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Crystal Units Manufacture Mechanization Program

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SYSTEM STUDY
FINAL REPORT

[redacted]

ABSTRACT

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[redacted] development of a system and prototype equipments for a mechanized plant to manufacture CR-18/U and CR-23/U quartz crystal units at the rate of 200,000 per month with one-shift operation. This report finalizes the System Study and describes the processes and a man-machine system designed to achieve this goal. The integrated manufacturing system will be highly mechanized and completely eliminate the demand for critical operator skill. Approximately fifty operators, none of whom require more than two weeks training, together with 112 pieces of major equipment will be utilized to produce 10,000 tested crystal units per shift. Predicted yields are in excess of 150 good diced blanks or 100 tested crystal units per pound of raw quartz, based on the production of first harmonic crystals of frequency between 4.3 and 18 mc. and third harmonic units ranging from 17 to 54 mc.

"The assembly line is one of mechanization's most effective tools. It aims at an uninterrupted production process. This is achieved by organizing and integrating the various operations. Its ultimate goal is to mold the manufactory into a single tool wherein all the phases of production, all the machines, become one great unit. The time factor plays an important part; for the machines must be regulated to one another."

MECHANIZATION TAKES COMMAND
S. Gideon
Oxford University Press, 1948

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FOREWORD

[redacted] Quartz Crystal Units Manufacture Mechanization Program [redacted] The objective of this program is to implement the production of 200,000 quartz crystal units per month from a single line with one-shift operation.

The development of such a facility is a long-range undertaking on the part of the Government. A plant of this type must be a smooth-working entity in which men and machines are well-integrated into a continuous work flow. Critical dependence on the skills of well-trained operators must be avoided if the facility is to be usefully activated on short notice, as in the event of national emergency. On the other hand, the production of quartz crystal units has in the past been an art rather than an engineering science, and manufacture has been of the job-shop, small lot type rather than straight line high-quantity production. If the facility is to achieve its goals and produce crystal units of high quality, a hitherto unachieved amount of skill must be built into the machines, while the operation of each machine type must fit smoothly into the operations of the next in line.

In summary, such a production facility is a *system*, not a collection of machines. Hence, as part of this contract, an intensive System Study has been implemented and has proceeded hand-in-hand with the actual machine development. This document is the final report of the System Study, and summarizes the work of many individuals who have contributed to the present concept.

Two years of study and development on the operations involved in the mechanized production of quartz crystals have established the validity of the broad principles outlined in System Study No. 1 of this contract (dated 3 January 1955), and have served to confirm many of the machine and process details with remarkable accuracy. The use of the *systems concept* on which this development program has been predicated is thereby amply justified. In the large, the results of System Study No. 1 have been confirmed, expanded, and altered where necessary to represent the latest advances in the art as known to us.

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The techniques of operations research, chemical and physical investigation, machine design studies, and extensive contact and survey of other workers in Government laboratories and industrial facilities have been fully utilized, and are hereby acknowledged. Without the aid of many people, both within and without the Bulova organization, it would not have been possible to prepare this comprehensive report.

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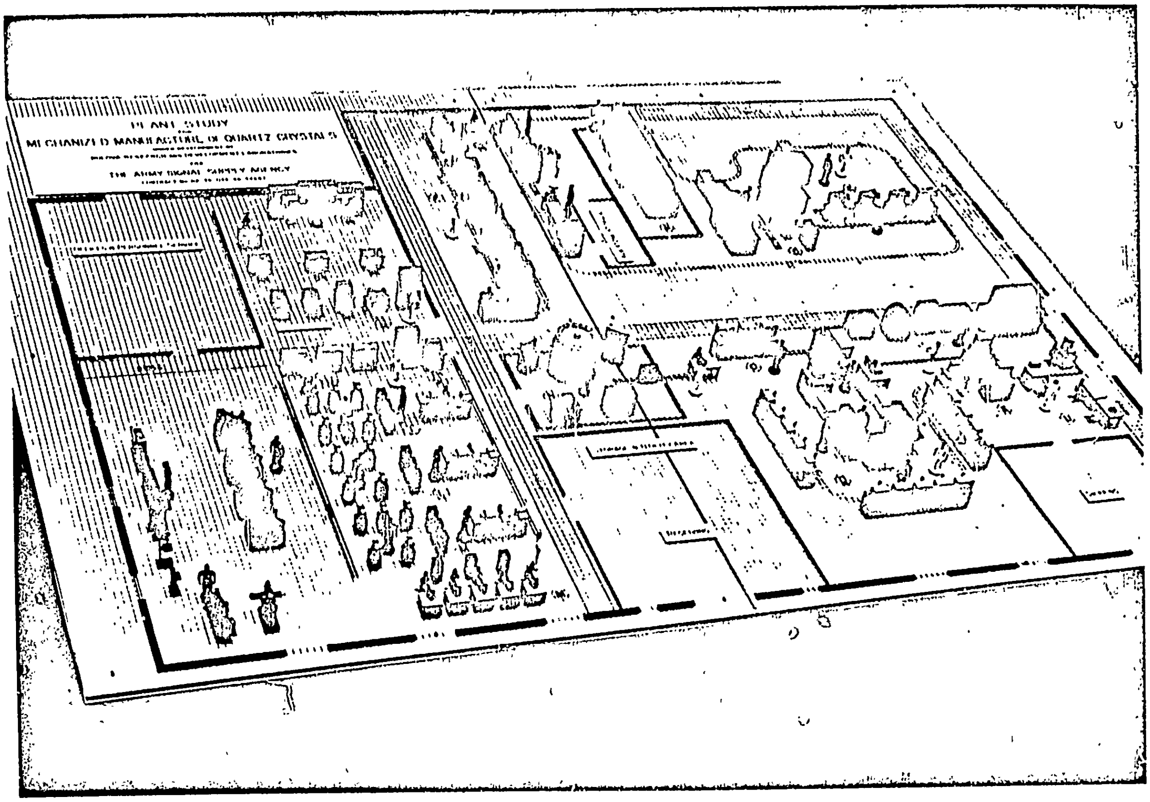


Plant Model, Mechanized Quartz Crystal Production Facility

PART I

Purpose of Program, Results and Conclusions

PURPOSE

The purposes of the Quartz Crystal Mechanization Program as outlined in System Report No. 1 are unchanged, and may be usefully quoted here. These are:

(1) To cut the delay between receipt of orders and delivery of large quantities of CR-18/U and CR-23/U crystal units.

(2) To cut the drain on the Nation's manpower resources and quartz resources during an emergency.

(3) To increase the quality of the product, especially in the early days of any mobilization.

(4) To decrease the cost of the product.

(5) To increase the general store of knowledge of crystal manufacture and put into practical use development gains made in recent years but not widely used in production.

More specifically, the technical goals of this program are to produce 200,000 crystal units per month, consisting of CR-18/U units from 4.3 to 18 mc. and CR-23/U units between 17.0 and 54.0 mc. The use of mechanization is to be introduced wherever necessary to reduce manpower skills below those which can be acquired within two weeks by the average operator, or where obviously required to eliminate an operation highly wasteful of manpower or raw material.

Many aspects of the system design of the plant must be founded on the distribution of frequencies which is specified in the orders, and on the number and size of the orders received each month. This is not to say that the plant is not capable of handling many different distributions of orders. On the contrary, the vast majority of the machines and processes specified are versatile to the extent that many types of crystal units may be manufactured and the production rate easily doubled by multi-shift operation. However, it is plain that a vast majority of orders comprising 100 or 200 units would convert the plant into a job shop, and largely defeat the goals of straight-line production. It is necessary to take some definite point of departure in a production system design, and this has been supplied on an informal basis by TASSA in the form of a sample Order Board. This is a listing of typical frequencies which might be ordered in any monthly period, and of the relative numbers of each unit which might be in demand. We have utilized this listing as a basis for design in many cases. Radical departure from this average will affect the production rate or may result in changes in the man-machine system.

The Maximum Order Board of Appendix I has been used as the basis of design.

INTRODUCTION

This Final Report summarizes the results of two years study on the processes and machines which make up the proposed Mechanized Production System. The report is divided into three main sections.

Part I is the summary and conclusions of the study, including data tabulated in the Appendix.

Part II is a detailed description of the processes to which raw quartz must be subjected to be converted into quartz crystal units meeting the rigid requirements of government specifications.

Part III describes the man-machine system, which implements these processes in an economical and efficient manner, together with the reasoning and calculations which lead to it.

It should be emphasized that the choice of processes which lead to a high yield of good crystal units is the most imperative phase of the program. It does not suffice to develop ingenious machines if the quality of the product is amiss. Hence, the first goal of the study has been to find processes which produce crystal units meeting military specifications and of the highest quality. The second most important objective has been to choose among the processes which produce good crystal units those which are most amenable to partial or complete mechanization. Thirdly, this study aims at creating an integrated system comprised of these processes, which combines manpower and machines in a manner most economical of human skills, of critical raw materials, and of overall production costs per unit of production.

Several topics of great importance have been excluded from this report, as being outside its contractual scope. To maintain high yields, a complete system of Quality Control consistent with present-day practice and program objectives must be implemented. A study of this phase should proceed hand-in-hand with the final machine development to take advantage of any closed-loop control opportunities that present themselves. Production Control is equally important, and a study of final integration, conveyance of material, stocking procedures and records must commence soon. The emphasis in this plant on sorting of crystal blanks as a major means of control in the intermediate operations (lapping to frequency), points up the problems. Finally, topics which rightly belong in the Operation and Maintenance Instruction Manuals and I. P. S. Reports are not covered. In addition we have omitted reference to plant location and construction problems.

RESULTS OF STUDY AND CONCLUSIONS

1. Plant Layout

The production of quartz crystals is divided into three phases:

a. Rough Cutting—stones to round blanks.

b. Sorting and Lapping—to final blank thickness.

c. Finishing—Final Etching to packaged crystal unit.

