxiliary equipment for reprocessing solvents to be used in aqueous growth processes.

IV ELECTRICAL POWER SYSTEM

There are numerous methods to consider for obtaining electrical power in space. It is not the purpose of this report however to discuss them nor to necessarily make a selection of the most desirable. A few simple considerations, however, lead to believing that a nuclear reactor is probably the best basis for such a system.

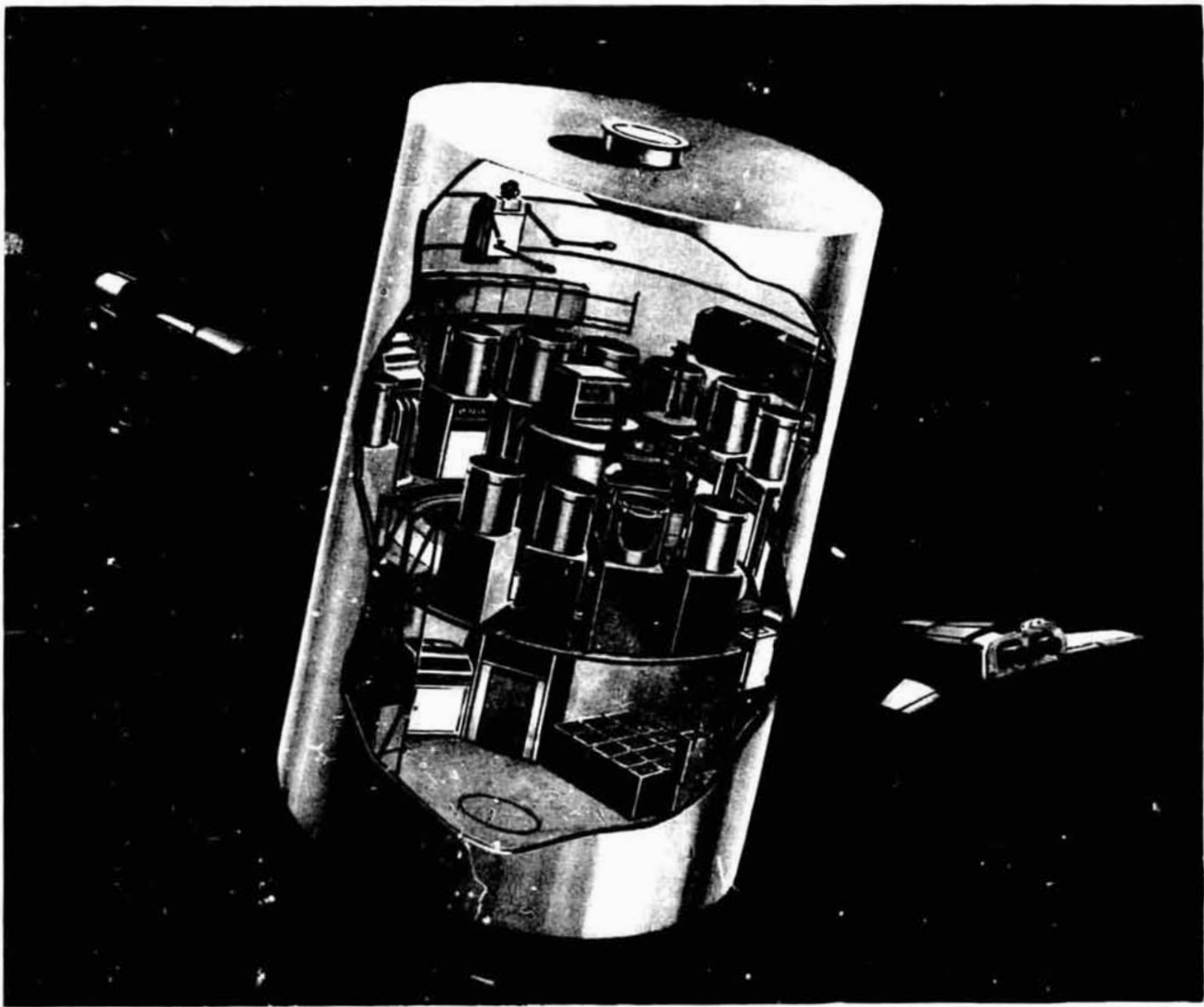


Figure 12. Space Processing Concept for Solvent Growth Process for Crystals

Power requirements are estimated to be about 30 KW for the float-zone growth process and 10 to 20 KW for the solvent growth process. To be on the safe side we will base our cost estimates on the higher of the two. Thus, a total power requirement of 50 KW is contemplated. This is clearly beyond the range of the state-of-the-art solar and isotope devices. In addition, the near earth orbit of the space factory will further militate against the use of solar power.

There is very little national effort devoted at the present time to the development of nuclear power plants in this range, so our estimates that follow are very speculative. Our investigations revealed that two basic approaches are under development: one is the zirconium hydride approach and the other, thermionic. The zirconium hydride reactor is in a relatively more advanced state of development than the thermionic reactor. But as distinct from the latter it requires a thermoelectric system to convert the thermo output of the reactor to electrical energy. This system has yet to be fully developed. But even after it has been successfully developed the overall efficiency of the zirconium hydride power plant is very likely to be less than 5 percent as compared with the 10 percent efficiency rating expected of its thermionic counterpart.

For the above reasons we have chosen a 50 KW thermionic nuclear reactor as the power source for crystal growth in space. According to the estimates of an industry source currently engaged in the early development of such a reactor**

* GE Space Division

the total cost would amount of about \$17 million (not including its pre-production development costs) broken down as follows:

Reactor	\$10M
Shield	2
Heat rejection system	2
Control	1
Power conditioning unit	1
Miscellaneous	1
	<hr/>
	\$17M

The reactor would have a service life of 20,000 hours at 100 KW output. But when operated at reduced temperatures for a 50 KW output its life could be extended to 30,000 hours or roughly 3.5 years. Its estimated weight is about 44,000 lbs. (of which 40,000 lbs. is shielding) which at \$100/lb. for launch services in the shuttle would add \$4.4 million to the total cost. Thus, the total power bill would be \$21.4 million over a period of 3.5 years, or \$6.1 million per year. Apportioned on the basis of 30 KW for float zone and 20 KW for solvent growth, we therefore estimate that the power cost would be \$3.66 million/year for the former and \$2.44 million/year for the latter.

V. PLANT COSTS

A. Float Zone Refined Process for 20 Boules

<u>Factory Costs (includes development)</u>	<u>\$ millions/year</u>
Structure 1500 lbs.	1.75
Mechanical system 500 lbs.	.8
Electrical 500 lbs.	.3
Induction heater and processing system 2550#	2.4
Ground support equipment	.8
System Eng. and test	.52
Program management	.42
Ground operations	.21
	<hr/>
	7.20
Contingencies	2.52
	<hr/>
	9.72

Silicon Prices

	Per gm	Per lb.
High purity powder	12¢	\$55
1 1/2" dia. boules	40-50¢	\$200-225
1 1/2" wafers	\$1.00	\$450

Operational Costs

	\$ millions/year
Factory (10 year life)	.97
Transportation	
Factory (5000#/10 years)	.05
Resupply (5000# x 10 flights @ \$100/lb.)	5.00
Power (unit cost + transportation)	3.66
Ground Proc. of charges, Wafers, etc.	
50,000 x \$60/lb.	3.00*
Raw materials	2.75
Service and maintenance	.25
	<u>15.68</u>

*assumes cutting and polishing and no ribbon drawing

Summary of Float-Zone Refined Process

	Production Cost \$ Millions	\$ Millions Value @ \$450/#	\$ Millions Value ● \$1000/#
Factory Output			
@ 40% yield or 20,000#/year	15.68	9.0	20.0
@ 80% yield or 40,000#/year	15.68	18.0	40.0

If these costs are correct, it is obvious that the present yield (40%) and selling price (\$450/#) for silicon wafers are incompatible with space processing. Either the costs/price or the yield, or both, would have to be improved substantially such

as by drawing ribbon directly from a molten boule to cover the costs of performing this operation in space.

B. Fused Solvent Crystal Growth

\$ Millions

Factory Costs (including development)

Crystal processing equipment 2400 lbs. (crucibles, housing, insulation, cable)	2.0
Structure 1500 lbs	1.65
Electrical system 500 lbs.	.3
Mechanical systems 100 lbs.	.2
Ground support (15% of airborne)	.63
System eng. and test (of airborne)	.42
Program management	.33
Ground operations	.17
	<hr/>
	5.70
Contingencies	2.3
	<hr/>
	8.0

Crystal Costs

Raw materials from 2.0¢ to \$100/lb.
assume \$3.00/lb. average
Crystals currently \$5000-\$15,000/lb.
but estimated to drop to \$1000-5000/lb.

Operational Costs

Factory (10 year life)	0.8
Transportation	
Factory (10,000#/10 years)	0.1
Resupply (20,000#/year x \$100/lb.)	2.0
Ground costs for materials and processing	2.41-4.86
Service and maintenance	0.25
	<hr/>
	8.00-10.45

Summary on Solvent Growth Process

Factory output	Production Cost \$ Millions Year Average	\$ Millions Value @ \$1000/#	\$ Millions Value @ \$3000/#
@ 25% yield or 5000#/year	8.00	5.0	15.0
@ 40% yield or 8000#/year	10.45	8.0	24.0

In this case, the estimates show that with an anticipated future reduction of price to \$1000 per pound for sophisticated compound type electronic crystals the total annual production cost will not be covered by revenue at 40 percent yield.

VI. ECONOMIC CONCLUSIONS

Having estimated the probable production cost of two types of crystal growth in space, we are now in a position to evaluate the economic feasibility of space processing versus earth processing.

It was postulated in the previous analysis that the optimum scale of production or minimum production cost can be easily reached as production volume increases. Furthermore, the competitive structure of the crystal industry tends to reduce crystal prices to the level of direct production cost plus overhead and profit. From the data we gathered, overhead cost and profit account for roughly 50 percent of the sales price. Thus, as the volume increases, crystal prices will be normalized to about twice the direct production cost.

The demand model yields the result that silicon demand for MOS will reach the range of \$380-400 millions by 1975 and the demand for garnets for bubble memories, \$1.168-1.295 millions by 1980. Given such ample demand, we can assert that normal crystal prices will prevail well before 1980. Since silicon already enjoys volume demand, further decline in its price from about \$450 per pound is unlikely save for major innovations in crystal growing technology. For the exotic crystals currently selling at high prices with negligible volume, it is generally expected that prices will be reduced to about 1/3 of the current levels as demand increases. For example, from Table 14 the price of gallium phosphide is expected to drop to \$8 per gram by 1980 from the current \$22 per gram (about \$3600 and \$9900/lb. respectively).

Since the future production cost on earth is not available, and the expected future prices of crystals can be more or less related to the future production costs, we will evaluate space processing by comparing its production costs to the expected future prices of crystals. Space processing is advantageous if the expected future prices of crystals can cover the total cost, including direct production costs, overhead and normal profit.

Table 15

Predicted Space Processing Costs, Normal Prices and
Market Prices for Silicon and Gallium Phosphide - 1980

Silicon -- Float-Zone Refined Process

<u>Yield</u>	<u>Production Cost/Pound¹</u>	<u>Normal Price/Pound²</u>	<u>Market Price/Pound³</u>
40 percent	\$784	\$1,568	\$450
80 percent	\$392	\$ 784	\$450

Gallium Phosphide - Solvent Growth Process

25 percent	\$1,600	\$3,200	\$3,632
40 percent	\$1,306	\$2,612	\$3,632

¹ Derived from the summary tables on float-zone refined process and solvent growth process.

² Normal price = production cost + overhead + profit = production cost x 2

³ Assume silicon price to remain at present level and gallium phosphide price to drop from the current level of \$22 per gram to \$8 per gram.

Table 15 is constructed by taking silicon as a representative product from the float-zone refined process and gallium phosphide from the solvent growth process. For silicon, even 80 percent yield, the price of \$450 per pound cannot cover overhead cost and normal profit. However, space processing of gallium phosphide looks promising from an economic viewpoint; even at a conservative estimate of 25 percent yield, the normal price, i. e., direct production costs plus overhead cost and normal profit is still less than the expected price from earth processing by \$ 432 per pound, or 11 percent. Since the demand for garnets in 1980 has been estimated at 115,000 to 130,000 lbs. per year this indicates that a total saving of over \$ 50 million per year could be expected.

However, the above estimate is predicated on the assumption of a 20% profit margin in the normal price of garnets. There are reasons to believe that this is too high to be compatible with the competitive nature of our economy. The electronics industry, for example, reaching a period of maturity and intense competition in the late 1960's, was able to maintain a profit margin of only slightly over 10% while seeing its return on investment (book value) decline from 14.6% to 10.16%⁽¹⁹⁾. It would therefore appear to be a reasonable expectation that in the long run, say by 1985, roughly the same level of profit margin and return on investment would also prevail in the production of garnets. Hence, the normal price of garnets could actually decrease by another 10% from 3,200/lb. to \$2,880/lb. at 25% yield or from \$ 2,622/lb. to \$ 2,351/lb. at 40% yield.