The final plant will be laid out in these three work areas so as to reduce the probability of contamination and to concentrate the supervision tasks.

A floor plan, consisting of a photograph of a plant model constructed in the course of this study, is included in this report as Plate I. The major flow of work is indicated in this plan, as is the general method of conveying work. Largely, the work will be transported by mechanical conveyor, although with the addition of extra workers, manual conveyance would suffice. Mechanical means should also greatly aid the task of Production Control.

Special mention should be made of the unit package concept by which work in various stages of manufacture is handled. Crystal blanks through Lapping and Sorting are handled in plastic cartridges containing 100 to 400 blanks. These cartridges are specially designed to integrate high-speed automatic sorting equipment with other processes, and provide a convenient unit in which material may be stored and handled. Lapping machine loading is accomplished through cemented assemblies of blanks and carriers. These contain either 3 or 4 blanks and may be handled as a unit. Lapping time, skill and labor are thereby much reduced. Again from cartridges, blanks are automatically loaded into Final Etch holders, in which they are uniformly etched and cleaned in groups of 100.

After this step, the blanks must be kept absolutely clean and free from moisture or finger marks. In order to accomplish this the blanks are handled in Base Plating masks between Final Etch and the Mounting and Cementing process. These masks hold a group of several oriented crystal blanks and can be mechanically loaded and unloaded without touching the blanks. They serve both as masks to limit the area of base plating and as carriers through the pre-heating, plating and pre-aging processes and into the Mounting and Cementing machine. Finishing operations are carried out through units of 10 or more crystals packaged in racks, allowing automatic handling from Base Assembly through Sealing and Frequency Checking.

Thus, from Final Lapping through Sealing and Final Frequency Check, manual handling of fragile quartz blanks is eliminated, so that both yield and quality are significantly improved.

The plant is envisioned as a single-floor layout. Similar or associated operations are grouped into Stations, of which there are twenty-one, from Mounting Stones to Packaging. The total floor space required for these stations, plus Receiving, Stockroom, Storage, Shipping, Office and Personnel Space is approximately 24,000 square feet.

2. Major Equipment and Direct Labor

The total plant requirement of direct labor and major equipment is 51 operators and 112 pieces of equipment, a saving of 80 to 85% over conventional methods. Preliminary estimates would add between 35 and 45 utility, maintenance, clerical and supervisory personnel for a grand total of 85 to 95 persons associated with the plant. Appendix II is a summary of the major pieces of equipment and the number of operators for each Station. Of the 112 pieces of major equipment listed, each is a separate, self-contained entity with a discrete input and output. Machines may be linked together with conventional conveying or transfer equipment, or material may be transported in tote boxes. In all cases, expansion of the plant to meet higher overall demands or a long-term change in military requirements (such as a preponderance of low-frequency crystals of which fewer can be lapped at one machine loading), can be compensated by the addition of one or more machines of each type, without affecting the production system. As a secondary advantage of this philosophy, practically all of the equipment which is or will be developed is applicable to smaller production quantities in job-shop lots.

Of the specific kinds of machines developed or being developed, many are completely unique in the quartz crystal industry. A few of the more outstanding examples are described below.

a. THE AUTOMATIC SORTERS, of which there are three types (X-ray or ZZ′ angle, Frequency and Thickness). These are of an unprecedented accuracy and speed compared with methods previously used for quartz crystals, eliminate human judgment and skill, and are of the utmost importance in reducing the time required for the intermediate operations.

b. PREPOSITIONING AND SAWING EQUIPMENT. The use of transfer jigs and of a system for prepositioning the jigs before they enter the sectioning and wafering saws is a novel procedure with many advantages. It results in a large saving in the number of saws and saw operators required, because of the more efficient use of saw time. (The operator is not required to adjust the position of the work-piece in the saw.) For the accuracy obtained, the saw design is less complicated, since adjustable tables, verniers and the like are eliminated. The time and skill required of the saw operator is much reduced, hence he can handle many saws at one time and needs little training. Pre-setting of the transfer jigs is accomplished in a double-crystal X-ray goniometer which is highly mechanized, resulting in the best possible precision with little skill demanded of the operator. Finally the use of multiple blades on the sectioning and wafering saws efficiently reduces quartz stones to wafers of the correct dimensions and orientation in the least time, again minimizing the number of saws and maximizing the yield of useful quartz. The integrated sawing-prepositioning system leads to the rapid, economical and foolproof production of wafers oriented to the best accuracy possible with currently available techniques. This in turn enables the plant to produce a high yield of crystals with essentially zero temperature-frequency coefficient.

c. ULTRASONIC DICING. Ultrasonic techniques have been advantageously utilized to cut specially shaped blanks directly from wafers, thus saving at least four steps in manufacture, none of which are easily mechanized.

d. FINAL ETCHING. A completely automatic device performs eleven different operations on quartz blanks and allows a degree of control over the etching and cleaning process previously found only in the laboratory.

e. AUTOMATIC PLATING. Both base plating (electrode formation) and final frequency adjustment have been completely mechanized to eliminate the critical skills hitherto required.

3. Processes

The major portion of our work in the System Study has been spent in determining the optimum methods of processing quartz, both from the study of industry and government practice or research and from our own tests and research. The goal has been two-fold—to find the methods which are most likely to lead to a high-quality product and to find those which are most readily mechanized; the results of this study are best shown by the Process Flow Sheet (Figures IIIa to IIIc of Appendix III).

Some of the major decisions which have been made as a result of the System Study are the following:

a. The AT cut will be produced by the X-section and wafering method. The steps in Rough Cutting, stones to round blanks, are illustrated in Plate II. Although this involves two sawing steps, the state of the art is not advanced to the point where reliable, mechanized, direct wafering is practical. Advances in the methods of growing synthetic quartz may eventually permit a simplification of our process.

b. Mechanized X-ray prepositioning and the use of highly accurate transfer jigs (adjustable to one minute of arc) will be utilized to control the precision of the AT cut. The use of the Hoffman Saw with multi-blade cutting, which is of an order of magnitude more precise than previous machines, permits this accuracy to be held throughout.

c. Round blanks will be diced by ultrasonic means directly from wafers, complete with orientation flat. Sorting and lapping are much facilitated through this scheme. Since the customary lapping of square blanks (before the cementing and rounding steps) is completely eliminated, the chipping of blank corners during lapping is likewise eliminated, hence crack-ups will be avoided.

d. Two blank sizes will cover the entire frequency range from 4.3 mc. to 18 mc. fundamental and from 17 to 54 mc. in the third harmonic mode. Contouring will be used in the lower ranges (below 9.0 mc.) to give good activity, and eliminate frequency dips and unwanted modes of oscillation.

e. Lapping will be accomplished in three stages, without the need to recirculate blanks or transpose them in any stage. Lapping simplification will be furthered by utilization of pre-assembled blank carriers. Spread-reduction will be accomplished by automatic high-speed sorting between each stage to supplement the limited reduction possible during lapping.

f. A hydrofluoric acid etch treatment will be used to provide the final surface finish. Etching will be precisely and automatically controlled, and will not require operator judgment.

g. The utmost care has been taken to maintain cleanliness of quartz after Final Etching, since it is unknown contaminants which are largely suspected of responsibility for frequency shift, low activity, and failure of crystal units upon aging. Hence, all finishing processes are carried out in some type of blank container which avoids operator contact with quartz.

h. Electrodes will be plated on blanks by evaporation of aluminum in high vacuum. Aluminum permits a high degree of control over thickness, and yet has good aging qualities. Final frequency adjustment will be accomplished through a similar step, using gold, the plating being controlled through feedback from the frequency of the crystal being plated. A large area of gold plating allows a large adjustment, although control of frequency spread will keep the adjustment required below $0.4f^2$.

i. A cemented mount similar in external dimensions and materials to standard HC-6/U bases and cans will be used to package the crystal units. The crystal supports have been redesigned to permit mechanized mounting and cementing.

j. Sealing methods will be completely mechanized to insure the minimum of contamination. The process that will be mechanized was developed by the Union Thermoelectric Corporation of Chicago.

A Frequency Chart has been established which specifies the variation and range of frequencies throughout the Intermediate and Finishing stages of manufacture. This chart is reproduced in Appendix IV. The thickness or frequency range (or spread) and quartz removal is given for specific frequencies which are of interest either because of the assumed demand (from Appendix I) or because they are terminal points in the range of this Study.

4. Yields

As a further result of the System Study, an estimate has been made of the yield and shrinkage of quartz in various stages of the mechanized plant. These data, summarized in Appendix V, have been the basis of multiple machine calculations in the body of this report (Part III). The estimates are necessarily preliminary, since development is not complete on many pieces of equipment. Nevertheless, they represent the best opinion that can be mustered at present, and have, in the large, been borne out by our experimental work. The yields are very high compared with existing practice; this is primarily due to our cutting and handling procedures. In summary, the best evidence to date is that we will be able to produce over 150 diced blanks acceptable for lapping and over 100 tested crystal units per pound of raw quartz, which represents a substantial saving of this important national resource.

PART II

Process for the Mechanized Manufacture of Quartz Crystal Units CR-18/U and CR-23/U (4.3—54.0 mc.)

PROCESS 1, INSPECT AND HEAT STONES

PROCESS 2, MOUNT STONES AND ORIENT Z AXIS

1. Incoming Material

The raw quartz to be processed will be clean Grade A stones with at least one natural face suitable for mounting. They will be selected or purchased with an average weight of 250 grams, and will vary between 175 and 300 grams, approximately. The problems of material procurement or source inspection will not be considered further since they are outside the scope of this report.

Preliminary studies of wafer size and blank yield indicate that the weight ranges stated are suitable for the blank size and dicing method we have chosen (as will be discussed in later sections). The weight of stone generally determines the wafer length, and since our blank dicing method cuts only a limited number of blanks from a wafer, too large a stone results in a waste of quartz. On the other hand, it is uneconomical to dice wafers containing less than two blanks, hence too small a stone is also wasted.