Moreover, in many ways the above estimate may be interpreted as a conservative one. In the first place it is confined to only one important application of one type of high-priced crystals, via., garnets in computer memory. There

are many other areas of application of this and other types of high-priced crystals where a reduction in cost will lead to substantial increase in demand. These include, as have been discussed earlier in this report: the use of electro-optic crystals for holographic memories and laser communication, the use of optoelectronic crystals in LED displays, etc. Since no historical trends have been established yet by these new applications, it is considered ill-advised to attempt any quantitative forecast of their demand. We are confident, however, that their expanded use will mean additional savings through the production in space of their high-priced crystal components.

Secondly, we have assumed a conservative 25 percent yield of crystals in the above estimate of savings. This is the yield generally obtained in today's earth-bound processes, and is partially attributable to the gravitational pull and minute tremors inherent in the terrestrial production environment. With these obstructive forces removed in a space environment there seem to be good reasons to expect a higher yield with consequent reduction in cost of production and concomitant rise in savings. For instance, if a 40% yield were achieved, which is not impossible, the annual savings in the production of garnets for computer memory devices would then be \$118 million as compared with \$50 million at 25% yield. However, because of the lack of hard data we have chosen not to use it as a basis for estimating potential benefits.

Finally, there are increasing evidences that significant qualitative benefits may accrue to crystals grown in space with its attendant unique characteristics of zero gravity and freedom from vibrations. For instance, we may expect space-grown crystals to have more regular shape thus permitting

greater yield, or to have lower defect concentration making possible higher performance. There is also the prospect of growing substrate platelets with natural faces, which if successful will greatly reduce cost because the expensive wafering and polishing operations will no longer be necessary. Although somewhat off in the technological horizon, these are nevertheless important qualitative benefits of space production which will have far-reaching impact on the whole spectrum of crystal technology for a long time to come. It would be unfortunate to have them obscured by an overriding preoccupation with short-term cost considerations.

If the above discussion seems tinged with optimism, we wish to emphasize the restraint currently placed on the optimism. First, the cost of space-grown crystals is a preliminary estimate attempted before the concept of growing crystals has been tested in space and before the technical details of the space factory have been completely worked out. Second, the projected maximum decline of earth-grown crystal prices in one example from \$22/gram to \$8/gram is based on the personal opinions of industrial experts. Presumably it reflects to a large extent the industry's prevailing thinking; however, if either of these two estimates should prove to be incorrect the total amount of savings determined earlier would be significantly affected. Finally, there is some questions at this time to whether the 50 KW nuclear power plant required by the space factory would be ready by 1980. The thermionic nuclear electric propulsion system currently under preliminary engineering study at the Space Division of General Electric is not expected to be ready for flight

test until 1983. We are hopeful, however, that additional motivation, such as the need for such a power system being explored here, might serve to shorten the schedule to meet the demand.

In conclusion, we feel that there is sufficient economic justification to warrant the funding of planning and development studies which are essential to the growth of crystals in space by 1980. The demand by 1980 and estimated savings for high-valued garnet crystals as substrates and epitaxial films for magnetic bubble memories and of high-priced electro-optic crystals for a wide range of advanced applications economically justify the funding of studies directed toward the space processing of these compositions

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APPENDIX A

COMPUTER MEMORIES

1. Introduction and Historical Perspective

Since the beginning of the modern computer era about 20 years ago, the size of memory directly accessed from a computing system has increased from a few thousand words (typically 10 to 36 bits of stored information per word) in the early and mid-1950's to well over several million bytes* currently in use on many systems today. Numerous physical mechanisms and devices have been proposed for memory storage systems with most technologies falling by the wayside as a result of inherent materials and device fabrication problems, and therefore uncompetitive costs. In the meantime, the magnetic core, introduced in the mid-1950's, and digital drums, and eventually discs, became the dominant technologies for direct access storage. Originally, these two technologies were far from what they were capable of providing both in size and speed. As the need for additional storage arose, cores and discs were capable of providing increased size and speed at a reduced cost per bit (binary digit) of stored

*One byte = 8 bits = 1 character

information. While there was no lack of alternative technologies in the 1960's, they could not easily challenge the potential improvements of cores and discs.

Current state of the art has room for improvements in cores and discs. However the ensuing limitations in these technologies and the appearance of numerous diverse applications permitting special purpose tailored systems have resulted in the emergence of a wide range of advanced technologies as alternatives or supplements.

Some of the more notable technologies currently receiving considerable attention are:

1. Semiconductor integrated circuit memories
 - a. Bipolar
 - b. MOS (metal-oxide-semiconductor)
 - c. Charge coupled (or charge transfer) devices
2. Magnetic domain memories
 - a. Magnetic bubble domains
 - b. Domain tip (DOT)
3. Holographic laser systems
4. Magneto-optic beam addressable storage
5. Surface wave acoustic delay lines
6. Switchable resistances
7. Strain-biased electronic ceramic page composers

The trends of the advanced technologies are toward media with increased storage density and read/write capabilities and toward memory systems with increased speed of the electronic scanning type. The pacesetters for meeting future memory requirements are those of the circulating information and beam addressable types. To a large extent these utilize electronic single crystals with ferromagnetic, ferroelectric, electro-optic, magneto-optic, piezoelectric and semiconducting properties. They can be classified into the integrated circuit memories based on silicon crystals and the magnetic bubble, holographic, magneto-optic beam addressable, and surface wave memories which are based on ceramic oxide single crystals.

In summarizing the technical assessment on computer memories, magnetic bubble and holographic memories using electronic ceramic oxide single crystals will play a dominant role in computer systems of the next decade. Bubbles, currently based on rare earth iron garnet single crystals, will complement silicon semiconductor memories in the computer hierarchal structure. They will fill the "access gap" between electronically addressable memories and electromechanical storage systems. Holographic systems, using electro-optic crystals, will be used by the late 1970's for very dense storage with reasonable access times and thus offer great potential for mass storage and even larger tape replacement type storage. At the present time surface wave acoustic delay lines using piezoelectric

crystals are not a serious challenger for mass memories; whether or not it becomes a potential candidate remains to be demonstrated. Magneto-optic beam-addressable memories, probably utilizing ferrimagnetic crystals, will not be utilized effectively in mass memories unless mechanical motion can be eliminated.

The importance of garnet single crystals to magnetic bubble technology cannot be overstressed. The potential importance of space processing for the growth of more perfect platelets and films with high yields in quantities required for further development and production cannot be overstressed either. Microgravity growth techniques hold the potential for controlling the perfection and uniaxial anisotropy which is the key to bubble size, and bubble movement, and therefore information storage and transfer efficiency. It also provides the prospects for controlling defect concentrations, and of growing substrate platelets with natural faces thus eliminating the wafering and polishing operations.

The use of electro-optic crystals for holographic memory storage media and page composers would be enhanced by the growth of large, high quality crystals under microgravity conditions, especially a natural face along a preferred plane. In fact electro-optics is where space crystal growth could show one of its biggest payoffs; it is an area which could be economically viable since there are demands for electro-optic crystals

in optoelectronics, laser communications, surface acoustics and pyro-electric thermal sensing as well as in computers.

At the present time space processing would not provide any economic advantage for delay line or magneto-optic beam addressable memories. While microgravity most likely would provide piezoelectric and ferri-magnetic crystals of superior quality, the market forecasts show that there are other problems to be resolved and potential to be demonstrated before the technologies become serious challengers.

In the next two sections we will look at the current core and disc technologies and the advanced technologies which have been proposed in the literature over the past years. Since switchable resistances and strain-biased electro-optic ceramics are potential technologies for future memory systems, they will be discussed briefly. Semiconductor integrated circuit memories and charge coupled devices will be discussed since they will be contenders along with oxide single crystal systems for a place in the computer hierarchy. Relative to the advanced technologies employing oxide electronic crystals, the following points will be considered:

- a. General Concept and Principle of Operation
- b. Future Need for Electronic Single Crystals and Space Processing
- c. Market Forecast

In order of discussion the specific approaches are

2. Current Technologies - Cores and Disc Memories
 3. Advanced Technologies - Single Crystal Silicon, Non crystalline,
Polycrystalline
 - a. Polycrystalline and Glass Media Technologies
 - b. Integrated Circuit Memories
 4. Advanced Technologies - Ceramic Oxide Single Crystal Systems
 - a. Magnetic Bubble Domain Memories
 - b. Holographic Memories
 - c. Surface Wave Acoustic Delay Line Memories
 - d. Magneto-optic Beam Addressable Memories
2. Current Technologies - Cores and Disc Memories

Cores are tiny ring-shaped magnetic ceramics (polycrystals called ferrites) which are strung on a mesh of fine wires. At the moment their advantage is low cost which is about one cent per bit of storage capacity. However, this cost mounts rapidly since it would cost about 100 million dollars to duplicate the estimated capacity of the human brain - 10^{10} bits - with cores. An electronic telephone central office requires 10^7 bits costing about 100 thousand dollars in a wire system. In order to assure reliability twice this capacity is required; thus a user would like to find a less expensive alternative.

Magnetic disc memories are used for high capacity storage. These systems depend on the mechanical movement of a storage medium below a "head" that can read out data that were previously entered, or write in fresh data. In magnetic recording in continuous media, the "heads" or read/write transducers can be shared over a large number of bits of information. This greatly reduces cost. However, the sharing of transducers results in slower access times since they must be moved mechanically among the numerous tracks. One cannot manipulate the stored information without reading it out and writing it in again. This process take appreciable time. In addition, since disc systems are mechanical, they are not as reliable as the all-electronic system. While mechanical motion has brought simplicity and low cost into storage technology in the past, it is now becoming one of the major problems.

Plated wire is a current electronically addressable memory technology. Because of the small volume usage in comparison to cores and discs, it will not be considered relative to advanced technologies.

3. Advanced Technologies - Non crystalline, Silicon Crystal, Polycrystalline Systems

a. Polycrystalline and Glass Media Technologies

Advanced technologies are being investigated whose storage media consist of glass (amorphous) and polycrystalline materials. These include

switchable resistances, strain-biased PLZT, and domain tip memories (DOT). Switchable resistance devices are those capable of exhibiting a variable resistance with a threshold in voltage or current. The chalcogenide glasses based on telluride compounds have received attention over the years. Historically such devices have fallen by the wayside. Before any commitment can be made to the technology, therefore, there must be developed a better understanding of the switching mechanisms and a demonstration of device capability.

Domain tip (DOT) technology is a moveable domain memory using polycrystalline (poly-crystal as opposed to single or mono-crystal) films as storage media. These are in current use and their future will be discussed relative to the magnetic bubble concept.

Strain biased PLZT page composers are transparent electro-optic, ferroelectric polycrystalline ceramics formed by the hot pressing of lead titanate, lead zirconate and lanthana powders. They offer media for high density holographic storage and have received considerable attention over the past two years. The basic materials appear to be readily available and relatively inexpensive. However their use in memories from a cost/performance standpoint remains to be seen.

b. Integrated Circuit Memories

The use of integrated transistor memories is well established. In

fact they are already appearing in products. These devices are fabricated on or within single crystal semiconducting silicon. While a mature technology, they are a major contender for future memories because of advances in photolithography, process technology, cost reduction, the development of new solid state device concepts, and the rapid translation of the concept to a working device.

By definition an integrated circuit is an interconnected array of active (transistor) and passive elements (conductors, resistors, and capacitors) inseparably associated on or within a single crystal silicon substrate. The two types are bipolar and field effect integrated circuits. Of the two, the use of bipolar integrated circuits as storage elements is well established for high-speed main memory applications where cost/performance for medium size systems (less than 10^8 bits) is of primary concern. These devices are too expensive for mass memory and do not offer the density potential of other technologies. High speed is not essential to mass memory. Field effect integrated circuits, based on metal-oxide-semiconductor (MOS) technology, offer a number of advantages. These include high density, equal or better speed, and lower cost and higher yield as a result of simplified fabrication.

Integrated circuit memories already surpass cores in speed and are within striking distance in cost, power and reliability per bit of stored

information. The debate of bipolar versus MOS is not settled at this time; however, it would appear that MOS would have advantage because of its lower cost. Integrated circuit memories have the advantage of being compatible with the other parts of computer technology at the speed and density required.

A new type of semiconductor is the charge-coupled device (CCD). The essential idea is to store information in the form of electric charges in a potential well. The charges are shifted along a silicon substrate through simple voltage switching on a pattern of electrodes. Basically it is the electrical equivalent to the magnetic bubble which is discussed in the next section. In magnetic bubble memories magnetic charges are generated at one point and moved around in a shift register fashion.

There is general concensus among scientists working in the field that charge-coupled devices and other similar surface charge transistor technologies will eventually emerge as the preferred ones. At this point CCD's are still laboratory devices. Their concept is limited to shift register operation. It remains to be demonstrated whether they or MOSFET's will be feasible in terms of cost and density as related to access time. Currently they are too slow for main memory; they are more compatible with large storage where writing time is not so critical. Unless significant advances can be made in device speed, the potential of these

devices may diminish. MOSFETS in comparison appear to offer a wider range of applications as well as having more potential.

4. Advanced Technologies - Ceramic Oxide Single Crystal Systems

a. Magnetic Bubble Domain Memories

(1) General Concept - Principle of Operation

Magnetic bubbles are a new technology wherein a magnetic material is divided into regions that are magnetized in different directions. These "domains" can be formed into small "bubbles". Data bits of information are stored in the form of "bubbles" and move in thin single crystal films of magnetic material. Physically the bubbles are cylindrical domains whose polarization is opposite to that of the thin magnetic film in which they are embedded. They can be moved from point to point at high velocity.

(2) Future Needs for Electronic Single Crystals and Space Processing

An oxide single crystal material with unique magnetic properties is the key element of a magnetic bubble device. The major technical problem is one of obtaining crystals of the required quality and with adequate parameters. Several classes of crystals exhibit bubble behavior but only a few within these classes meet the requirements for reasonable density and speed. The single crystal must: (1) sustain small bubble-like magnetic regions so

that information can be stored more efficiently than before; and (2) permit the bubble to run at a high velocity so that tremendous amounts of information can be processed in a relatively short time.

Crystals were prepared initially by flux-growth methods. Rare-earth ferrites were first investigated. These are a special class of ferrites with the chemical formula $RFeO_3$, where R represents yttrium or one or more rare-earth elements. They are grown as single crystals by mixing raw ingredients with a suitable flux, melting the mixture in a crucible, and allowing the melt to cool over a period of several weeks. At the end of that time a few crystals of good size will normally be found. Another method is to pull single-crystal rods directly from the melt and cut wafers from the rods.

In general, the bubble size of the orthoferrites is too large. This is unsuitable for the very high density application required for mass storage. Samarium terbium orthoferrite comes close to satisfying the need for a bubble mobility which will allow a data-processing rate of a million bits per second; however, it fails to attain the packing density of a million bubbles per square inch because the bubbles are three times too large (one mil in diameter). Another family, the magneto-plumbites such as $BaFe_{12}O_{19}$ can be grown but the resultant bubbles are too small for practical devices. The smallest bubbles yet observed - one micron or 1/25 mil in diameter -

have been in hexagonal lead ferrite ($\text{PbFe}_{12}\text{O}_{19}$), but they move too slowly.

Recent work indicates that single crystal rare-earth garnets such as europium erbium iron garnet with the proper composition can yield bubbles of 0.25 mil diameter. The preferred properties of bubble materials as shown by the garnets are shown in Figure A1. Flux techniques for growth are well established. However, the most economical device configuration will probably involve a structure wherein an epitaxial single crystal film has been produced. Specific compositions include the deposition of single crystal of erbium europium gallium iron garnet, terbium erbium iron garnet, gadolinium terbium iron garnet and yttria iron garnet on solution grown substrate crystals of $(\text{RE})\text{Ga}_5\text{O}_{12}$ where Ga represents gallium and RE, rare earth oxides of dysprosium, gadolinium, samarium up through neodymium.

The importance of single crystals to the future potential and manufacture of bubble memory technology cannot be overstressed. Bubble size is supported by the uniaxial anisotropy of the crystal which is thought to be induced by strains accompanying growth striations. Without advances in crystal technology and fabrication, bubbles appear to be limited to their present density and speed. Yields with present growth techniques are low; obtaining the crystal quantities necessary for production and development is a problem. Garnet crystal will have to be available in the large quantities that silicon is available for integrated circuit manufacturing.

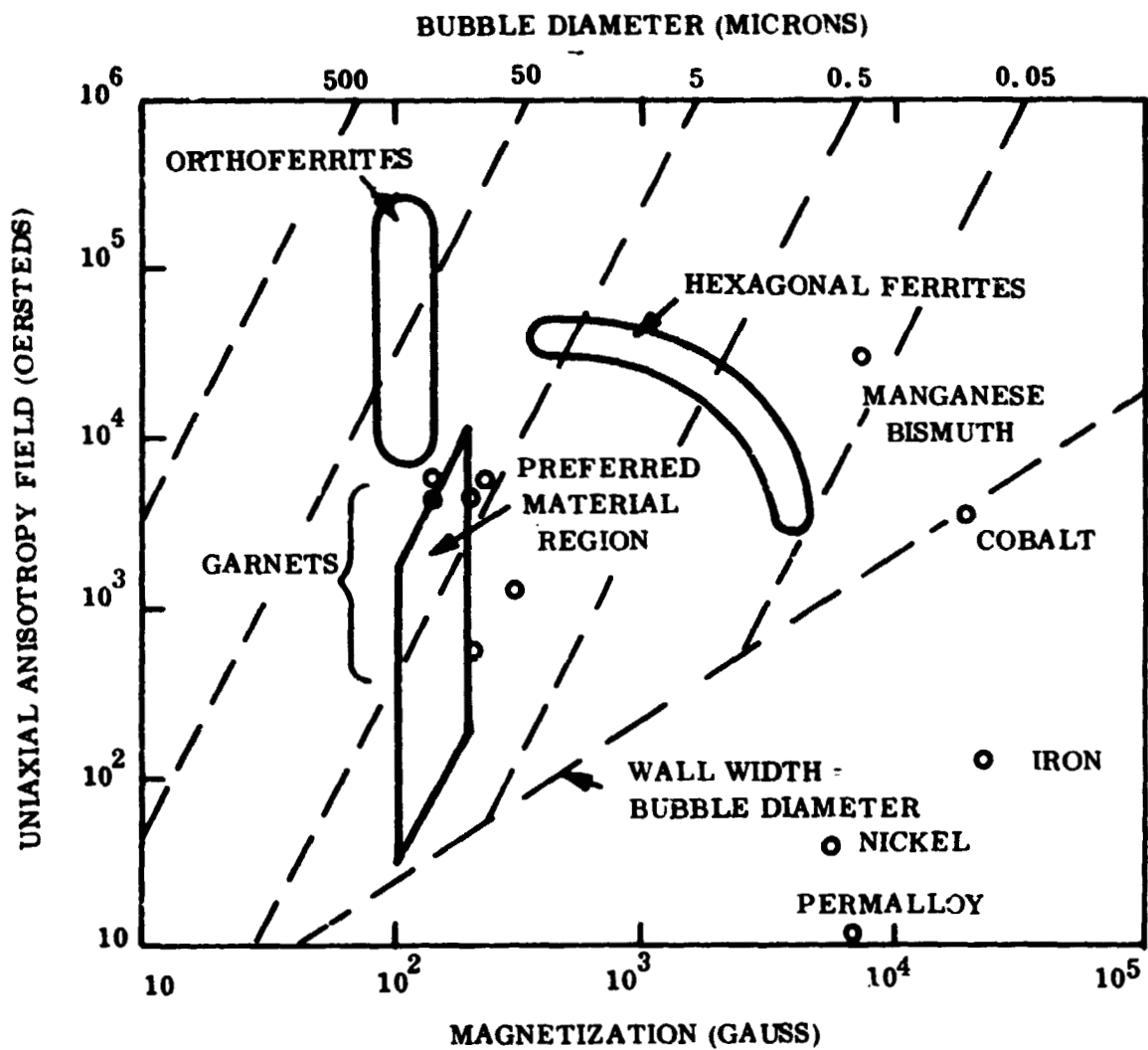


Figure A-1. Properties of Magnetic Bubble Crystals Uniaxial Anisotropy vs. Magnetization and Bubble Diameter (After Bobeck, A.H. and Scovil, H. E.D., *Scientific American* 224 (6) 78-90 (1971)).

The space manufacturing of garnet crystals may provide some of the advances necessary for obtaining sufficient quantities of highly perfect crystal with good yields. The crystal boules for substrates of rare earth gallium garnets are grown from the melt by the Czochralski technique. The substrates are cut, wafered and polished from the boules. Rare earth and yttrium gallium iron garnet single crystals are deposited by liquid phase epitaxy (LPE) from fluxed melts.

The garnets have zero magneto-striction but exhibit the largest and most uniform uniaxial regions which are needed to form cylindrical magnetic domains in the presence of a bias field. The easy direction of magnetization should be perpendicular to the plate to support bubbles with 5 to 25 micron diameter. The uniaxial anisotropy is thought to be induced by the ordering resulting from growth and not uniform stress in the film. The regions of uniaxial anisotropy are growth bands or striations. They are compositional variations and result from temperature fluctuations during the growth process. These are thought to be process-independent and gravity-related. The fluctuations are caused by thermal convection currents which are driven by the force of gravity. If growth striations are responsible for uniaxial anisotropy in iron garnet, space processing is of interest to develop crystal growth techniques which will allow this effect to be controlled.

The growth habits of flux grown crystals produce natural facets; the material directly beneath the facets are magnetically uniaxial. The formation of facets can be controlled or prevented by the advancement of a flat solid-liquid interface. This is one of the promising prospects of space growth of garnets.

The substrate defects and surface scratches are greatly enhanced in the film crystals. The faceting and hillock concentrations are increased by the high temperature processing. The growth of platelets with smooth, flat perfect surfaces in a direction such that the surfaces are along specific crystallographic planes is another unique potential of space processing, which would promote perfection in the epitaxial films. In addition, each section of the substrate boule has to be wafered parallel to a specific plane because of the growth induced magnetic alignment relative to a natural face. Platelet growth under microgravity may eliminate the wafering step and prevent mechanical cracking of this high value, but brittle, crystal.

(3) Market Forecast

In forecasting the market growth for bubbles, the following factors must be considered:

1. Where will bubble memories fit in the computer memory hierarcial structure?

2. How will they compete with current technologies in performance and cost?
3. How will they compete with other advanced technologies in performance and cost?

Projections to 1975 are that the electronically addressable memory technologies - semiconductor and ferrite-core - and the electro-mechanical - magnetic drums, discs and tapes - will continue to dominate until 1975. By 1975 semiconductors will replace a significant part of the ferrite-core markets. Beyond 1975 drums or fixed-head files will no longer compete with the lower cost semiconductor technology. By 1985 the dominant forms of electronically addressable and electro-mechanical storage will be, respectively, semiconductor and magnetic discs and tapes.

The most commonly identified hardware problem is that of the gap that exists between electronically and electro-mechanically addressable storage. With all of the levels in a memory hierarchy, there is still a difference in access time of three to four orders of magnitude (10^{-6} to 10^{-2} seconds) between the electronic bulk memory and the electromechanical peripheral storage unit. This gap has existed since the development of the computer and projections of future technology indicate that it will continue for some time.

Bubbles are an excellent candidate as an intermediate memory to fill the gap if its cost can be reduced. This is very likely. It will be economical in smaller sizes and capable of very respectable bit-transfer rates. At the present time the electronically addressable memories are the poor price/performance technologies. If semiconductor technology costs are reduced the gap may narrow to two orders of magnitude. In this case, the successful introduction of gap-filling technology such as bubbles will be more difficult.

During the next decade integrated circuit and magnetic domain technologies will complement one another in hierarchal computer structures. By 1975 semiconductor bipolar and MOS integrated circuits will be used in computer mainframes. These will be capable of subnanosecond speeds and used in the fast memory section. Although semiconductor technology has reached a high degree of maturity, growth will continue because of improvements in photolithography and semiconductor processing techniques.

In the rest of the computer system where bulk storage is important, memory blocks of moving magnetic domain storage will be used (Figure A2). They will provide high density storage with microsecond access times at speeds competitive with current core, disc and drum memories.

Currently magnetic domain storage elements, especially the DOT's, offer fast memory blocks at low cost and power dissipation with high

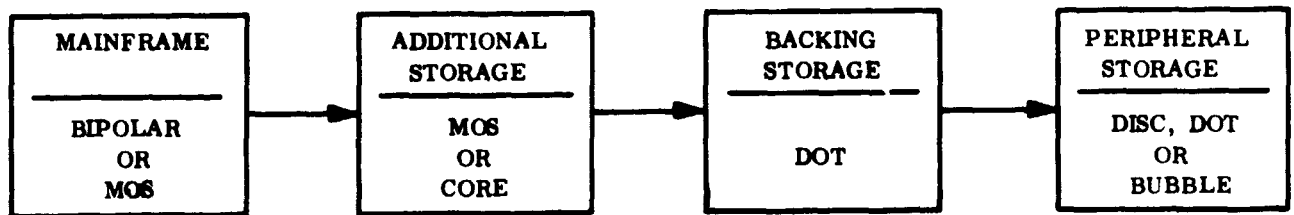


Figure A-2. Hierarchal Computer Structure (After Allan, R.S., Electronic Design 19 (25) 22-24 (1971)).

reliability. The low costs have been attributed to excellent yields. DOT block access time is less than fixed-head discs and their non-mechanical operation make them more reliable than the moving mechanisms of discs and drums. Cost-wise they are competitive with disc and drum memory and an order of magnitude less than semiconductors and cores. However, when commercially available, bubble memories will leave all other types, including DOT's, far behind in density and cost advantage.

The relative merits and costs of bubbles, cores, IC's and charge-coupled devices are compared in Table AI. CCD's and bubbles will cost less than integrated circuit memories. This will be on the order of millcents per bit by 1975. Bubbles will probably have the lowest cost of the two, but currently are slower. CCD's will fill the 10-20 MHz regime; bubbles cannot reach this and be competitive. All three advanced technologies exhibit the adaptability which may overcome the size and access limitations of cores.

Present densities in bubble memories of 10 megabits per square inch can be easily designed and evaluated. Work is in progress to increase this to 1000 megabits per square inch, the highest density of any existing technology. In comparison to disc files, a moderate size disc file - 10 million to 100 million bits - would occupy two feet in a side; the bubble memory would require only 2 to 3 inches on a side. For power, the bubble

TABLE A-1
(1)

RELATIVE MERITS OF MEMORY TECHNOLOGIES

Simultaneous RAM Specs.