The same reasoning indicates that small stones should be used for small blanks and vice versa. Hence the first process will be a rough division of the stones into "small" and "large" categories. No rigid specifications will be set for this process, and it will be performed manually.

2. Mounting Stones

Sections and wafers must be cut from the stones with precise orientation relative to the crystallographic axes of the quartz, in order that the temperature coefficient of the final crystal unit be within specifications. In the chain of processes leading to this accurate orientation, the first is the preparation of the stone for X-ray diffraction measurements which precisely locate the atomic planes. A rough orientation of the stone is made, a saw-cut accomplished along this oriented axis, and the stone treated further so that X-ray methods can be used.

The first operation is therefore to mount the stone on a plate by means that will be suitable for sawing in a later stage, and to make an orientation of the crystallographic Z axis. The Z axis being the optical axis, it can be detected by rotating the stone on a natural face (a plane parallel to the X-axis) between two crossed polarizing screens until a minimum of light is transmitted by the assembly. We have adopted without substantial change, a means of performing this operation accurately, developed by Union Thermoelectric Corp., in which a photoelectric semiconductor and a long-scale meter replaces the human eye in judging the minimum illumination. The photoelectric polariscope will locate the Z axis within better than 2°. The stones are to be mounted on ceramic plates, which have previously been used for wafering. They will be given an orientation saw cut, etch bath, and sectioning cut while so mounted, after which the quartz will be separated from the ceramic and the plates recirculated or discarded. The plates are 3-5/8 x 2-3/16 x 3/8 inches thick, contain two square holes (for passage of the polarized orientation light beam) and beveled edges suitable for mating with the sawing jig. The plates must be fairly cheap, since they are to be used only four times before discarding, must be shaped accurately to fit the jigs, and should withstand moderately high temperature, thermal shock, acid attack, and fairly rough handling. The material fabricated by American Lava Co. meets all these requirements and has proven satisfactory in practice.

The method used for joining the stones and plates must meet the physical and chemical requirements stated for the plates and form a firm bond unaffected by strains of sawing, must be conveniently applied, and additionally, must be removed at will after the sawing operations. A plasticized shellac cement, commercially available in stick form has proven to be suitable for this purpose. The cement, De Khotinsky type, is thermoplastic, and the surfaces (stones and plates) must be heated to approximately 155°C.(311°F.) before the wax is applied.

The procedure to be followed for inspection, mounting, and rough orientation can be summarized as follows:

a. The stones are examined in the storage room and roughly separated into "large" and "small" categories.

b. The stones are stored in an oven, capable of heating a day's supply, and gradually raised in temperature to 155°C. Since it may be desirable to start with heated stones in the morning, the oven may be loaded in the afternoon and a timer set to turn on the oven approximately 3 hours before starting time.

c. A day's supply of ceramic plates, previously used for wafering, is placed in the oven at the same time as the stones.

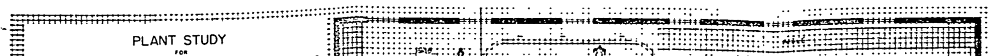


Plate I. Plan View of Mechanized Quartz Crystal Production Facility Model

STATION DESIGNATIONS

Station A — Mount Stones and Orientation Cut

Station A′ — Mount Sections, Sense Code and Saw X-ray Flat

Station B — Initial Etch

Station C — Preposition Stones and Sections

Station D — Saw Sections from Stones

Station E — Saw Wafers from Sections

Station F — Dice Wafers

Station G — ZZ′ Angle (X-ray) and Thickness Sorting

Station H — Load Lap Carriers

Station I — Primary Lap

Station J — Condition Lap Plates

Station K — Frequency Sorting

Station L — Secondary Lap

Station M — Final Lap

Station M′ — Contouring

Station N — Final Etch

Station O — Base Plate

Station P — Mounting and Cementing Blanks

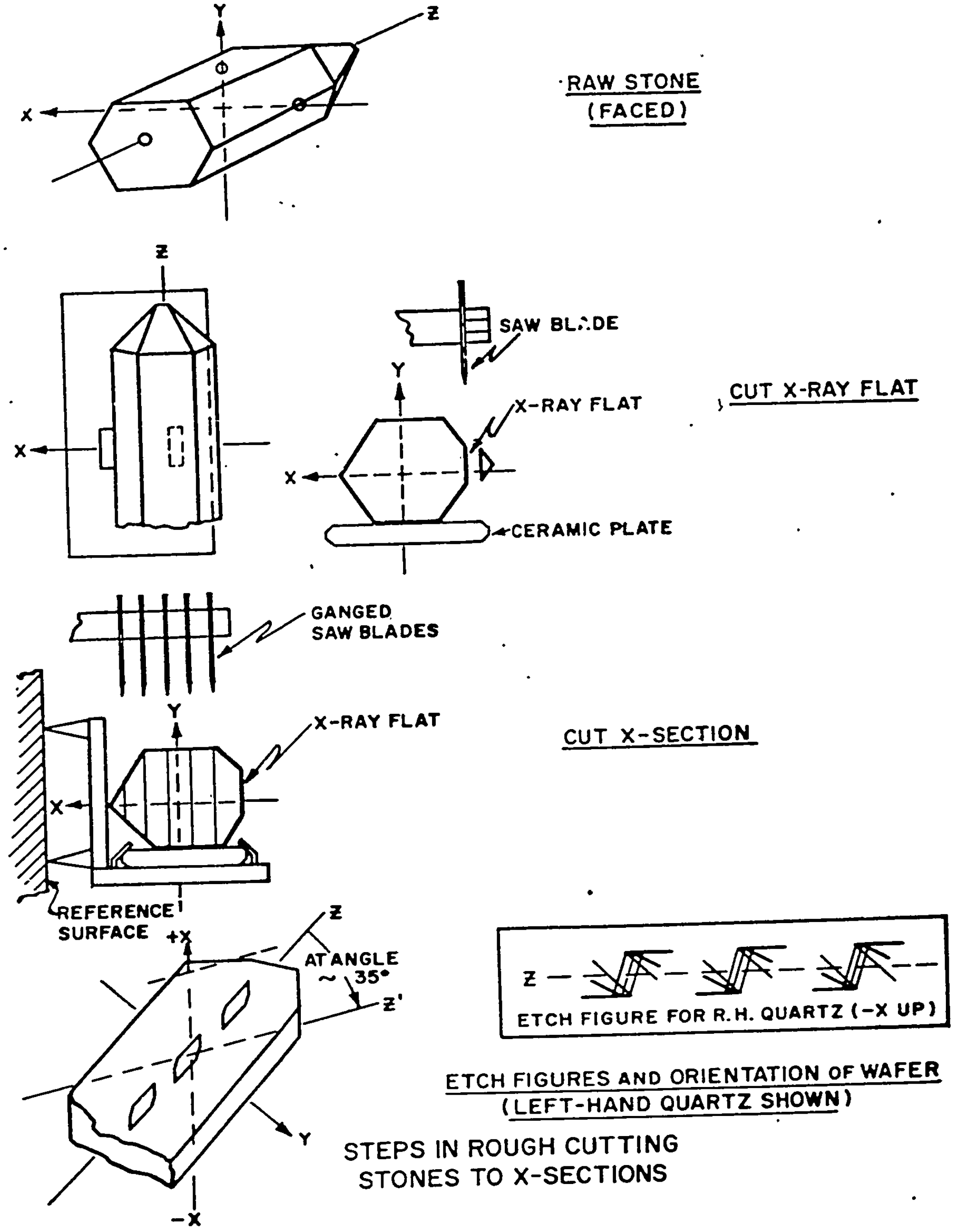
Station Q — Adjustment Plate

Station R — Can Preparation

Station S — Base Sealing

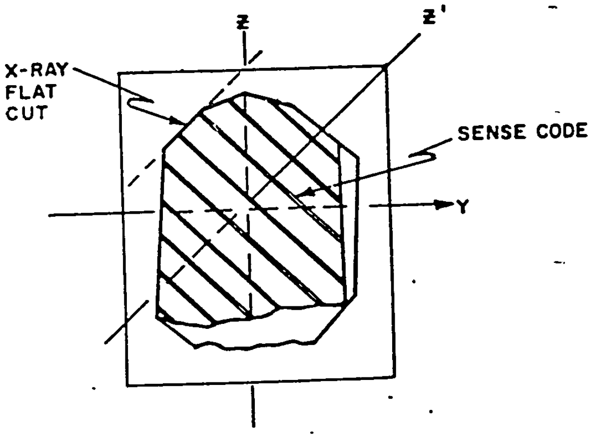
Station T — Frequency Check

Station U — Packaging

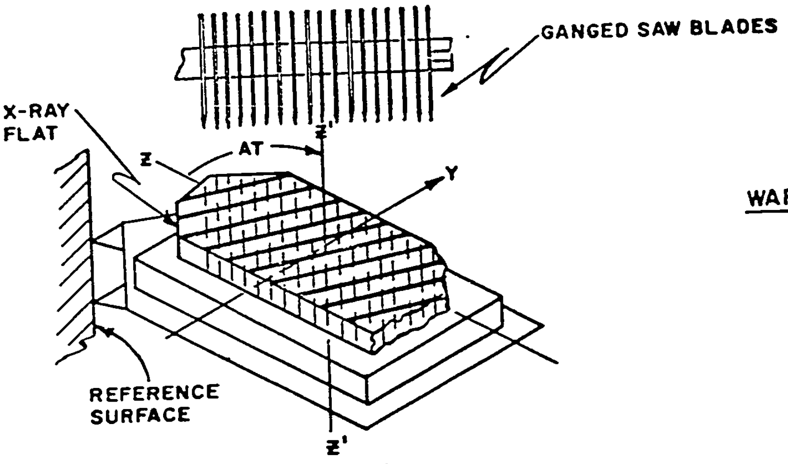


STEPS IN ROUGH CUTTING STONES TO X-SECTIONS

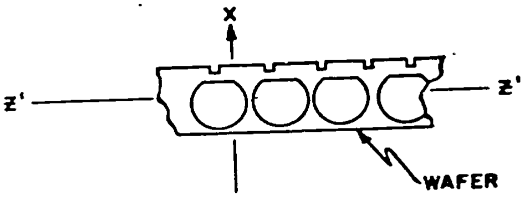
Plate II (a)