	CORE		IC		BUBBLE		CCDs	
	Now	Future	Now	Future	Now	Future	Now	Future
Components per bit (#)	1	1 ⁴	4	1-2	n/a	n/a	n/a	n/a
Bit Density (bits/inch ²)	3 x 10 ³	10 ⁴	5 x 10 ⁴	10 ⁶	1.5x10 ⁶	10 ⁷	5x10 ⁵	4x10 ⁶
Maximum block (or chip) size (bits)	1	1	10 ² -10 ³	2x10 ⁴	10 ⁴	10 ⁵ -10 ⁶	10 ³	4x10 ⁴
Power per bit (microwatts)	100	50	3x10 ² -10 ⁴	10	0.5	0.2	n/a	15
Cost (cents per bit)	1	0.5	1-10	<0.1	n/a	<0.01	n/a	<0.01

	CORE	IC	BUBBLE	CCDs
<u>Technology Quality</u>				
Process Simplicity	good	complex	good	good
Reliability	good	low-good	good	good
Cost/Performance Trade-offs	limited	good	good	good
Pactitionability and Architecture Flexibility	limited	good	best	good

Note: n/a = not applicable

(1) After Morton, J.A., The Electronic Engineer, 33-35, August 1971.

requires 10 watts, but the disc needs 500 watts. Access time for the bubble is an order of magnitude less while its storage density is three orders of magnitude better. The price probably will be one-tenth that of disc files per bit of storage. The cost of the two or three inch cube might be then about \$300.

b. Holographic Memories

(1) General Concept

Holograms are photographic records made through a form of lensless photography. They are best known for their ability to produce 3D images. However, equally important is their potential to store an enormous amount of information. Holographic schemes in a stationary continuous media can circumvent the mechanical motion of the rotating disc and provide large storage capacity at reduced cost. Optical techniques offer the potential of high information storage density since the information packing density is theoretically limited only by the wavelength of light. A figure of the order of 10^{12} bits/cm³ can be quoted as a theoretical limit for information stored in a volume of a medium.

(2) Principle of Operation

Holographic memories have the general arrangement shown in Figure A3. It consists of:

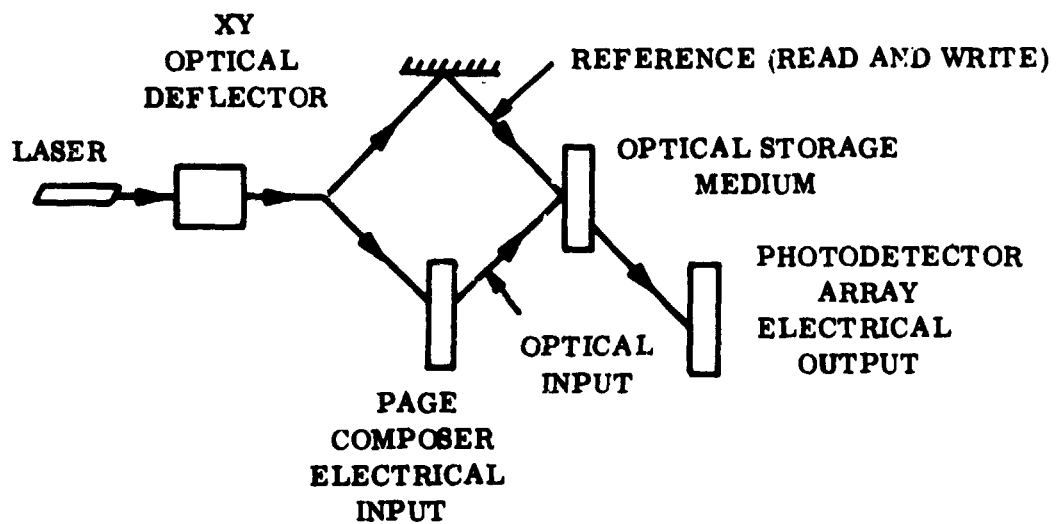


Figure A-3. Holographic Optical Memory (After Taylor, G. W. and Kosonocky, W.F., IEEE Trans. Sonics and Ultrasonics, SU-19, 81-99 (1972).

- (1) Deflector for the laser beam used for reading and writing
- (2) Optical storage medium
- (3) Page composer or optical pattern generator for converting electrical signals into an optical pattern of the type needed to write into the memory
- (4) Photodetector for converting optical read-out signals into suitable electrical signals.

In operation, acousto-optical crystals deflect a laser beam in proportion to the frequency of sound waves passing through them. The collimated, deflected, beam is split into object and reference beams. The object beam illuminates a page composer, which is, in effect, an electronically variable reflective data mask. Light from the page composer is now spatially modulated by the data to be stored. It interferes with the reference beam on the selected area of the recording medium to form a hologram. For readout the object beam is blocked and the reference beam, now serving as a read beam, projects the contents of the selected hologram onto the readout plane.

An electroptic crystal functions as a holographic plate. The crystals record the interference patterns of the light waves as the laser beam is split into two parts - reference and object beams. The reference beam shines directly on the crystal, while the object beam shines through a

transparency of the object being stored. After a hologram is formed through the one-centimeter thickness of the crystal in one direction, the crystal is rotated one fraction of a degree for each new hologram to be stored.

Holographic storage is basically an interferometric process. Information concerning each stored bit is spread over substantially the entire area of the hologram. Reconstruction of the stored pattern occurs by diffraction without the need for imaging optics. Further, since diffraction can occur directly from optical variations in the index of refraction in the recording medium, no analyzer is needed.

(3) Future Needs for Electronic Single Crystals and Space Processing

The technical problems are centered around the need for lasers, light deflectors, page composers, and new storage materials, all of which are based on electronic single crystals. The first has been discussed in Sections C and D, on Optoelectronics and Optical Communication Systems; however, page composers and storage media suitable for holographic recording are the most important areas in need of further development.

Volume holography constitutes the only optical storage technique that allows straightforward exploitation of the greater potential storage capacity of thick media. Many different types of holographic storage media have been

investigated in the past ranging from dichromated gelatin to magneto-optic MnBi films. MnBi films offer the important feature of reversibility but have efficiencies of less than 0.1%. However, single crystals can be used as a holographic material. Electro-optic crystals represent the only type of holographic storage media to combine very high efficiency with reversibility.

The specific crystals referred to are lithium niobate (LiNbO_3), undoped or doped with iron, and barium sodium niobate ($\text{Ba}_2\text{NaNb}_5\text{O}_{15}$), doped with iron and molybdenum. The sensitivity of the materials is considerably better than that of most photochromics; their storage time is much longer since thermal fixing techniques for these crystals can achieve high erasure resistance. Lithium tantalate, barium titanate and bismuth titanate are also capable of recording volume holograms.

Lithium niobate, one of the most significant crystals, is grown directly from the melt and commercially available. Although crystal boules as large as one inch in diameter and six inches in length can be prepared in this manner, dynamic growth at elevated temperatures introduces chemical imperfection and compositional inhomogeneities. Compositional nonuniformity along the length of the crystal, nonuniform growth regions, and compositional differences from crystal to crystal arising from variations in the melt composition, rate of growth, crystallographic axis of pull, etc. cause variations in index of refraction and other properties which are essential to electro-optic applications. Distortion of the holographic patterns will

arise from long range refractive index variations. In addition a perfect surface is required; however, polishing introduces scattering centers causing short-range refractive index variations. Since optically induced electrical conductivity is the basis of holographic storage in these materials, a high defect density will probably interfere with the photo-induced charge transfer requirement of holographic storage.

The use of LiNbO_3 for hologram storage media would be enhanced by the growth of large, high quality crystals under microgravity conditions. It has been cited by crystal industry spokesmen that laser electro-optic crystals have the single largest potential. This in fact is where space crystal growth could show its biggest payoff since there are demands for large, perfect crystals in laser communications and optoelectronics as modulators, second harmonic generators and parametric oscillators, as well as computers for these crystals. These are discussed in detail in Appendices B and C. Further, surface acoustic, as well as storage media applications, demand a supply of large platelet crystals with flat, perfect surfaces. Microgravity growth offers the fascinating possibility of growing natural faces along a preferred crystal plane.

Ferroelectric-photoconductor sandwich structures have also been used to record holograms in bismuth titanate single crystals ($\text{Bi}_4\text{Ti}_3\text{O}_{12}$). There is, however, a severe problem in achieving both high resolution and

high diffraction efficiency. This puts the $\text{Bi}_4\text{Ti}_3\text{O}_{12}$ sandwich structure at a competitive disadvantage with thermoplastics and photoconductives which can achieve higher diffraction efficiencies.

Another important component of a holographic, optical memory is a page composer or optical pattern generator for converting electrical signals into an optical pattern of the type required to write into the memory. The optical pattern represents a page of information which is transferred holographically by forming an interference pattern to the optical storage medium. Gadolinium molybdate, $\text{Gd}_2(\text{MoO}_4)_3$, is a ferroelectric-ferro-elastic crystal which shows promise as a page composer. It is grown by the Czochralski technique and must be defect free so that it can be switched an indefinitely large number of times without fatigue. However, temperature fluctuations in the melt during crystal growth causes the boule diameter to change discontinuously. Thus, severe strain are introduced which influence the threshold field. In addition stoichiometry in the melt must be closely controlled and a flat solid-liquid interface maintained. Growth under micro-gravity in space would greatly benefit this crystal since it offers the prospects for providing the conditions for the advancement of a smooth planar solid-liquid interface and the elimination of turbulent convection giving rise to temperature fluctuations.

Bismuth titanate is a ferroelectric whose optical behavior is completely different from other ferroelectric crystals such as barium titanate,

triglycine sulfate and potassium dihydrogen phosphate. It provides nearly maximum transmission in the intensity of transmitted light and a most attractive material for a high-speed page composer.

The lamellar crystals of $\text{Bi}_4\text{Ti}_3\text{O}_{12}$ grown by the flux method are at most about 1 mm thick and possess a face area which is too small for practical display purposes. Efforts to grow them by other techniques have proven unsuccessful. To obtain a crystal area suitable for memory storage and display applications, it would be necessary to cut the plate-like crystals parallel to specific planes and stack narrow slices side by side, a tedious and costly procedure. This is a unique application for the growth of large, flat platelets in a zero-gravity environment.

Single crystals of lead molybdate (PbMoO_4) are important components in solid state acousto-optic light deflectors. The acousto-optic interaction is very large and has great advantage in optical deflection systems for holographic memories. Boules of 15 mm in length can be grown. At this time the quality of earth grown crystals is satisfactory. Space processing would not provide any economic or technological advantage.

(4) Market Forecast

The astronomical storage densities are far from practical for the near future. They will find real use by the late 1970's since they do offer

a high density, non-mechanical, medium access time store. They would tend to displace memories using magnetic surface recording rather than the internal memory such as core or semiconductors. The potential for dense storage with reasonable access times also make them attractive for larger tape replacement type storage. A million bit read/write memory is currently being built which may be the forerunner of a 10^{10} bit system. Single crystals can be regarded as serious contenders for dynamic storage and read/write memory applications. The successful implementation of fixing techniques has also opened new application areas for these materials such as read-only memories, storage for display devices, and holographic optical components where the nondestructive readout capability is important.

c. Surface Wave Acoustic Delay Line Memories

(1) General Concept and Principle of Operation

Surface waves represent one of the more recent technological candidates for mass memory. It has begun to receive considerable attention and has made substantial progress over the past two to three years. This progress has been aided by the fact that this phenomenon has many other potential applications, as well. These are discussed in Appendix E on Surface Wave Acoustics and Ultrasonics.

The principle of operation for surface waves is discussed in detail in Appendix E. For memory applications surface waves are most easily launched

in a piezoelectric crystal through a transducer consisting of two interlocking comb-like structures which are deposited on the crystal surface with a small high-frequency voltage applied between the two.

(2) Future Need for Electronic Crystals and Space Processing

Both the internal structure and the surface condition of the piezoelectric crystal are important. LiNbO_3 and $\text{Bi}_{12}\text{GeO}_{20}$ are good single crystal materials for analog operations. Analog mode is used due to a lack of digital instrumentation at these frequencies; single crystals will probably still be required for digital operation due to the large losses at high frequencies. The major technical problem is finding or obtaining inexpensive high quality crystals with low acoustic attenuation, high frequency operation, high velocity of propagation, and, other required properties. In addition to quartz, lithium niobate, lithium tantalate and lithium germanate, yttrium iron garnet, yttrium aluminum garnet, spinel (MgAl_2O_4), MgO , $\text{Y}_3\text{Ga}_5\text{O}_{12}$ and $\text{Y}_3\text{Al}_5\text{O}_{12}$ are candidates for producing low attenuation at high frequencies. Crystals with a high velocity of propagation are sapphire, rutile, spinel, YAG and aluminum nitride. The importance of space processing to the growth of large, high quality crystals with natural, flat, perfect surfaces is discussed in detail in Section F on Surface Wave Acoustics.

(3) Market Forecast

The recirculating surface acoustic delay line is suitable for a bulk

memory where moderately fast access and very high data rates are desirable. However, while surface wave technology has advanced from the theoretical to the practical in high performance functional single-processing components, this technology is not a serious challenger to others for mass storage; whether or not it will become a potential candidate remains to be demonstrated.

d. Magneto-optic Beam Addressable Memories

(1) General Concept - Principle of Operation

Beam addressable memories are considered as another technology which could fill the access gap in the memory hierarchy between electronically addressable and electromechanical storage systems. Magneto-optic beam addressed memories consist of a magneto-optic sensitive storage medium illuminated by a laser. The memories all make use of Faraday rotation for readout and a combination of laser beam and magnetic field for selective thermomagnetic writing.