MOUNTED SECTION



WAFERING



ULTRASONIC DICED BLANKS

STEPS IN ROUGH CUTTING
X-SECTIONS TO ROUND BLANKS

Plate II (b)

Twenty seconds per stone may be allowed for performance of the above three tasks.

d. At commencement of the day's work, the operator removes approximately three plates and three stones, placing them on a thermostatically controlled hot plate, mounted on a bench of a convenient height for a standing operator.

e. Cement is applied to the flat side of the hot stone and it is joined to the plate. The plate is immediately placed in the polariscope, two adjacent edges fitting snugly against an L-shaped jig which aligns the hole in the plate over the polarized light beam (coming from below the table surface.) While still hot, the stone can be moved about the plate, and it is rotated until a point of minimum deflection of the meter is located. At the same time, the edge of the stone is moved laterally until the stone slightly overhangs the plate edge and touches an edge of the jig which locates the relative position of the saw blade. The stone is now correctly located on the plate, its Z axis is parallel to the edge of the plate (±2°) and the stone edge is in a position for an orientation saw cut.

Approximately 40 seconds per stone is allowed for steps (d) and (e). (U.T.C. allowance for similar process is 36 seconds.)

f. Without altering the stone's alignment, the plate is transferred to an adjacent cooling area on the bench. The area has sufficient space to hold a day's supply of stones. The stones are left undisturbed until the cement sets hard.

3. Alternate Methods

a. Orientation can be accomplished in an oil bath, also using polarized light and with visual observation of extinction. This means would be necessary if river quartz (having no natural faces) or very dirty material were to be used. Using the oil bath method (the oil having an index of refraction equal to quartz) results in accurate Z axis location, however, the Z line must be marked in some way and the stone then transferred to the mounting area and realigned. Thus two separate operations are required, extending the time needed and degrading the accuracy.

The present orientation scheme could also be accomplished by visual, rather than photoelectric observation of extinction. However, there is no doubt that the mechanized method is far more accurate and consistent while adding very little complication to the system.

b. Glass plates have been used for mounting and have proven moderately satisfactory, however they are fragile after use in multiple-blade sawing (the depth of cut being such that the mounting plate is grooved) and therefore difficult to use on both sides. Ceramic is slightly more expensive, but is tougher and can be used four times (twice on each side, once each for wafering and sectioning, the two types of cut being made at different angles.) Most important, ceramic has the property of dressing the saw blade, while glass has the opposite characteristic. The ceramic plates presently in use are standard in other segments of the industry. Some slight modification (a double-beveled edge with a flat center strip) will be made for greater ease in fitting either side into our jigs.

c. Wax can be used instead of De Khotinsky type cements for mounting stones to be cut with a single-blade saw, Courtwright #70C being a particularly good composition. It has the advantage of being easily removed with degreasing solvents. However its bond strength is lower than De Khotinsky and its use in multiple-blade sectioning appears marginal. For wafering, the stronger cement is mandatory.

4. Condition of Material Leaving Process

The stones, when cooled, are firmly bonded to the ceramic plates with the Z axis parallel to one edge of the plate within ±2°, and with the stone overhanging that edge sufficiently to permit a small saw cut.

5. Yield Expected

No reason for loss in stones is contemplated except thermal shock. With careful heating and static air cooling this should easily be reduced to the point when the yield will be substantially 100%, based on the number of stones entering the oven.

PROCESS 3, X-RAY ORIENTATION CUT

1. Incoming Material

The cooled, mounted stones of Process 2 will be brought individually to a saw for the rough orientation cut.

2. Sawing Process

A flat cut roughly parallel to the Z and Y axes (an "X-cut") must be made and the cut plane etched before a more accurate orientation can be determined by X-ray methods. The mounted stones will be secured in a jig, mounted on the saw table, which will have a predetermined orientation with respect to the saw blade. A plunge-cut will be made parallel to the mounting plate edge (to which the Z axis of the stone was aligned). The saw will remove a small portion of the stone overhang, the amount being determined by the locating stop of the mounting jig in Process 2. Approximately 80 seconds per stone is allotted to this process.

3. Alternate Methods

Sawing by means of diamond wheels is easily performed by relatively unskilled operators, utilizing readily available machines common in the industry. It is faster and more accurate than grinding, for example.

Using the mounting method previously described, no mechanization is required except for the jig into which the mounting plate is fitted, since one operator and one saw can handle a day's production, in addition to the mounting task. Other methods, such as mechanical clamps to hold the stone, are rendered unnecessary by the cementing scheme, and the expense of these mechanical devices is avoided.

4. Condition of Material Leaving Process

After cutting, the stones are unlocked from the jig and placed to one side, preparatory to being placed in etching baskets. The jig and saw blade will be aligned to better than ±3°, hence the saw-cut will be aligned to the Z axis to better than ±5°.

5. Yield Expected

No loss of stones is expected. A small amount of quartz (perhaps 4 grams per stone) is lost in the cutting and will be scrapped.

PROCESS 4, INITIAL ETCH STONES

1. Incoming Material

The stones, mounted on ceramic plates and with an X-ray flat saw cut, enter this process before undergoing X-ray prepositioning.

2. Etching Process

The purpose of this process is to smooth the sawn surface of the X-ray flat and to improve its X-ray reflection properties. This will result in a greater sharpness of the reflected X-ray beam and ease the prepositioning process.

A number of different chemical treatments are used in the Quartz Crystal industry for this purpose. We have found that hydrofluoric acid, 48% by weight, used at room temperature, is a relatively inexpensive material and superior in etching qualities to others used. By varying the etching time, HF can be used not only for this process and for No. 14, which is identical, but also for Processes 9 and 19 in which the visual properties of defects and of orioscope etch figures are to be enhanced by the etchant.

In order to insure that the etching process is effective, the quartz should first be washed in a detergent and rinsed. Following the etch, the quartz is again rinsed several times to terminate chemical action.

The etching process is conceived as being carried out in a continuous semi-automatic machine. The mounted quartz stones, contained in acid-resistant baskets which hold five stones, will be inserted into the machine and treated as in the following table:

Table 4-1

INITIAL ETCH PROCESS (Stones)

Operation	*Temperature*	*Time (Min.)*
1. Detergent	40°C.	2.5
2. Water Rinse	40°C.	1
3. Water Rinse	R.T.	1
4. Etch, 48% HF	R.T.	11 (approx.)
5. Water Rinse	40°C.	1
6. Water Rinse	60°C.	1
7. Air Dry	—	5.5
	Total	23

Time and temperature of this process may be automatically controlled, but need not be highly precise.

At the conclusion of the treatment, the basket will be returned automatically to its starting point and removed by the operator.

3. Alternate Methods

Other materials which have been investigated are listed in the table below:

Table 4-2

1. Dallon's etch	1.74 liter/gal. Methanol 1.74 liter/gal. Fluoroboric acid 47% 6.95 lb./gal. Ammonium bifluoride
2. Modified #1	(water substituted for Methanol)
3. Modified #1	3.48 liter/gal. Fluoroboric acid 47% 6.95 lb./gal. Ammonium bifluoride
4. Standard Quartz Etch	Ammonium bifluoride Molasses HF acid (exact percentage unknown)

Etch figures obtained with pin-hole orioscope after etching X-sections at room temperature gave the following results as compared with HF acid alone (48%):

Table 4-3

ETCH FIGURES AFTER ETCHING FOR:

Etch	*1 hour*	*2 hours*
#1	fair	good
#2	poor	fair
#3	good	good
#4	very poor	poor
HF acid 48%	good	very good

The approximate cost of these materials for 200 gallons, not including freight, etc., is compared in Table 4-4:

Table 4-4

Etch	*Approximate Cost/200 gal.*
#1	$910.
#2	875.
#3	1250.
#4	750.
HF acid 48%	260.

The tables above indicate that HF is the best etchant and the least expensive of all materials tested. It is easier to provide corrosion-resisting lining for HF tanks than with other etchants. All the materials are equally poisonous but HF requires more care in handling. If an automatic machine with a good exhaust system is used, as contemplated, there will be no contact of the operator with the acid and hence no danger involved in its use.

4. Condition of Material Leaving Process

The stones will leave the etching process clean and dry, with a smooth surface on the X-ray saw cut.

5. Yield Expected

No loss is anticipated in this process.

PROCESS 5A, INSERT MOUNTED STONES IN TRANSFER JIGS

1. Incoming Material

The stones mounted on ceramic plates, having an etched X-ray saw cut within ±5° of the Z-axis, enter this process to be assembled to a transfer jig.

2. Assembly Process

The purpose of this step is to secure the stone in an adjustable mechanism in which it can be precisely oriented by means of X-ray diffraction, then transferred with this same orientation to a saw which will cut the X-sections. The procedure is intimately associated with that of the next process, X-ray prepositioning of stones and with the sectioning process following. Even more fundamentally, it is connected with the whole system of producing AT cut crystal blanks.

The basic objective of the rough cutting stages of quartz crystal manufacture is to produce blanks, which are thin slices having plane surfaces exactly parallel to the X-axis of the crystal and to the AT angle (ZZ′) with the Z-axis. The ZZ′ cutting angle will vary between 35° 15′ and 35° 26.5′ in our process, depending on the final frequency desired and which AT angle gives the best temperature coefficient in the finished units. (See Appendix 15-1.)

Many different means have been conceived for producing blanks from natural quartz crystals, in addition to the variations or simplifications that oriented synthetic quartz would introduce. For example, wafers may be sliced directly from natural crystals, then cut into squares of the proper dimensions, stacked and ground into blanks. For each method proposed, consideration must be given to the sawing time, utilization of quartz, degree of skill and number of machines for each operation, together with many other tangible and intangible factors.

Although an exhaustive formal study comparing all possible methods has not been prepared within the scope of this project, considerable thought has been given to the subject and the experience of others in the industry has been culled. The conclusions have definitely pinpointed the X-sectioning method as being most economical of quartz and of the greatest potential for mechanization. By sectioning prior to wafering, one of the important orientations of the eventual blank is established with a small number of sawcuts, while the stone is still in one piece. Advantage is taken of the atomic regularity and rigidity of the natural material as long as possible. If both X-axis and AT angle orientation must be established on an irregular wafer, a much more difficult inspection and mechanization problem is presented and the yield of blanks will be poorer.

Hence, the purpose of orienting the stone is to establish the first saw-cut perpendicular to the X-axis, or parallel to both Z and Y-axes.

The transfer jig will permit the stone to be rocked in two mutually perpendicular directions, and a locking device will hold the positions, once set. The stone will be supported on the upper movable surface which will be capable of being adjusted by micrometer actuators on the X-ray positioning table. The ceramic plate holding the stone will be clamped to the moving part so that the orientation cut is accessible to the X-ray beam.

The stone is now secured in a position so that the orientation cut may be illuminated by the X-ray beam.

The actual assembly will be very simple. The mounted stones will be obtained from the previous process and clamped into the jig, being locked with a single motion.

3. Alternate Methods

Other methods have been investigated for orientation of stones for sectioning, among them being the use of adjustable saw tables and the correction of angle by external measurements on a preliminary cut. This method does not lend itself to high-speed production as the saw is tied up while awaiting X-ray results. The transfer jig, by separating the two steps (measurement and sawing) allows each to be performed with greater speed and minimum of equipment.

4. Material Leaving Process

The jigs and stones are transferred to the X-ray table for measurement.

5. Yields

There is no loss in this process.

PROCESS 5B, X-RAY PREPOSITION STONES

1. Incoming Material

This consists of the assembled jigs and mounted stones of the previous process.

2. X-Ray Prepositioning

The objective of this step is to level the stone with respect to a reference surface so that the X-axis of the stone is perpendicular to the reference surface within ±5′ of arc.

The accepted method of measuring the tilt of the X-axis is to observe the intensity of reflection of a collimated beam of X-rays from a smooth surface of the stone which is already approximately perpendicular to the X-axis (the orientation cut). The apparent reflection is actually diffraction of the beam from the 11.0 atomic plane, which is exactly perpendicular to the X-axis. Maximum intensity occurs when both incident and reflected beams correspond to the Bragg angle (18° 17.4′), with the 11.0 plane.

The tolerance of ±5′ is not an absolute requirement. Actually the combined tolerance of sectioning saw and measurement are of interest. The cut surfaces of the sections may be as much as ±15′ away from being perpendicular to X without affecting the quality of the ultimate crystal unit. It is well known in the crystal industry that significantly greater deviations (over 1°) may adversely affect the temperature coefficient of frequency of the final units. The specification of ±5′ we have set is with the expectation that the saw tolerance would not add more than 10′ to the error. For a discussion of the effect these errors have on X-ray (ZZ′ angle) sorting (Process No. 26), see Appendix 26-3.

In actuality, we will achieve significantly better than 5′ in the leveling procedure. This is because we are using the same type of X-ray apparatus for stones as for prepositioning sections (Process 15), which latter measurement has a much smaller tolerance. The method we are using is the so-called "double crystal" X-ray goniometer, in which the X-ray beam is collimated by being reflected from a fixed crystal before being directed to the crystal undergoing measurement. A much narrower beam is achieved in this way than by slit collimation, and accuracies much better than 1′ can be obtained.

Although the double crystal goniometer requires a somewhat more sensitive X-ray detector than older methods, these are now available in the form of scintillation counters and high gain amplifiers. The additional complexity or cost is slight, and is offset by the fact that other machines in the plant will require the same components, hence maintenance will be simplified and standardized. The greater degree of accuracy, although not necessary for prepositioning stones is certainly not harmful and may well lead to better over-all quality and control.

The process to be used in prepositioning the stone for X-sectioning can be described as follows:

a. The X-ray apparatus is pre-aligned over a horizontal turntable so that a standard crystal with its 11.0 plane parallel to the table will give a maximum deflection of the detector's output meter.

b. The mounted stone in its jig is placed on the reference turntable and the latter raised until the cut surface of the stone touches a pointer. (The X-ray beam is directed at the pointer, which is exactly over the center of rotation of the turntable.)

c. The turntable is rotated so that one edge of the jig is parallel to the beam.

d. The table micrometer actuating the jig is manipulated by the operator, tilting the stone about a line perpendicular to the beam, until a maximum reflection is indicated. (This micrometer may be motorized, automatically stopping on a signal from the peak reflection.)

e. The table is rotated exactly 90° so that the other micrometer is in position to tilt the stone as above, and the maximizing adjustment repeated. The jig is then locked.

f. The 11.0 plane is now parallel to the reference surface (turntable) and the jig and stone may be removed without disturbing the adjustments.

Approximately 50 seconds per stone is required to perform this task and that of Process No. 4 (Assemble Stones to Transfer Jig.)

3. Alternate Methods

Two-axis orientation using two machines is possible, but is less desirable than the turntable method. Since one machine will be sufficient to preposition all stones, there is no advantage in splitting the task.

A one-axis orientation utilizing the natural face of the stone as one reference does not seem to be possible or practical at this time.

It is possible to eliminate the initial etch procedure prior to X-raying, since the accuracy required is less than will be required for sections. However, the same operator will preposition both stones and sections and since the reflection peak is less sharp in unetched material, consideration of uniformity in operator training favor retention of the etch.

4. Condition of Material Leaving Process

The stones mounted in their jigs are sent to the X-sectioning process pre-aligned to better than ±5′.

5. Yield

There will be no shrinkage in this process, either from loss of quartz or from inaccuracies.

PROCESS 6, SAW X-SECTIONS FROM STONES

1. Incoming Material

The stones secured in pre-oriented transfer jigs which are clamped to the ceramic mounting plates, are transferred to the sectioning saw.

2. Section Sawing

The stones are to be cut into X-sections, the direction of cut being parallel to the Z- and perpendicular to the X-axis. The thickness of the sections is determined by the desired width of wafers which will be sliced from the sections in a later stage. The wafer width is in turn determined by the desired crystal blank diameter.

Early in the course of this study it was decided that the frequency ranges of both CR-23/U and CR-18/U crystals which have been specified could be covered by two blank sizes, 0.490 and 0.375 inches in diameter. (As discussed elsewhere in this report, the blanks are round, to prevent chipping of corners during the lapping processes, and have a flat to permit orientation in the sorting and mounting stages of manufacture.) The choice of diameters has been based on studies of industry practices, and to some extent on experimental measurements of crystal activity as a function of blank diameter. This work has been described in some detail in Progress Report No. 19 (dated 27 April 1956) of this Contract. A table of effective resistance vs. frequency for the different diameters is reproduced in Appendix 6-1 of this report for convenience.

From consideration of the desired blank size, the method of producing blanks (discussed under Dicing, Process 22) and the saw tolerances, a theoretical section thickness of 0.423″ ±.005 has been established for 0.375″ blanks and 0.535 ±.005 for the .490″ blanks. Since the yield of sections is very little affected by small increases in width (since two end pieces are discarded in any case), an additional allowance has been made, so that the actual thickness of sections will be: for 0.375 blanks 0.430″ ± .005, and for .490″ blanks 0.542″ ± .005.

From the Order Board (Appendix I), the ratio of 0.490″ to 0.375″ blanks is computed to be 0.542 to 0.458, hence the number of sections sawn to each thickness will be approximately in the same ratio.

The equipment we have chosen for sawing is essentially the same as the P.R. Hoffman sectioning saw and was chosen as a result of the experience of the Signal Corps Engineering Laboratories and our own investigations on the possibilities of other methods. A multiple-blade arbor will be used (five Felker diamond blades), which can be quickly changed on the spindle for different widths of cut. Blade life will be extended by reason of internal coolant feed with special coolant slots and wells incorporated in the spacers. All experience to date shows that the angular error of this saw is far less than the over-all requirements (±15′) of the X-sections. The thickness errors will depend to some extent on the variation in saw blade set, on the blade spread, as well as the ratio of blade to spacer diameter and on the type and speed of cut, but in all cases the allowance of ±.005″ in this process will be easily achieved.

A full step-cut will be taken to the depth of the stone and slightly penetrating the ceramic plate. The jig will be clamped to a table sliding horizontally on precision ways, and will be propelled into the blades.

The jig will be clamped against a vertical reference surface mounted on the table and aligned precisely with the blades. Thus the stone prepositioning established in Process 5 will be maintained. Once the stone is in place, the remainder of the process may be automatic, the saw drive started and the table released into the feed. At the end of the table travel, the saw will stop and the operator removes the jig so that the table can be returned for the next stone.

The entire procedure of loading, sawing, and unloading the jigs will require not more than 2.4 minutes.

It must be possible to change arbors (section thickness) in less than 15 minutes.

3. Alternate Methods

The entire procedure of loading, sawing, and unachieved with the P. R. Hoffman sectioning saw make it a natural choice for this operation. Other saws investigated have included the Felker, Hardy, and British Inner Periphery, discussed in System Study Report No. 1, none of which have shown advantages over the Hoffman since that time. The Raytheon developments on ultrasonic cutting have likewise shown no economic or mechanical advantages.