(2) Future Need for Electronic Single Crystals and Space Processing

The major technical problem is centered in the magneto-optic material. Four materials have been implemented in a memory configuration. These include europium oxide, manganese bismuth and single crystal films of

gadolinium iron garnet or yttrium iron garnet. None of these is ideal. Each of the materials with the exception of europium oxide requires argon or helium-neon lasers which are too expensive. Europium oxide has technical advantage in being transparent and having a very specific rotation (number of degrees per unit thickness). However, it must operate at cryogenic temperatures. In "archival stores" which contain large quantities of information only occasionally referred to, a failure of the refrigeration equipment for cryogenic operation could destroy all the stored data in a matter of hours. Manganese bismuth can operate at room temperature; however, its opacity and low specific rotation are disadvantages.

Single crystal ferrimagnetic gadolinium iron garnet films can be used for high-density magneto-optic and thermomagnetic reading. The written information is thermally stable and the crystal as a storage media has the inertness of refractory ceramics. While space processing will probably improve the quality and performance of the crystals by decreasing the defect concentration, the economic viability of microgravity growth cannot be determined until the problems outlined below are resolved.

(3) Market Forecast

Three major commercial firms are reported to be investigating this technique. One has built a magnetic disc memory using this principle and

is working on a machine built around this technology which can be character-oriented rather than bit-oriented.

However before this technology can be placed on the market, there are two other problems to be resolved in addition to the storage media problem which potentially can be met with single crystals. First, the arrays are limited in density by the laser beam wavelength. Second, the lack of deflectors to address large field sizes requires the introduction of mechanical motion to address large arrays. This means mixing slow mechanical mechanisms with fast electronic switching in a questionable compromise. If this technology is to compete with other technologies for mass storage, improved system configurations are required.

APPENDIX B

OPTOELECTRONICS

1. Scope

Our technical assessment showed that optoelectronics will have the next greatest demand for electronic single crystals after computer memories. Optoelectronics is the implementation of electronic functions by optical means and is that branch of electronics which incorporates optical technology in all types of equipment. Optoelectronics are finding their way into computers, industrial processing controls and optical character recognition equipment.

Many of the present and new optoelectronic components and systems operate on the solid state phenomena of electronic single crystals. These include crystals for storage media and page composers in holographic mass memories as discussed in Appendix A. They include the crystals used for optical sources, modulation, harmonic oscillation and parametric amplifiers used in the large capacity laser communication systems discussed in Appendix C. They include crystals for infrared pyroelectric detection discussed in Appendix D. It has been shown in the respective sections how the growth of these crystals can benefit from space processing.

In this section our attention is directed toward four other areas of optoelectronics:

- (1) Light-emitting diodes (LED's) and LED displays
- (2) Optoelectronic detectors
- (3) Lasers
- (4) Ferroelectric Graphic Displays

While LED's, lasers and detectors play an important role in optical communications and optical memories, their roles as components related to crystals and space manufacturing are discussed in this section. The future market need for crystals in these applications has been assessed.

2. Light Emitting Diodes and Displays

a Principle of Operation

The light emitting diode is an optoelectronic device of increasing importance with a variety of promising applications. Conversely, there are many applications needs for such a solid state device. The wide range of applications of LED's are based upon the display of information from instruments to people. They can efficiently convert electrical energy into electromagnetic radiation most of which is visible to the human eye.

b Future Need For Electronic Single Crystals and Space Processing

LED's are fabricated from electronic semiconductor single crystals. Semiconductor crystals for which advanced technologies are available, such as silicon (Si), germanium (Ge) and gallium arsenide (GaAs) cannot be used since crystals are required which will support visible luminescence. Research and development efforts have been directed at semiconductor compound crystals which consist of Groups III and V elements from the Periodic Table of Elements. At present gallium arsenide phosphide (GaAsP) diodes that emit red light are most widely used. Newer materials, such as gallium phosphide (GaP) for green emission, indium gallium phosphide (InGaP) for yellow, and gallium nitride (GaN) for blue, are being developed. GaP is the source of three-color displays - red and amber as well as green. They will become more important as the materials problems limiting their reproducibility are overcome.

Light emitting diodes are fabricated from material consisting of single crystal films which have been deposited on single crystal substrates. GaAsP diodes have gained widespread commercial attention since manufacturing costs per crystal have been substantially reduced. The costs have been reduced due to the ready availability of large high quality single crystal gallium arsenide substrates, the scaling up of systems for the large scale vapor phase epitaxial deposition of GaAsP, and the deposition of smooth GaAsP layers free of surface imperfections. This eliminates the need for lapping and polishing.

GaAsP currently enjoys the lead in seven-segment numeric displays which are the major applications of LED's. A single GaP diode chip costs the same price as a large bar of GaAsP crystal into which several diodes can be processed by gaseous diffusion and monolithic arrays fabricated. Individual display figures usually are about 6 millimeters tall; there is a display line with 15 mm on the market. Monolithic arrays can be fabricated into alphanumeric displays.

GaP substrates are melt-grown. Their present quality is too poor to permit the reproducible fabrication of diodes. The defect concentration changes from one end of the boule to the other. The epitaxial layers which are deposited by liquid phase epitaxy can contain a high concentration of imperfections and a large deviation from stoichiometry. This will affect the generation and extraction of light from the crystal. There are several loss mechanisms for each process caused by crystal imperfection which can limit the overall performance of a LED and, in particular, the electroluminescence of the epitaxial single crystal film.

It appears that the liquid-encapsulation crystal pulling of GaP substrates under microgravity conditions would decrease their high defect density and thus increase efficiency. Further, large-area GaP crystal could probably be grown in space for large monolithic displays which might reduce cost and make them economically viable with individual segment displays.

The space growth of crystals could decide the future for new and presently unknown crystals. New materials include:

Indium gallium phosphide	InGaP
Aluminum gallium arsenide	AlGaAs
Gallium nitride	GaN
Indium aluminum phosphide	InAlP
Silicon carbide	SiC

However, the application of the potential of each is crystal limited. The electroluminescence potential of InGaP is very high but problems in crystal growth have prevented its full scale exploitation. It is difficult to prepare melt grown ingots and liquid phase epitaxial films have a high dislocation density. It has been reported that AlGaAs diodes grown by liquid phase epitaxy have the highest brightness to date. These also emit at 8000\AA , the wavelength needed to pump Nd:YAG (neodymium doped yttrium aluminum garnet) crystal laser rods. Zero-gravity processing may help in reducing the defect concentration of the promising AlGaAs crystals and in growing reasonably sized InGaP.

Gallium nitride is an unexplored crystal. If low resistivity crystals with p-type "doping" could be fabricated, they could become a single source of efficient light emission across the entire visible spectrum. InAlP has a high brightness potential; however, much difficulty has been reported in synthesizing these crystals. While silicon carbide has, in principle, the capability of yielding luminescence throughout the visible spectrum, it requires high temperature processing (2000°C) and extensive development which cannot be justified in view of the promise of GaP and GaAsP technology. Space processing does not appear to be attractive in this case: however, it does appear to have promise with GaN, and InAlP.

c Market Forecast

Bergh and Dean comment of the future of LED'S: "Although LED's have been commercially available for only three years, they have already found various applications in the fields of signaling and display devices. The general trend has been a rapid increase in efficiency coupled with a rapid decrease in cost. During the past three years, both parameters have changed by a factor of approximately twenty. During the same period the reliability of the devices improved by almost five orders of magnitude. In view of this combination, it is tempting to forecast a bright future for LED's ." (1)

LED's have low cost, high performance and reliability. They are compatible with modern electron devices and with the increasingly important visual displays. Low power requirements, low operating voltages, small size, fast switching speed, long life, and manufacturing technology for LED's

(1) Bergh, A.A. and Dean, P.J. "Light-Emitting Diodes," Proc. of the IEEE, 60 (2) 156-223 (1972)

are compatible with silicon integrated circuits.

With the advancement of the computers, the need to display symbolic information, such as letters and numbers is rapidly increasing. This replaces the voluminous paper records now produced in many business activities and expedites a variety of service operations. Decimal numerical displays rather than the earlier digital form are becoming prevalent in all types of electronic instrumentation.

According to the Electronics 1972 forecast, LED display sales will double. This is the brightest spot for optoelectronics. The growth of LED displays is due to the calculator and instrument market. The discrete LED market will pick-up in the consumer segment as unit prices drop. This will open up opportunities in light-level indicators for cameras and pilot lights for appliances for example.

According to the Electronics 1972 annual market survey (Table B.1) U.S. sales of optoelectronic devices alone will total almost \$51 million with sales expected to reach \$ 89 million by 1975. ⁽²⁾ Of this LED's account for \$ 18.5 million in 1972 and \$ 40 million in 1975. In referring to a market analysis on worldwide sales of optoelectronic devices, Electronics cites that sales of \$ 65 million in 1972 will jump to \$ 225 million by 1976.

3. Lasers

a Scope and Application

The laser is probably the single most important optoelectronic device: it is central to almost every new industrial, communication and scientific system application which relies on optical techniques. The

(2) Electronics, January 3, 1972

TABLE B. 1

OPTOELECTRONIC DEVICE MARKET FORECAST ⁽²⁾

	1970	1971	1972	1975
Optoelectronic devices, total dollars (millions)	36.3	39.5	51.0	89
LED's	2.1	4.0	6.5	12
LED DISPLAYS	2.0	5.0	12.0	28
Photo transistors (includes arrays)	9.0	9.0	9.0	12
Photodiodes (includes arrays)	2.1	2.5	3.5	6
Couplers	1.5	2.5	5.0	9
Silicon targets	3.0	3.0	3.0	9
Photovoltaic (solar) cells	7.3	7.0	7.0	8
Photoconductive cells	9.0	6.5	5.0	5

fields of data processing and storage and optical communications have been enhanced by laser technology.

Laser devices are finding applications in materials processing, instrumentation and measurement, optical communication, medicine, holography, data processing and storage, displays and safety. Industrial materials processing is finding an important use for lasers with the introduction of high-power lasers giving ever greater potential for deeper welds, faster drilling, and larger working area. In the optoelectronic industry conventional printing and copying methods will be seriously challenged within the near future by laser character generators, copiers, microfilm recorders and typesetting systems. The consumer impact of laser holography may soon be felt with tamperproof identification cards, "lock and key systems" and nondestructive testing for automobile safety. In medicine lasers are being used to perform cell surgery and to serve as photocoagulators in ophthalmology. Acoustic holography using lasers is superior to optical or x-ray techniques for imaging soft tissue and detecting cancer.

b Future Need For Electronic Single Crystal and Space Processing

The use of lasers in computer memory systems and optical communications was discussed in Appendixes A and C. Solid state lasers use oxide single crystal which usually are doped with trivalent neodymium (Nd^{3+}) to produce the specific wavelength. These include ruby (Al_2O_3 , sapphire, doped with chromium), yttrium aluminum garnet

(YAG or $Y_3Al_5O_{12}$), yttrium aluminate (YALO or $YAlO_3$), calcium tungstate and yttrium iron garnet (YIG).

The crystalline lasers are presenting new material problems. YAG is currently the most important host material utilizing Nd^{3+} fluorescence for laser action. For optical sources they are pumped by LED's. YAG is well suited for continuous power applications. Using the conventional rod design, however, high averaged pulsed power cannot be produced; the crystals are limited in size and homogeneity by crystal-growth considerations. YAG crystals are expensive. The demand for YAG crystals appears to be large enough for space processing to be considered from both manufacturing and cost points of view. The imperfections and defects in these crystals from high temperature growth are convection-related. The cost for a three inch long, three millimeter diameter rod of this high valued crystal is about \$1000.

The YAG laser with its high power capability and fast chopping rates also demands a faster nonlinear optical material capable of withstanding power densities of 150 megawatts. Coated $LiNbO_3$ crystals are being investigated.

Solid state optical sources also use non-oxide single crystals in light-emitting devices and gallium arsenide (GaAs) injection lasers. The LED crystals and their perfection improvement from space processing have been discussed earlier in this section.

In 1971 the GaAs injection laser became the most efficient source of coherent light, largely due to the development of a new double heterojunction structure. Now operating at higher power and room temperature, this small compact device is finding its way into an ever widening assortment of ranging and communications systems; closed circuit TV, data links, line-of sight multichannel voice communicators, and IR surveillance systems. High quality GaAs crystals can be earth grown. Space processing may further decrease the defect density of epitaxial films grown on GaAs substrates.

Single crystals are finding use in lasers which can be tuned to the exact wavelength of pollutants for on-site monitoring. It must emit in the infrared band, because the absorption spectra of almost all known pollutants fall within the infrared and semiconductor crystal lasers are of one or two types which emit in the infrared. Diode materials under consideration for the new lasers include such binary compounds as indium arsenide, indium-lead, germanium-lead, lead-selenide, lead-sulfide, lead-telluride and pseudo-binary alloys such as lead tin telluride, lead sulfide selenide, mercury cadmium telluride and indium gallium arsenide. One current development is that compact PbSnTe diode lasers are being developed to emit throughout the spectral region range of the major pollutants found in automobile exhausts.

Lead tin telluride crystals are grown from the melt using the Bridgman technique. While homogeneous crystals can be grown by very close control of the growth condition, the microgravity environment of space may reduce convection to the point wherein cellular substructure, voids, other defects, and alloy composition inhomogeneity can be reduced to a larger degree with less control and cost.