4. Condition of Material Leaving Process

The quartz will leave this process as sections 0.430 or 0.542 ±.005 inches thick and as scrap (end pieces), cemented to ceramic plates and clamped to the prepositioning jig.

a. The thickness variation of sections will be less than ± .005 inch.

b. The crystallographic X-axis will be perpendicular to the cut plane of the section to better than ± 15′ of arc.

c. The section planes will be parallel to approximately ± 3′ of arc.

d. The surface finish will be adequate to permit observation of orioscope etch figures after moderate etching.

5. Yield

The number of useful sections obtained from a stone varies considerable with shape and weight. From 246 and 290 gram stones we have obtained three or four sections in preliminary experiments, but all of these sections are not equally useful for wafering. As a means of estimating, we have arbitrarily based the yield on an average section (approximate weight 60 grams) that would yield 20 wafers.

The average yield on this basis is estimated as 2.6 sections per stone (250 grams).

The yield of quartz on a weight basis is between 60 and 65%, that is approximately 37% of the quartz will be unusable scrap.

PROCESS 7, REMOVE PLATES AND DEGREASE TRANSFER JIGS

1. Incoming Material

The sawn sections and scrap enter this process cemented to ceramic plates, which in turn are clamped in prepositioning jigs.

2. Process

The ceramic plate is removed from the jig by unlocking a quick-acting clamp, and sent to the next process where the cement is unbonded and the quartz separated.

The jigs are taken to a washer in order to remove oil and quartz dust before being re-used. A standard degreasing treatment using trichloroethylene or a similar solvent will be adequate for this purpose. A conveyorized degreaser is envisioned in order to conserve manpower and expedite jig recirculation.

3. Alternate Methods

The process is so simple that additional study does not seem warranted.

4. Material Leaving Process

The clean jigs will be returned to the jig assembly process, No. 4. The ceramic plates and quartz will be sent to the next process, No. 8.

PROCESS 8, SEPARATE SECTIONS

1. Incoming Material

The quartz scrap and sections are bonded to ceramic plates with a DeKhotinsky type (shellac) cement, which must be loosened before they can be separated.

2. Separation Process

The cement is slowly soluble in several solvents, the degree to which it is soluble depending on the exact composition of the cement. If a very hard cement is used, several hours or days may be necessary to soften the bond. If the cement is too soft, it will not withstand the pressure of the saw blade, particularly in multiple-blade sectioning.

A cement composition will be chosen that will permit the bond to be released in approximately one hour. Denatured ethyl alcohol will be used as a solvent, since it will also serve as a degreasing means (to remove the cutting oil). A slightly elevated temperature (40°—50°C.) will hasten the process.

The ceramic plates will be placed in baskets and the baskets inserted in a container where they will be immersed in alcohol and agitated to some extent. A suitable cover and adequate ventilation will be provided to prevent loss of solvent and fire hazard. At the end of one hour of this treatment, the baskets will be removed, the sections separated by hand and placed in other baskets which are used for the Initial Etch process.

The ceramic plates will be inspected, and if they have been used twice on each side (for section sawing and wafering), they will be discarded. Otherwise they will be set aside to be returned to Process No. 1.

The scrap will be discarded.

3. Alternate Methods

The only other efficient solvent known to us for this cement is caustic soda solution (Na OH). This is a more difficult material to handle and would require special precautions to protect the operator. Furthermore, a rinsing and drying operation would be needed to remove the caustic.

Other cements which are more readily removed have not so far been demonstrated as adequate for our multiple blade sawing.

4. Material Leaving Process

The quartz sections (in baskets) may still retain traces of cement on their edges, however, this will be removed in the etching process.

5. Yield

No loss, except for scrap already accounted for, is to be expected.

PROCESS 9, INITIAL ETCH SECTIONS

(See Process 4)

1. Incoming Material

The material to be etched at this stage consists of unmounted X-sections which have been cut and separated from the remainder of the stone.

Sections are 0.430 or 0.542 (±.005) inches thick and average about 1 cubic inch in volume and 70 grams in weight.

2. Etching Process

The process is to be carried on with the same equipment as Process 4, and utilizing the same etchant (HF). The purpose of etching in this case is to permit the quartz to be examined for twinning and left- or right-handedness utilizing ordinary light. The degree of etching must therefore be greater than in Process 4 and the time in HF extended to one hour.

If an automatic, conveyor-fed etching process is used, extension of etching time is most easily accomplished by slowing the conveyor, hence the washing, rinsing and drying steps will also be slower.

Table 9-1

ETCHING PROCESS (SECTIONS)

Operation	*Temperature*	*Time*
1. Detergent	40°C.	15 min.
2. Water Rinse	40°	7 min.
3. Water Rinse	R.T.	7 min.
4. 48% HF Etch	R.T.	60 min.
5. Water Rinse	40°	7 min.
6. Water Rinse	60°	7 min.
7. Air Dry	—	22 min.
		125 min.

3. Alternate Methods (see Process 4)

4. Condition of Material Leaving Process

The sections are etched to a degree which permits good etch figures to be observed with a pin-hole orioscope. They are clean and dry.

5. Yield Expected

No significant loss is expected.

PROCESS 10, HEAT SECTIONS AND PLATES

1. Incoming Material

Etched Sections, unmounted.

2. Process

Sections and ceramic plates are both heated to 155°C. in order to permit the application of DeKhotinsky-type cement in stick form. This is necessary in order to mount the sections for further processing and wafering.

Since over 2-1/2 times as many sections must be processed per day, as were stones, a conveyorized oven is envisioned for this step.

3. Alternate Methods

A hot plate or conventional oven could be used, but would increase the manpower requirements.

4. Condition of Material Leaving Process

The heated sections and plates will be delivered to the operator position on a moving belt or some other convenient means.

5. Yield Expected

Heating must be gradual so as not to set up excessive strains in the quartz. If this is accomplished, there will be no significant loss.

PROCESS 11, ORIENT SECTIONS FOR MOUNTING SIDE, INSPECT FOR TWINNING

1. Incoming Material

The sections are delivered in a heated condition, approximately 155°C. As a result of prior operations, the X-axis is perpendicular to the sawn faces of the section (±5').

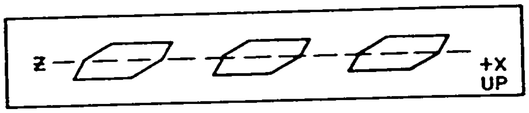
2. Process

In this step, right- and left-hand quartz must be distinguished so that the AT wafering cuts may be made in a uniform manner in subsequent processing. The most convenient and accepted method of doing this is to observe the etch figures with a pin-hole orioscope.

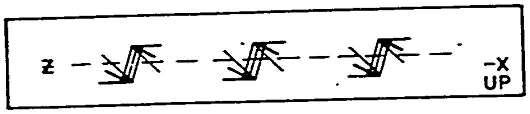
If the section is mounted with the +X-axis up for left-handed quartz and the —X-axis up for right-handed quartz the AT line will tilt to the right (i.e., will be in the first quadrant) in both cases. (See I.R.E. "Standards on Piezoelectric Crystals", 1949). The orientation for further steps up to wafering will then be the same.

a. The operator will place the stone on a pin-hole orioscope having three pin-holes in a line, and look for following figures.

For left-hand quartz, a parallelogram.



For right-hand quartz, an inverted "Z".



The section is placed with the side facing upward which gives one of the above two figures.

b. The Z-axis is roughly marked by drawing a line parallel to the pin holes. (This step may be expidited by means of a marking jig or stamp.)

c. Twinned areas (of opposite handedness to the major part of the quartz), are marked. These may be observed in the orioscope or by reflected light.

If the operator observes excessive twinning at this point, the section may be put aside for future salvage or scrap.

3. Alternate Methods

The AT line could be marked directly at this stage, but the polariscope method (See Process 12) is more accurate. This step could be also accomplished before heating, but would require an extra operator.

4. Condition of Material Leaving Process

There is no change in the condition of the sections, but the Z line is indicated on the side to be mounted upward and the twinned areas are marked off.

5. Yield Expected

It is expected that between six and seven percent of the sections examined will be twinned badly enough to be rejected. Some of these may be salvaged by sawing into two pieces, as for example where 180° twinning runs through the center of the section.

PROCESS 12, MOUNT SECTIONS, ORIENT AT LINE, AND COOL

1. Incoming Material

The sections are marked with the Z line, twinned areas and side to be mounted upward. They are still hot enough to melt the mounting cement. Hot ceramic mounting plates are also delivered to this area.

2. Process

a. The ceramic plates are placed in an L-jig over a source of polarized light in a photoelectric polariscope substantially identical to that used for stones. (See Process 2.) Mounting cement is applied to the plate or section.

b. The sections are placed on the plate with the marked Z-line upward and parallel to the long edge. The section is shifted until one corner is in a position to be cut by the X-ray flat saw, as indicated by a marker which shows the relative position of the saw blade when the mounted section is put into the saw jig.

c. If the corner to be sawn is marked as twinned, the section will be moved until the twinned portion will be cut off. If this is not feasible, the section can be turned 180° on the plate.

d. The section is rotated slightly until the polariscope meter shows a minimum reading.

e. The stone is slid out of the jig and onto a cooling table.

Since the same operator will perform both this task and Process 11, the question of judgement with respect to twinning and rejection will be reduced. On the other hand, there is no doubt that the doctrine for these processes must be carefully established in order to maintain satisfactory yield.

It is believed that an operator with two weeks training could accomplish this task and that of Process 11 in less than one minute per section.

Since the mounting cement to be used must withstand the force of multiple-blade wafering (in a further process), it must be of a type to give high bond strength. The DeKhotinsky type has proven adequate.

3. Alternate Methods

See Process 2 for discussion of polariscope and cements. Because of the judgement required at this stage, further mechanization does not seem possible.

4. Condition of Material Leaving Process

The mounted sections will have their Z-axis aligned with respect to the mounting plate by ± 2°.

5. Yield Expected

See Process 11.

PROCESS 13, SCORE SENSE CODE AND SAW X-RAY FLAT

1. Incoming Material

Sections mounted on ceramic plates, with Z-axis parallel to one side of the plate.

2. Process

In this operation the upper side of the mounted section will be marked, and a saw cut will be made within ± 5° of the AT line (approximately 35° from the Z axis). These objectives will be accomplished in two steps.

a. SENSE CODE: The upper surface of the section (+ X for left-hand and —X for right-hand quartz) provides the proper sense for the further steps of X-ray sorting and mounting. This surface is marked before wafering so that it may be recognized and the sense preserved in the dicing stage.

Since the section will be wafered along the AT line, the sense code will be marked at right angles to the AT line in order to appear on every wafer.

The section will be serrated approximately 1/32 inch in depth by means of a ganged set of saw blades.

The mounted section will be clamped to a table which will slide under a fixed set of saw blades. The mounting plate will be fixed at a preset angle so that the blades will score the top surface of the section at 90° to the AT cut as the table travels under the blades. A height adjustment must be provided so that two different thicknesses of sections can be accommodated.

b. X-RAY FLAT: When the table has traveled under this saw, the jig holding the section will be rotated 90°. The table will then be propelled under a second saw with a single blade set to cut off the corner of the section designated for the X-ray flat. This cut will be parallel to the AT line within ±5°, and at right angles to the sense code serrations.

The operator will remove the section and it will be transferred to the initial etching area.

The operations are conceived as being manually carried out, with the aid of appropriate jigs and suitable safety precautions. Both operations are performed by the same operator and should require about one minute total.

3. Alternate Methods

The sense code cut is made before the X-ray cut in order to eliminate the possibility of chips on the X-ray flat, which could cause errors.

A dye would be preferred to the serrations but it would need to withstand the subsequent etch and wafering treatments. No such dye has as yet been found by us.

Ultrasonic cutting of the sense code would almost surely be slower and more expensive.

4. Condition of Material Leaving Process

Mounted sections with X-ray flat cut ± 5° to the AT line and sense code serrations at right angles.

5. Yield Expected

100%

PROCESS 14, ETCH MOUNTED SECTIONS

This process is identical to Process 4 and serves the same purpose.

PROCESS 15, INSERT SECTIONS IN TRANSFER JIGS AND PREPOSITION

(See Process 5)

1. Incoming Material

Mounted sections with an etched X-ray flat ±5° to the AT line.

2. Process

Insertion of the mounting plates into transfer jigs is an operation similar to Process 5A. The jigs are different, however, in that they are equipped with a single adjustment; for the AT angle only.

A study of the requirements of the frequency range of AT cut crystal units called for in the Order Board, and of the published information regarding temperature coefficients of crystal versus the ZZ′ angle, has revealed that the entire range can be covered to a satisfactory degree by means of six AT angles, providing these angles are cut to within ± 3 minutes of arc. These optimum angles, and the corresponding frequency ranges, are listed in Table 15-1. (See also Appendix 15-1.)

Table 15-1

OPTIMUM ZZ′ ANGLE VS FREQUENCY FOR AT CUTS

Frequency Range	*ZZ′ Angle (± 3′)*
(First Harmonic)	
4.3—6.0 mc.	35° 15′
6.0—9.0	35° 17.5′
9.0—11.5	35° 20′
11.5—18.0	35° 22.5′
(Third Harmonic)	
17.0—25.0 mc.	35° 25′
25.0—54.0	35° 26.5′

The prepositioning equipment must therefore be capable of adjusting the sections to be cut along any of these six angles.

The target error for the entire wafering process is, as stated, ±3′ arc. The prepositioning equipment must be capable of adjustment of ± 1′ arc in order to allow for the saw error.

The double crystal method outlined in Process 5 is capable of achieving this accuracy when measuring diffraction of the 01.$\bar{1}$ atomic plane through an etched surface. Hence the same apparatus specified in Process 5 will be utilized.

The sections will be slid into the prepositioning jig and the ceramic plates locked in place with a quick-action cam. The plates will be held at an angle with respect to the feet of the jig, one of which is adjustable by means of a fine-pitch screw or other device, which may be located on the X-ray fixture. The jig will be slid into the X-ray fixture, the feet pressing against a reference bar (which represents the line of motion of the wafering saw), and with the X-ray saw cut of the section toward the front of the jig. As in Process 5B, the X-ray flat will be pressed against a hardened pointer which locates the point of impingement of the collimated X-ray beam.

The X-ray table and an indicator will be mounted on a swinging arm which can be adjusted to any of six positions, representing the six desired AT angles. With the indicator in the correct position, the adjustable jig foot is moved until maximum deflection of the detector output meter is obtained. The screw adjustment may be motorized and the detector output used to generate a signal which will cut off the motor drive. The prepositioned jig is then removed.

3. Alternate Methods

(See Process 5)

It has been found that leveling of the X-Y plane is not required, since the accuracy of sectioning using the Hoffman saw is within the requirements (± 15′).

Standard X-ray methods other than the double-crystal system chosen will, on the other hand, not provide sufficient accuracy.

4. Condition of Material Leaving Process

The sections leave the prepositioning fixture with the jig feet parallel to the desired ZZ′ angle to within one minute of arc.

5. Expected Yield

Over 99% of the sections will be aligned according to the above criteria. No rejects will occur at this stage since the total error will be determined by the wafering saw accuracy, and will not be detected until the X-ray sorting process. (No. 26.)

PROCESS 16, SAW WAFERS FROM SECTIONS

1. Incoming Material

The sections will be conveyed to the wafer saws secured in jigs which have been adjusted to establish the correct ZZ′ angle for the frequency order. (See appendix 15-1.)

2. Wafering Process

It is desired to cut the section into wafers parallel to the selected AT line and to the X-axis, so that blanks for the lapping process can be cut from the wafers.

The optimum wafer thickness depends on a number of conflicting factors, among them being the excess of lapping time vs. the capabilities of the saw and wafer fragility. These are discussed in detail in Appendix 16-1. We have chosen three wafer thicknesses as targets, one for all bianks of 0.375″ diameter and two for 0.490″ blanks.

Table 16-1

WAFER THICKNESS

Crystal Type	*Blank Diam.*	*Frequency Range*	*Thickness of Wafer*
CR-18/U	0.490″	4.3-6.0 mc.	0.033″
CR-18/U	0.490″	6.0-9.0 mc.	0.029″
CR-23/U	0.490″	17.0-25.0 mc.	0.029″
CR-18/U	0.375″	9.0-18.0 mc.	0.025″
CR-23/U	0.375″	25.0-54.0 mc.	0.025″

As a result of surveys discussed in System Study No. 1 and mentioned under Process 6, Section Sawing, we have selected a multi-blade saw essentially the same as the P.R. Hoffman Wafering Saw to perform this task. Our tests with this saw indicate that it will produce a good yield of wafers at thicknesses less than 0.025″ with a range (3 sigma) of less than 0.003″ in thickness and 3′ of arc in ZZ′ angle, thus meeting our specifications for the Mechanized Plant.

Certain modifications will be made to the basic Hoffman saw. The arbor is interchangeable on the spindle, so that saw set-ups for different thicknesses can be rapidly switched. The saw table will be equipped with a reference bar aligned with the blades, and with a quick-acting clamp to hold the jig with its alignment feet against the reference bar. Means will be provided so that the jigs can be slid onto the table and removed in the same way when the wafering process is finished.

The blades will be cooled by a flow from the center of the spindle, outward through slots in the spacers.

The entire wafering process will be mechanized after the jig is clamped. The operator will receive pre-aligned jigs and clamp them to the table of the saw having the blade spacing corresponding to the job or order. A push-button operation will actuate the saw and table actuator, so that no operators' attention will be required until the process is completed. At the conclusion of the cut, the saw will automatically stop, so that the jig may be safely removed.

The operation of the saw will be an initial plunge-cut followed by a step cut. This has been found to result in wafers with parallel sides, to a greater degree than other methods.

The cutting time will of course vary with the section, but we estimate that the average time will not exceed 3.5 minutes per section, including insertion and removal of jig.

3. Alternate Methods

These have been discussed under Process 6.

4. Condition of Material Leaving Process

The thickness of wafers will be as specified in Table 16-1. The ZZ′ angle variation will be less than ±3′ from that specified in Table 15-1-1 of Appendix 15-1. The finish and depth of saw marks will be such that not more than .009″ removal from both sides (using 25 and 12 micron abrasive) will be required to remove them in subsequent lapping stages.

5. Expected Yield

Approximately 25 wafering blades will be used. Results of our experience with various shapes of stones indicate that we may expect an average of 20 useful wafers per section or 52 per 250 gram stone. The average wafer weight will be 0.8 grams and the yield, based on weight of section, 27%. Of these wafers, approximately 12% will be unsuitable for dicing, owing to cracks or being undersize. These will be rejected in a subsequent process (No. 20, Inspect and Layout Wafers).

PROCESS 17, REMOVE PLATES AND DEGREASE TRANSFER JIGS

This process will be identical to Process No. 4, following Section Sawing.

PROCESS 18, SEPARATE WAFERS FROM PLATES

This process is the same as Process No. 9, which followed removal of sections from transfer jigs.

The separated wafers will be placed in baskets or trays to be conveyed to the initial etch area.

The ceramic plates will be returned to the section or stone mounting area where they will be re-used.

PROCESS 19, ETCH WAFERS

1. Incoming Material

The wafers which were separated from scrap are approximately 1/2 inch wide and 1-1/2 to 2 inches long, and are between 0.022" and 0.036" thick. They are transported to the initial etching area in baskets.

2. Etching Process

The purpose of etching the wafers is to enable defects such as cracks and twinning to be more easily detected, so that the unsuitable wafers can be rejected prior to entering the blank dicing stage; and to aid in X-ray Sorting (Process No. 26).

The equipment, etching chemical, and processing conditions are identical to those used for sections (see Process 9). The wafers leave the process in similar condition as regards their surface, and with no significant shrinkage.