Concurrent with the advancements in new single crystal lasers, there are appearing new material demands for other parts of the optical systems. These can best be met by single crystals. However, the trend is not only to other materials combinations, but to crystals which are larger and more perfect. There are other areas in which the application of space processing will be most important: Examples are:

- 1) Large, economic 10.6 micron crystal window capable of the high power densities of the 10.6 micron carbon dioxide laser.
- 2) Laser beam deflection techniques utilizing the acoustic-optic effect require crystals which will transmit laser radiation while maintaining the proper acoustic properties.
- 3) The importance of crystals for modulation and second harmonic generation must be restressed

The importance of space processing to modulators has been addressed in Section C on optical communications.

(3)

Sypek discussed future trends in modulators and pointed out that the era of low input power electro-optics modulators (less than one watt) has begun; concurrently, the era of the acoustic-optic modulator

(3) Sypek, D., Optical Spectra, 6 (2) 22-23(1972)

has made its debut. Electro-optic and acousto-optic lines are more complementary than competitive. Even with these advances, a good modulator (electro-optic or acousto-optic) is needed for the middle and far infrared. The former are used in optical ranging, communications, and real time holography; the latter are used in laser scanning and deflection as found in data processing and readout displays, laser recording and optical memories.

c Market Forecast

In its review and outlook for 1972 Laser Focus cites that during 1972 there will be added emphasis on optical communications and data handling relative to laser products and services.⁽⁴⁾ The largest market in dollars will be industrial with sales for materials working and related measurement increasing 16.7% to \$ 31.5 million. Increasing faster will be information handling applications including communications where an 18.9% increase to \$29.6 million is forecast. Biomedicine, paced by the growing acceptance of argon-laser photocoagulation, will increase by 36.3%

Looking further ahead, the growth fields in the mid 1970's will be information handling and industrial application. By 1975 these markets should be \$ 60 million and \$ 70 million respectively, reaching \$270 million and \$ 240 million by 1980. Because lasers work closely with product of other technologies, every laser sale has an impact on a related field, often exceeding the value of the laser itself.

(4) Laser Focus, 8 (1) 23-27 (1972)

4. Optoelectronic Detectors

The areas of optoelectronic devices which are based on single crystal silicon should be mentioned. They represent the well-known phototransistors and photodiodes as well as a rapidly growing number of new components. These include beam lead emitter and detector arrays for sophisticated optical character recognition, photodiodes of speeds compatible with those of computer peripherals, self-scanning photodiode arrays for complex reading and facsimile equipment, optically-coupled isolators, and optically pumped amplifiers that could find a variety of uses in communications systems. At this time it does not appear that the growth of silicon crystals in space for this market would be economically viable. Crystal improvement, other than large diameter crystals which are not to be required in optoelectronics, would only be marginal.

While there will be growth in the LED and LED display market, a market analysis also shows considerable growth in the detector and coupler field by 1976. Of the many types of detectors available, phototransistors make up the bulk of market activity. It is important to point out that optoelectronic systems are dependent on both silicon and non-silicon single crystals for performing their essential solid state functions. For example, optical character recognition, OCR*, makes use of non-silicon LED indicator lights and numeric readouts along with silicon discrete phototransistors and

* An OCR system has a retina or scanner which detects the characters to be recognized, a recognition unit which compares the detected input with the machine vocabulary and a vocabulary computer that contains the basic set of character masks (5).

(5) Electronics, November 8, 1971.

diode sensors, silicon discrete and monolithic detector arrays, and CRT displays. These are finding many applications in business to include customer credit billing, stock inventory, packaging routing, business and banking transactions, point-of-sale terminals and post office address reading.

5. Ferroelectric Graphics Displays

While there are some areas in displays where ferroelectrics seem to hold promise, their application does not appear to be imminent because of economic and technological factors. In addition while space growth of crystals does not appear to offer any economic advantage now, it may by 1980 if size becomes an important consideration.

There is considerable uncertainty about the role of ferroelectrics in direct-view alphanumeric displays. In this application, the main advantage would be long storage time since the average power distribution is reduced in comparison to a light emitting diode. However, technology for alpha- numerics is very cost conscious and as of now ferroelectric single crystals are not economic in the relatively large sizes required for a direct view display.

Ferroelectric crystals may play some role in animated TV-type displays. This market is now dominated by cathode-ray tube (CRTs). There are many limited applications such as large screen theatre TV

which cannot be filled by a direct view CRT but which require some form of projection.

Successful displays of this type have been constructed using a scanned electron beam writing directly on the surface of a potassium dihydrogen phosphate (KDP) crystal. Preliminary experiments have shown the feasibility of storage of electron beam written images on plates of bismuth titanate crystal ($\text{Bi}_4\text{Ti}_3\text{O}_{12}$). However, there are many technical difficulties to overcome as well as the cost factor to consider. The principal competitors to ferroelectrics are liquid crystals and laser-machined thin metallic films. While the latter is not erasable and must be replaced between frames, its cost is so low that for many display applications this may be perfectly feasible.

There are a number of potential specialized applications which can exploit the combination of long-term storage and large optical effect observed in certain ferroelectrics. The most immediately accessible would be in slow scan analog graphic display units in applications now stored by complex electro-mechanical apparatus. This would use an optically addressed strain biased ferroelectric ceramic rather than a single crystal. Real-time animated TV display using ferroelectrics are a long way off.

There is an important economic distinction between displays and page composers. Because of their widespread use displays can be classified as a consumer item and thus cost is an overriding consideration. To be economically competitive, the price per light valve in a display must be 0.1 to 0.001 cents. By comparison since there is only one page

composer per memory and since the light valves number in the composer is limited, the price per light valve can be as high as 10^2 cents.

While less stringent economical requirements on a page composer make it possible to consider the processing of high valued ferroelectric crystals in space, there appears little economic advantage of using ferroelectric crystals in displays and therefore the superior crystals attributed to space growth would not be economically viable at this time.

APPENDIX C

OPTICAL COMMUNICATIONS SYSTEMS

1. Introduction

Optical communications will eventually be needed to meet the ever increasing demand for communication services. Since the first demonstration of a laser in 1960, much work has been directed toward the potentially very-high bandwidths of optical transmission made possible by the coherence of laser radiation. Recent technological advances in low-loss glass fibers for optical guiding structures are making optical-fiber transmission in communication systems a reality. Along with the fiber optics, repeaters and terminals are required. Repeaters regenerate the optical signals which have experienced transmission loss and distortion. Terminals process the optical signals in a form compatible with the existing electronic communication network.

In order to regenerate and process the optical signals, solid state optical sources, modulators, harmonic generators, and photodetectors are required, all of which employ electronic single crystals. Solid state optical sources use non-silicon semiconductor crystals in light-emitting diodes (LED's), discussed in Appendix B, on Optoelectronics, gallium arsenide (GaAs) injection lasers, and neodymium-doped yttrium aluminum garnet (Nd:YAG) lasers pumped by LED's. Modulators and harmonic generators consist of nonlinear optical crystals, the most common being electrooptic. Photodetectors are fabricated with silicon crystals. The technical assessment will be directed at the semiconductor and

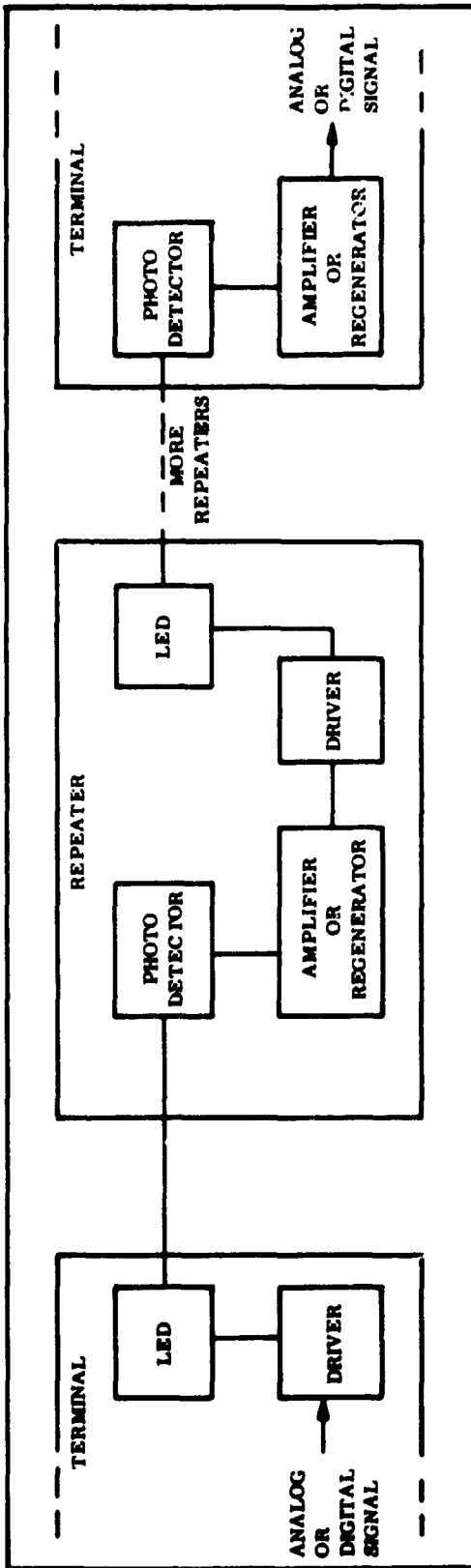
electrooptic crystals for the optical sources and modulators rather than silicon for photodetectors since the former are those crystals which will benefit most from space processing.

2. Principle of Operation

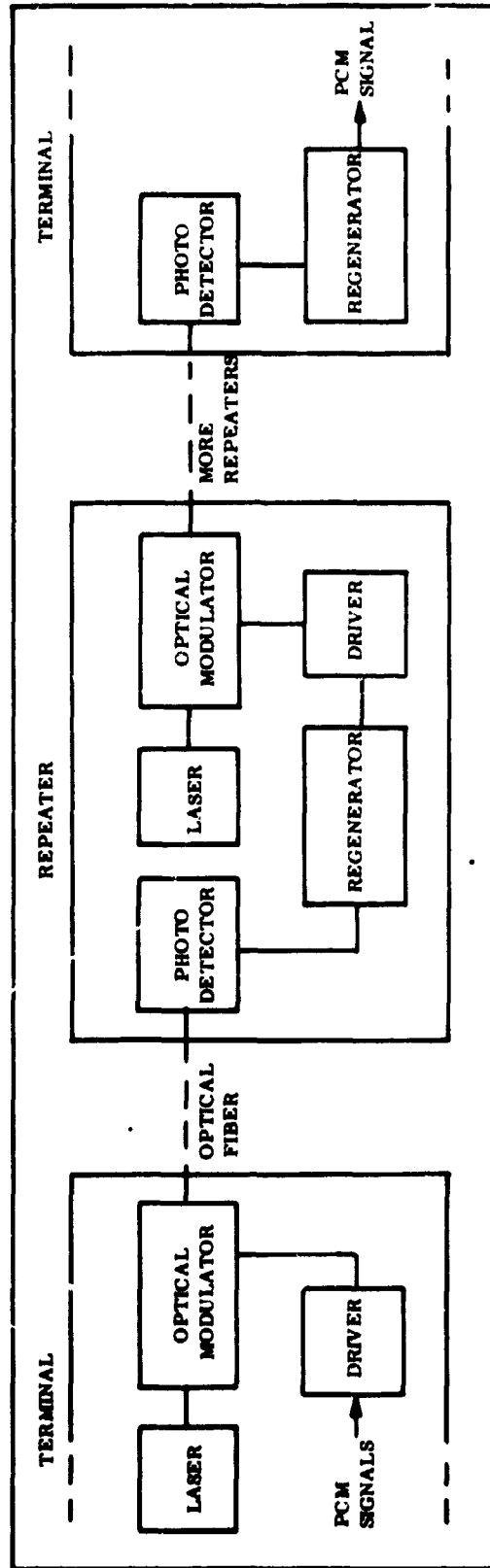
The principles of operation of optical-fiber transmission systems employing LED's or lasers are shown in Figure C I. In the LED system the signal to be transmitted is applied directly to the LED through a drive which provides the necessary current gain. For the laser system an optical modulator is used to impress the information on the optical carrier.

3. Future Need for Electronic Single Crystals and Space Processing

Injection light sources in the form of the coherent GaAs injection laser and the non-coherent light-emitting diode offer designers of optical transmission systems characteristics that have advantages over other methods. The GaAs injection lasers have become the most efficient source of coherent light, largely due to "heterostructures" of sandwiched layers of gallium arsenide and gallium aluminum arsenide (GaAl As) crystals. Their direct transfer of energy is more efficient than the intermediary forms of energy transfer in optically pumped and gas lasers, and has the greatest potential for obtaining inexpensive and efficient large bandwidth signal carriers. In addition they are the most practical because the emission wavelength matches the sensitivity peak of silicon crystal detectors.



OPTICAL-FIBER TRANSMISSION SYSTEM EMPLOYING LED'S



OPTICAL-FIBER TRANSMISSION SYSTEM EMPLOYING LASERS

Figure C-1. Optical Communication Systems Employing Lasers and Light-Emitting Diodes (LED'S) (After Li, T and Marcatili, A. J., Bell Laboratories Record 49 (11) 330-337 (1971))

LED's use silicon doped gallium arsenide, gallium phosphide, gallium arsenide phosphide, gallium aluminum arsenide and silicon carbide crystals. These were discussed in Appendix B. Better crystals will result in more efficient and more highly directional diodes which will permit longer-distance operations, or will open up new applications areas where very high speed modulation is required.

The third type of crystal based laser, the LED-pumped Nd:YAG laser, is a much larger device than the former and is capable of producing over a tenth of a watt of output power at 1.06 microns. The laser rod is pumped by an array of AlGaAs crystal LED's.

Optical modulators are required to impress the communications information on the optical carrier from YAG lasers or from self-pulsating injection lasers. The most important modulator is a Pockels or Kerr cell in which the index of refraction of some nonlinear crystal is preferentially varied with an applied modulating voltage. It can also be an amplifier, in which the gain or loss of a piece of semiconductor crystal is changed with an applied modulating current.

The changing of the index of refraction by an electric field is known as the electro-optic effect. Crystals which exhibit this are quartz, potassium dihydrogen phosphate (KDP), lithium tantalate, lithium niobate, barium sodium niobate and barium strontium niobate.

The efficient interfacing of solid state circuitry with the electrooptic crystal modulator is vital for high information capacity optical communications systems. Large aspect ratio crystals, such as lithium tantalate, are required to effect a gain-bandwidth tradeoff. Mechanical properties dictate the feasibility of fabrication of the large crystals and should be greatly improved by space processing.

The electrooptic effect also is found in a number of binary semiconductor crystals which are of interest at infrared wavelengths. These include ZnO, ZnSe, ZnTe, CuCl, GaP, GaAs and CdS.

The electroacoustic effect in piezoelectric single crystals such as barium titanate and quartz is another modulation technique finding wide usage. Their bandwidth is limited to 10% of the carrier frequency; however, microwave carrier frequencies can be used. Another possible modulation technique which depends on oxide crystals is the Faraday magneto optic effect. It is used at microwave frequencies and employs gallium doped yttrium iron garnet single crystals for modulation.

A practical optical communication system requires many carrier frequencies. Harmonic generators are devices which can double the frequency of laser light and provide coherent light at many more frequencies.

Parametric devices are useful for providing additional frequencies different from the input frequency and may lead to an efficient technique for providing tuneable coherent frequencies. Crystals which are useful as harmonic generators are also useful as parametric devices. Crystals with a large electrooptic effect

have a potential as harmonic generators. The large birefringence of lithium niobate and barium sodium niobate make these crystals applicable for harmonic generators; the latter is about two times as effective as LiNbO_3 .

As pointed out in Appendix A on holographic memories, the growth of electrooptic crystals is an area of high potential for space processing. LiNbO_3 is one of the most significant crystals being considered for use in optical communication links with laser as the principle medium at 2-3 GHz or small point to point computer data links using optical waveguides. Compositional nonuniformity along the length of the crystal can cause variations in index of refraction, birefringence and optical single harmonic generation. The efficiency of phase matching interaction is reduced and the second harmonic peak power is depressed, thus limiting nonlinear optical activity. Microgravity growth may greatly enhance the optical quality of the LiNbO_3 crystals which are required.

Tungsten-bronze structures, which include the aforementioned barium sodium niobate, $\text{Ba}_2\text{NaNb}_5\text{O}_{15}$, and potassium lithium niobate, $\text{K}_3\text{Li}_2\text{Nb}_5\text{O}_{15}$, have large nonlinear coefficients and are resistant to optical damage. Crystal boules of barium sodium niobate which are one inch in length and 5 millimeters in diameter can be grown. However, yields are low; the density of artifacts is high. The price could fall by 2/3 if yields could be improved.

There are many kinds of defects, cracking and striations which degrade the quality of these linear optical crystals and their efficiency as second harmonic generators or optical parametric oscillators. In addition compositional

nonuniformity causes inhomogeneities in the index of refraction and reduction in conversion efficiency. These are good candidates for growth in microconvection wherein the economies of their use in a optical system dictates high value.

Lead germanate ($5\text{PbO}\cdot 3\text{GeO}_2$) is a new ferroelectric material having large electro-optic and non-linear optic constants or desirable switching properties for electro-optic device applications. Of particular importance is the discovery of switchable optical rotary power. Crystals which are $4 \times 4 \times 0.4$ mm in size are grown by the Czochralski method. However, switching time is strongly sample dependent due to the crystal inhomogeneities. This crystal probably will be important enough to warrant consideration for space processing, particularly for a light switch, light modulator, or a second harmonic generator.

Electronic crystals such as potassium dihydrogen phosphate (KDP), ammonium dihydrogen phosphate (ADP) and deuterated potassium dihydrogen phosphate (KD*P) are used for electrooptic applications in spite of their low electrooptic properties and deliquescence. This is mainly because of the ease of growing large, good quality optical crystals from aqueous solutions. They are finding use in oceanographic applications and pollution particle detectors as well as optical communications.

There are other aqueous solution grown crystals which have much better electrooptic figures of merit and physical properties but which cannot be grown in large sizes with good quality. Lithium iodate is a good example of such a crystal which may benefit from growth in space.

Lithium iodate, LiIO_3 , is in demand because of its high second-harmonic efficiency for YAG:Nd³⁺ (yttrium aluminum garnet:Nb³⁺) and ruby lasers. It is grown in aqueous solution at ambient temperatures with good optical quality up to 20 by 50 millimeters. In comparison to lithium niobate and lithium tantalate it has better optical homogeneity and higher resistance to damage from visible light. Its figure of merit is four times that of potassium dihydrogen phosphate. However, with increasing size, haze, occlusions and growth striations occur. This is thought to be caused by thermal convection. The striae from growth discontinuities cause a severe distortion of the laser beam which is similar to that caused by striations in barium sodium niobate.

Potassium iodate, sodium iodate and alpha-iodic acid are other aqueous solution grown crystals whose use is in demand, but restricted, because of growth striations and hopper growth. Space growth should show significant improvements in both perfection and yield.

4. Market Forecast

Optical communication systems are still in the research stages and will be introduced in the 1980's. Currently coaxial systems and microwave relay systems are used for long-distance, heavy traffic communications. By the late 1970's broadband millimeter wave systems operating in the band from 40 to 100 GHz will be introduced. These will yield an initial capability of a quarter million two-way voice channels. By the 1980's this medium will have reached

saturation so that there will be a need for more bandwidth. Since several orders of magnitude are gained in the region of optical frequencies (100,000 to 1,000,000 GHz); the optical range opens up possibilities for the equivalent of hundreds of millions of voice conversations.

The consensus is that glass fiber optical transmission may appear in 10 years time in communications systems such as: (1) intercity routes over hundreds of miles requiring medium to high-capacity transmission; (2) interoffice trunks over distances of a few miles with channels of low capacity (single voice) to medium capacity; and (3) interconnections of communications equipment over distances of a few hundred to a few thousand feet.

The LED system will probably have use as interoffice trunks in metropolitan areas; fibers as used here might afford a simple method of spatial multiplexing that is more economical than multiplexing via frequency and time. For a laser system, in contrast to the LED system, each channel or fiber would have considerable capacity-potentially hundreds of megahertz bandwidth. This would have future application in intercity routes.

At least two systems look competitive with fiber-optics. They are: atmospheric links with ranges of up to a kilometer or so where security or freedom from RF interference are needed and intersatellite communications probably using carbon dioxide lasers.

Cautious optimism is justified in the development of wide-bandwidth optical communication systems. There is no real problem in providing short-range

high-capacity or long-range low-capacity communication systems. However, large funded efforts are underway in several countries to develop very high-capacity communication systems with bandwidths of order 10^{10} Hz or greater for use over vast distances.

Relative to the future of optical communication systems, according to White: "practical laser communications systems already are in use (in Japan and Russia) and the exponential growth in bandwidth requirements will undoubtedly force a greater exploitation of the laser portions of the electromagnetic spectrum. Even the high information rates described nowhere near approach the theoretical bandwidth capabilities of optical communications systems. The ultimate limit will probably only be realized with improved optical processing of logic so that the potential of the extremely short pulses now available from such lasers as the neodymium yttrium aluminum garnet and the solid state GaAs forms can be realized".⁽¹⁾

(1). White, G., "Optical Modulation at High Information Rates", Bell System Tech. Journal 50 (8) 2607-2645 (1971).

Appendix D

PYROELECTRIC SENSORS

1. Introduction

The application of the pyroelectric effect to the detection of thermal radiation was first suggested some thirty years ago. Only recently has it begun to compete with established methods of thermal detection. The reason has been the development of new pyroelectric single crystals.

This is considered to be a dynamic area of optoelectronics. Because of its future technological importance it is being treated as a separate section. Pyroelectric crystals are high value crystals whose quality, size, thickness, and surface condition should be markedly improved by the microgravity peculiar to space growth.

2. Principle of Operation

Pyroelectric detectors make use of the changes in ferroelectric properties of crystals with temperature. The polarization axis of the crystal is changed by the absorption of radiation in the infrared.

3. Future Need for Electronic Single Crystals and Space Processing

Triglycine sulphate and barium strontium niobate (BSN) are the basic crystals for a new family of infrared detectors which provide significant advantages over the conventional infrared thermal detectors. It is not possible to write a simple figure of merit to use as a guide in selecting the best crystals. Barium strontium niobate is superior in certain respects such as fast response at room

temperature. However, in general TGS and its new triglycine sulphate-triglycine selenide derivatives are generally superior to BSN and other crystals such as lithium sulphate, sodium nitrate, lithium niobate and lead titanate.

Very thin lamellar sheets of highly perfect crystals are required currently, the infrared detectors made from TGS crystals fail to achieve the theoretically expected performance. Present aqueous solution growth techniques in the presence of gravity result in crystals with flaws and inclusions of solvent. Polishing and lapping of the crystals to a few tens of microns thickness results in surface imperfections. Cutting of the crystal to obtain orientation of the surface perpendicular to the polar axis introduces strain and defect which modify the ferroelectric properties and degrade the behavior of the devices. The low yield, high imperfection density, and chemical non-uniformity in BSN boules was discussed in Section C.

The growth of TGS in space should yield large, flawless crystals. The method of growth by slowly lowering the temperature of saturated growing solutions is suitable to the possible growth of lamellar, thin crystal with natural faces perpendicular to the polar axis. The elimination of polishing and lapping would enhance the yield, strength, surface perfection, and mechanical strength. The merits of growing BSN, a high temperature growth process, in space have been presented in Section C.

4. Market Forecast

These new crystals, especially TGS, are responsive to a wide range of frequencies from optical to microwave. They have high detectivities and fast re-

response time and are replacing conventional devices as the universal room temperature detector. They are being used in thermal imaging systems, and as targets in infrared camera tubes.

Triglycine sulfate provides the fast detector long sought for use with lasers and thus can be used for earth-bound applications such as laser-ranging for clear and turbulence detection. The crystals are the basis for advanced sensor systems for new applications which include (1) earth resources surveying, (2) pollution monitoring, (3) thermal imaging for medical diagnostics, (4) fire location and (5) infrared astronomy.

APPENDIX E

SURFACE WAVE ACOUSTICS

1. Introduction

Acoustic surface wave devices are a new field of advanced technology. The increasing interest is evidenced by the growing number of potential applications being investigated. It makes use of many of the theoretical techniques already developed for the microwave field and the experimental techniques developed for semiconductor integrated circuits. Practical devices are beginning to be used in radar and communications systems and studies of many new concepts are being carried out.

The materials being used in the exploratory studies of new devices are electronic single crystals. These include single crystals of bismuth germanate ($\text{Bi}_{12}\text{GeO}_{20}$), lithium niobate, lithium tantalate, quartz and potassium sodium niobate, as well as aluminum nitride, rare earth garnets, spinels, and sapphire. It should be stressed that crystal surface perfection is as important as perfection within the crystal itself. The growth of surface acoustic crystals with flat, perfect surfaces in a microgravity environment is believed to be one of the unique areas in space processing.

2. Principle of Operation

Surface acoustic waves depend on vibrations on the surface of a crystal. In an elastic, isotropic solid vibration energy propagates in three basic modes. They are longitudinal and two shear, designated V and H. A medium such as a crystal will support combinations of these simple modes. The simplest example of a surface wave without penetration of the crystal is the Rayleigh wave. This consists of a shear V and longitudinal components. In the former, the vibrating element moves perpendicular to the free surface of the solid; in the latter the vibration element moves parallel to the energy flow vector. The longitudinal is also the mode of the common sound wave in air. A more complex variety of modes may exist for the case of a general direction in an anisotropic medium.

3. Future Need for Electronic Single Crystals and Space Processing

Piezoelectric electronic oxide crystals are the key to the extraordinary possibilities for the application of surface acoustic waves. The characteristics of the acoustic waves along the surface of the crystals include high power density, and energy which is physically accessible. It can be tapped, guided and manipulated along the path of propagation without requiring penetration of the crystal. The power density is high because of confinement to the surface.

The third and most important characteristic of surface acoustic waves along piezoelectric crystals such as lithium niobate for example is demagnification. This can be described as follows: Surface wave propagation velocity is 10^5 slower

than that of electromagnetic waves. For a given frequency, the wavelength is also smaller by a factor of 10^5 and all functions which scale with wave length are smaller by the same factor. Thus at 400 MHz the wavelength in LiNbO_3 crystals is about eight micrometers (approximately 0.00032 inches) compared with 80 centimeters (approximately 30 inches) for electromagnetic waves found in space. This is minifaction by a factor of nearly 100,000.

In surface waves, it may be necessary to have short delays. For tapped delay lines where the taps must be placed close together, there is cross-coupling, signal distortion, and the physical problem of spacing at high frequency. In this case it is desirable to have crystals with a fast velocity and loss delay per unit path length. The distance between taps could be spread out. Crystal candidates are sapphire, spinel and diamond. Diamond has the fastest velocity and lowest loss, but the disadvantages are cost and growing large samples. Earthbound crystals are up to 5 millimeters in length. Crystals which are 1 to 2 inches in length are required. The feasibility and economics of growing diamond in space has not been determined at this point.

Lithium niobate is an example wherein large crystals can be grown but whose use is severely restricted because of the chemical inhomogeneities and variation caused by convection, a gravity-related phenomenon. In the state of the art, LiNbO_3 crystals are pulled at elevated temperatures directly from the melt. Although crystals of up to one each in diameter and up to seven inches in length can be grown, these are only of moderate quality. In surface acoustics, growth ridges interfere with the propagation of the high-frequency surface waves.

Because of mechanical damage and imperfections introduced during even careful lapping and grinding, polished surfaces do not transmit a signal as undistorted as that expected from an equally, large flat natural surface.

Growth in space under nearly zero gravity offers the exciting possibility of growing the crystals in a direction such that the top surface comes out in a plane, providing a naturally flat surface free of the imperfections of convection growth. This also eliminates the costly lapping and polishing process which is estimated to add 60% of the cost to these high value crystals.

For high frequency operation, size becomes most important concurrent with surface roughness. Long crystals of LiNbO_3 which are six to ten inches in length are required for dispersive delay lines. Currently a long delay cannot be obtained in one crystal. In short crystals a long delay can be obtained by joining; it would be desirable instead to use long crystals or two inch crystals with round edges. Surface waves can travel around curvatures. The space growth of crystals may be a means for obtaining not only large high quality crystals of LiNbO_3 , with natural, flat perfect surface but also smaller crystals of high perfection with rounded edges. The best candidate is $\text{BiGe}_{12}\text{O}_{20}$ with its low velocity of propagation, short wavelength, and therefore long delay. The delay is 2 cm longer than with quartz.

The demagnification of eight micrometer waves is comparable to the dimensions commonly encountered in microelectronics. The geometric compatibility will permit the combination of microsonic signal processing elements with large scale

silicon integrated circuits to provide compact subsystems. Schemes for achieving generation, guidance, and amplification of surface waves depend on processing techniques similar to those for producing large scale silicon integrated circuit arrays. These are of the same dimensions and processes as for the silicon integrated circuit memories discussed in Section A. It is interesting to note that these circuits are also compatible in dimensions and processes with single crystal garnet magnetic bubble memories.

The attainment of dimensions which will permit operation at high frequencies is limited by earth processing. Thin layers of metal are vacuum deposited on the crystal surface. Interdigitated sets of fingers or electrodes for tapping the energy are formed using chemical etching and optical photolithographic techniques. The problem is to control the linewidths due to irregularities in the etching process. Work has been done at 3 to 4 GHz with earth techniques; the wavelength get smaller as one goes to X-band. For example, the linewidth is 2 microns at 16 Hz and 0.1 micron at 10 GHz. At these frequencies, the surface roughness of polished earth grown crystals is in the range of the linewidth or wavelength. This, therefore, is detrimental and would benefit from the smoothness of the natural surfaces of space grown crystals. In addition to zero gravity the vibrationless environment of space would permit the etching of very fine lines by electron beam etching. Electron beam etching of the interdigitated lines could eliminate irregularities of chemical etching. A line 100^oÅ wide could perhaps be drawn if free of vibrations and gravity.

4. Market Forecast

Surface wave acoustic devices are having a profound effect on signal processing ranging from delay lines to special purpose signal processes. The most obvious use of surface waves is as linear delay lines. A 0.25 microsecond of delay requires about 50 meters of wave guide but less than 1 millimeter of LiNbO_3 . The advantage of demagnification is demonstrated here.

The next application is the tapped delay line which is characterized by the continuous accessibility of the signal along its entire propagation path. Biphasic correlators are a variation of the tapped delay line. Other tapped delay lines are programmable correlations and frequency-modulated pulse compression filters employing dispersive transducers.

According to Vollmer and Gandolfo there are many important and challenging future applications for surface wave acoustic devices fabricated from electronic single crystals: "Speculating a little on the future, one may envision; (i) switchable correlators used in integrated communication, navigation, identification (CNI) systems; (ii) simple correlators used in lightweight radar systems; (iii) large time-band-width delay lines, incorporating gain, for use in electronic warfare and radar systems; (iv) band-pass filters in color television systems; and (v) parallel processors employing long, complex transmission paths". (1) The latter leads to interesting discussion. Metal films alter the surface wave velocity just as glass alters the velocity of light. Surface waves can therefore be manipulated with planar analogs of optical elements thus making possible all optically achievable mathematical transforms and operations.

(1) Vollmer, J. and Gandolfo, D. Science "Microsonics", 175 January 14, 129-133 (1972)

APPENDIX F

ULTRASONICS

1. Introduction

Piezoelectric crystals are the fundamental materials for electronic delay lines and filters in the communications industry. In an ultrasonic device acoustic waves confined within a crystal are used to produce an electronic result. Acoustic waves include audible sound, but extend far beyond the range of the human ear. The importance of acoustic waves in communications is due to their relatively low speed and short wavelengths. They move about 1/100,000 as fast as electromagnetic waves and their wavelengths are about 1/100,000 as long. Thus, an ultrasonic device can be put in an electronic circuit and do in inches what would otherwise take miles for an equivalent device to do.

2. Principle of Operation

During utilization of an ultrasonic device, electrical energy is first converted to acoustic energy. A useful operation takes place within the ultrasonic crystal and then the ultrasonic energy is converted back to electrical energy. The energy conversions may take place within the piezoelectric crystal itself or within a separate transducer attached to the crystal. The crystals may themselves be used as transducers on another device.

3. Future Need for Electronic Single Crystals and Space Processing

While monolithic quartz crystals can do some jobs extremely well, the frequency and bandwidth requirement of other applications exceed the capabilities of quartz. There is a severe limitation on the available bandwidth which is associated with the weak electromechanical coupling in quartz crystals.

Lithium tantalate is an oxide electronic single crystal with all of the desirable features of quartz but which also has a stronger electromechanical coupling. A number of precise wideband filters have been constructed. As a result of the success with LiTaO_3 , interest in the competitive piezoelectric ceramic filter has decreased. The bandwidth of LiTaO_3 crystal is close to that of ceramics; in addition, for a ceramic filter with the required precision, over 90 percent of the cost is consumed in shaping the ceramic, applying electrodes, assembly and testing.

Shown in Figure F.1 are the areas of application of various types of filters with reference to center frequency and bandwidth. As can be observed, LiTaO_3 offers a wider bandwidth than quartz. For frequency application above 50 MHz surface-wave filters become available which are fabricated from LiTaO_3 flat plates. These are now in the realm of surface wave acoustic devices.

This is an area which should benefit from space processing since surface tension forces may be utilized for preparing thin, flat uniform sheets of lithium tantalate. Under zero gravity conditions extended sheets of liquid material could be supported and held flat by the surface damage which is unavoidable in the use of

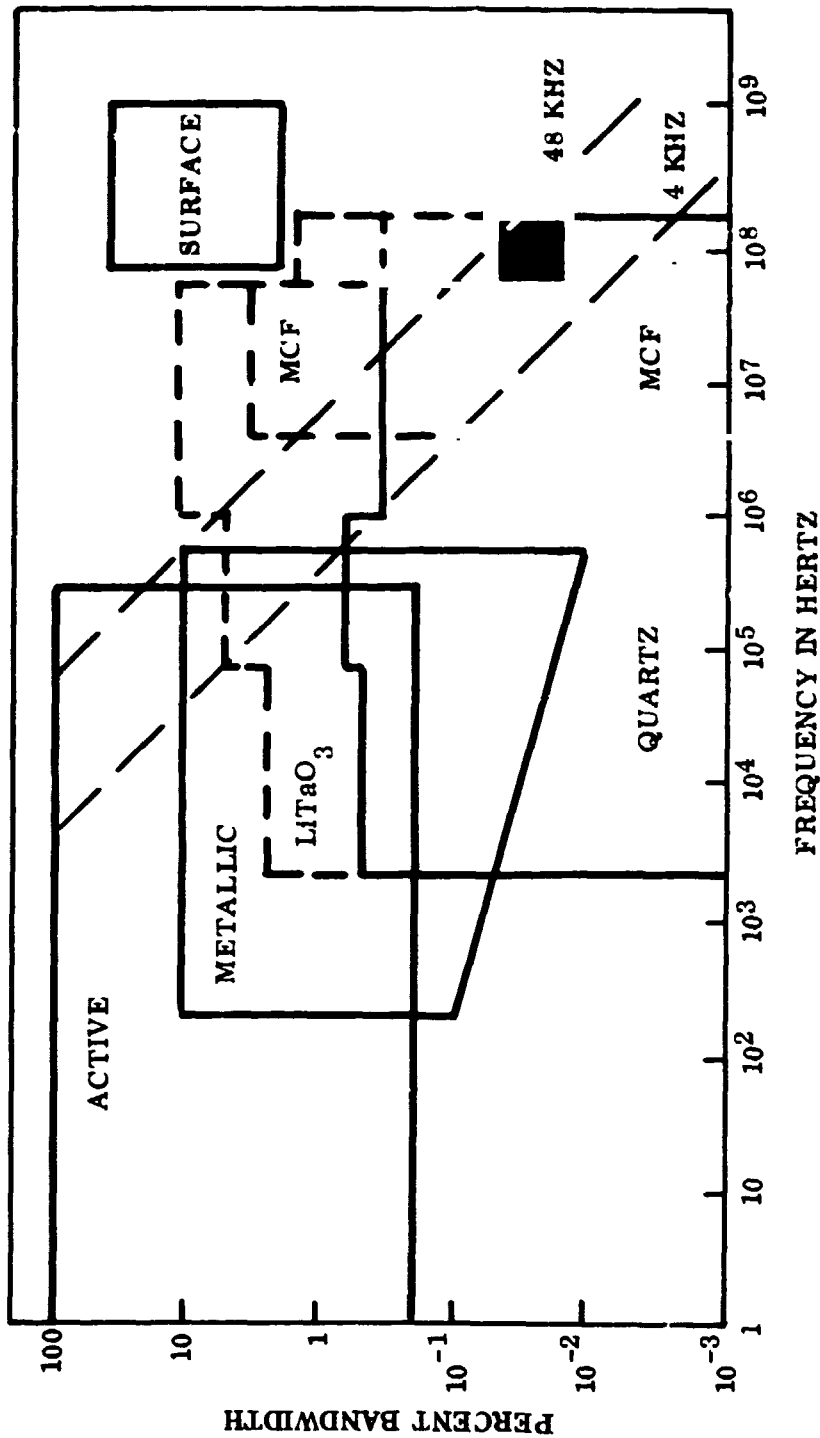


Figure F-1. Areas of application for various types of filters with regard to center frequency and bandwidth as a percentage of center frequency. MCF refers to monolithic crystal filters. Active refers to filtering by resonators used with an LRC circuit. Dotted lines show the percent bandwidth corresponding to one voice channel (4 kHz) and a "group of 12 channels (48 kHz). (Bowers, K. D., Bell Laboratories Record 49 (5) 139-145 (1971))

grinding and polishing processes on earth.

Another application of space processing to the growth of LiTaO_3 crystals is the continuous pulling of crystal ribbons. Ribbons could possibly be drawn along an orientation having zero temperature coefficient of delay.

At present the most widely used temperature compensated cut known are on the ST-cut, X-propagating orientation of quartz discovered in 1970. Unfortunately crystalline quartz has a very low piezoelectric coupling constant which leads to undesirable high insertion losses in devices. Several zero-temperature coefficient bulk wave cuts have been predicted and verified for LiTaO_3 . Space processing of crystals may be a method for growing a natural, temperature compensated orientation of LiTaO_3 .

4. Market Forecast

The communications industry has a high demand for precise filters and oscillators for precise frequency selection, rejection and control. The demand arises from the need to conserve frequency space and because of the economic need to multiplex many information-carrying channels into a single conductor. In this case quartz crystal resonators are used. The role of quartz crystal resonators in crystal-controlled oscillators should remain unchallenged except for the very few applications where a stability of better than one part in ten billion is needed. For filtering applications however, the competitive situation is complicated by the progress in hybrid integrated circuits.

The second use for ultrasonic devices in communications is as a sequential memory in the form of a delay line. This was discussed from a computer memory viewpoint in Appendix A. The advantage is the comparatively low velocity of ultrasonic waves wherein one inch of crystal will provide 10 microseconds of delay as compared to a mile of coaxial cable. The delay makes it possible to store several thousand bits of sequential information in acoustic form.

There is a need for miniature memories in the communications industry; these are too small for magnetic discs to be economical. The need for precision filters however, utilizing LiTaO_3 crystal plates or ribbons is much greater.

APPENDIX G

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