PROCESS 20, INSPECT AND LAYOUT WAFERS

1. Incoming Material

Etched wafers are received in baskets from the initial etch area. The wafers will be in two widths, 0.430" or 0.542". One edge of the wafer is coded by means of saw-cut score marks.

2. Process

The wafers are inspected to weed out those unsuitable for the dicing process of making blanks. In that process (see Process 22), round blanks with an orientation flat are cut directly from the wafer. The economic balance of the cost of quartz up to this stage and the additional cost of mounting, dicing, inspecting and sorting, is such that it is more favorable to reject a wafer unless at least two good blanks can be cut from it.

The two wafer widths will be used to produce two blank diameters, the larger for 0.490" blanks and the smaller for 0.375" blanks. The blanks will be cut from the wafer by a tool (capable of cutting four blanks in a row), having a fixed position with respect to the unscored edge of the wafer.

The inspection will consist of examining the wafer by means of transmitted or reflected light (or a combination of these) and of marking the defective areas by means of transmitted or reflected light (or a comstand the action of abrasive slurry in the dicing process.

If the wafer is too small to yield two blanks it will be rejected forthwith.

The remaining wafers will be compared in a jig to the position which the dicing tool will occupy. If the unmarked (undefective) portion will not cover the area of two blanks, the wafer will be rejected. Two jigs, one for each wafer width (and blank size), will be provided. The remaining wafers will be sent to the adjacent mounting station. It is estimated that wafers will be inspected at the rate of ten per minute per operator.

3. Alternate Methods

This operation is entirely manual, since it will depend on the judgement of the operator and the correlation of several visual and spatial factors which are impractical to mechanize.

4. Condition of Material Leaving Process

The wafers will contain an undefective area large enough to yield at least two blanks of the size (0.490" or 0.375") corresponding to their width. The defective areas will be marked with a resistant paint or ink so that they may be readily identified after dicing.

5. Yield Expected

About 12% of the wafers entering are expected to be undersized or otherwise rejected.

PROCESS 21, MOUNT WAFERS

1. Incoming Material

Inspected wafers from Process 20, with one edge coded by means of saw-cut scoring marks.

2. Process

The wafers are to be mounted on individual glass plates, so that they can be handled in the blank dicing operation without excessive chipping of the edges.

The plates, approximately 2-1/4" x 5" x 1/8", are preheated and coated with a film of wax. Wafers are located on the plate with the unscored edge close to and roughly parallel to one long edge of the plates. The assembly is then cooled and is ready to be sent to the dicing machines.

Because of the number of wafers to be processed daily, it may be economical to mechanize this operation. Plates and wafers would be loaded into hoppers or fed to the machine by mechanical conveyor, and the remaining operations (heating, waxing, mounting and cooling) would then proceed automatically. One wafer will be processed every five seconds.

3. Alternate Methods

Cementing of the wafers is important in the ultrasonic dicing operation (22) since the edges of the blanks tend to chip unless undercut by the tool through a cemented boundary. Glass is preferable to other materials tested, ceramic, for example, because it does not wear the cutting tool and is also comparatively inexpensive and may be re-used (twice on each side).

The wax used (Courtwright #70C) forms a good bond, lends itself to mechanized application and is readily removed in trichloroethylene.

4. Condition of Material Leaving Process

The wafers are conveyed to the dicing machines, firmly bonded to glass plates. Wafers of the two widths will be kept separate; those of different thicknesses may also be separately scheduled so as to reduce the sorting problem.

5. Expected Yield

In a mechanized process, no loss will be expected.

PROCESS 22, ULTRASONIC DICING

1. Incoming Material

Wafers of widths 0.430" or 0.542" mounted on glass plates. One edge of the wafer is coded to represent the direction and sense of the X-axis.

2. Dicing Process

A shaped tool, round with a flat parallel to the coded edge of the wafer, will cut similar shaped blanks from the wafer by ultrasonic action. 0.375" ±.002 diameter blanks with a flat 0.143" ±.004 will be diced from the narrower wafers, and 0.490" ±.002 diameter blanks with 0.179" ±.004 flats from the wider wafers.

The flat, being perpendicular to the X-axis, and hence in the direction of Z' will key the blanks for automatic sorting by ZZ' angle in a later operation.

The dicing process will be semi-automatic, in that the wafers will be hand-loaded but will otherwise be processed without assistance. A four station turntable mechanism will be used. The mounted wafer will be loaded in the first station by sliding the plate forward until two locating points contact the uncoded edge of the wafer. The operator will adjust the wafer laterally with respect to a template showing the cutting tool position, until the best yield of blanks is indicated. The mounting plate is then clamped. At the next station a multiple tool is lowered against the wafer and agitated ultrasonically as a slurry stream is directed under the cutting edge. At the third station, the diced wafer and plate are ejected, and at the fourth the alignment jig and clamps are washed and scrubbed clean. One operator will be required for each dicing machine.

The multiple tool will be capable of cutting four or five blanks at a time. The target production time will be between 10 and 11 seconds per wafer. Tool life is estimated at 500 wafers per tool.

3. Alternate Methods

The purpose of dicing round blanks is to eliminate the problem of chipping at the corners of square or rectangular blanks which occurs in the lapping stages. Chipping not only leads to poor quality or dead crystals but may also cause "crack-ups".

In the past, it has been necessary to cut square blanks so that they may be properly aligned in X-ray equipment used to check the ZZ' angle. In the automatic X-ray sorting apparatus to be used in the Mechanized Plant (and described further in this report), round blanks with a flat are aligned by means of a system of three rollers and a slide. It has been found by analysis that a 0.375" diameter blank may be aligned if its flat between 0.125" and 0.187" in length, and similarly for a 0.490" blank having a flat between 0.163" and 0.245". This analysis is presented in appendix 22-1.

Hence the blanks may be diced directly in their final state, rather than go through the steps of forming square blanks, cementing, and rounding.

An economic comparison of the traditional and ultrasonic processes is presented in appendix 22-2. It has been found that the direct-dicing method will result in a saving of 4 mills per blank. More important, the degree of operator skill, training time per operator, and number of operators is reduced, the latter, by approximately 3 to 1. Additional advantages are the simplification in material handling and consequent possibility of increased mechanization and an increase in quartz yield of approximately 5%. These advantages will out-weigh the higher capital cost and greater maintenance skill required.

The ultrasonic method is, of course, the most direct and rapid means of cutting a complex shape from the quartz wafers. The various problems involved, such as accuracy of X-axis alignment, have been worked out in experimental models and have resulted in the procedure described. Some data remains to be determined, particularly cutting rate and tool life. The tools will be easily interchanged and made by an inexpensive forming process. It is believed that the target cutting times will be met.

4. Condition of Material Leaving Process

The diced blanks will be automatically ejected and conveyed to a separation station. They will still be cemented to the glass plates along with the scrap, and defective areas previously marked will be visible.

The error in flat orientation with respect to wafer edge will be less than ±15'. The combined orientation error due to dicing and to section prepositioning and sawing will be less than ±30'. For 95% of all blanks it will be less than ±22', since the errors are combined statistically. These accuracies are more than sufficient for the subsequent processes of X-ray sorting and of mounting the crystal unit. The effects of these errors on X-ray sorting are discussed fully in Appendix 26-3.

5. Yield Expected

Of the wafers diced, the average yield will be in the neighborhood of 2.5 blanks per wafer. This figure may be conservative since no wafer will be diced unless it will yield two or more blanks.

PROCESS 23, DEWAX BLANKS

1. Incoming Material

Blanks and scrap, cemented to glass plates with wax.

2. Process

The plates will be subjected to a solvent bath in which the wax cement will be dissolved. Warm trichloroethylene liquid or vapor is probably the most effective commercial agent for this purpose. A conventional type of conveyorized degreaser is presently conceived as the probable mechanism. It should require no attention with the possible exception of loading and unloading.

3. Alternate Methods

The process is standard and should require no investigation.

4. Condition of Material Leaving Process

The glass plates, good and poor blanks, and the quartz scrap will leave the degreaser in a separated state, but mixed together in a basket or on a conveyer.

5. Expected Yield

No loss is contemplated.

PROCESS 24, INSPECT BLANKS

1. Incoming Material

Blanks, scrap and glass plates will be discharged from the degreaser of process 23. The defective portions of the quartz (cracks and twinning) will be marked.

2. Process

The unmarked (good) blanks will be separated and sent for further processing. The glass plates will be removed and the remaining quartz scrapped.

If the glass plates have been used twice on each side, they may be discarded here. If not, they will be returned to the wafer mounting area (Process 21).

Although manual separation and inspection is contemplated, a certain amount of mechanization is probable. For example, if the degreased material is fed to a conveyor belt, the unmarked blanks may be picked out and the remaining material conveyed to a scrap container. The glass plates may be screened automatically owing to their larger size, and examined later for rejection or recirculation.

It is estimated that an operator can detect and remove good blanks at the rate of one per second.

3. Alternate Methods

Further mechanization may be possible but does not seem warranted at this time.

4. Condition of Material Leaving Process

Separated blanks leaving the process will be free of visible flaws.

5. Expected Yield

A yield of better than 80% based on all blanks diced, is anticipated. The yield will depend greatly on the quality of stones initially sent into the plant, as well as the quality of the sawing process.

PROCESS 25, LOAD BLANKS INTO CARTRIDGES

1. Incoming Material

Separated blanks, 0.375" or 0.490" in diameter.

2. Process

The design of the X-ray sorter and subsequent handling throughout the plant, requires that the blanks be pre-loaded into cartridges. These are plastic tubes, equipped with a slot and gate at the bottom. The design of the cartridge has been coordinated with that of the sorting machine.

Blanks may be loaded into the top of the cartridge without attention to their orientation (flat direction).

A vibrating hopper, similar to the Syntron design, has been found capable of forming the blanks in a single file and dropping them into the cartridges. The operator need only fill the bowl and switch on the mechanism. However other types of parts feeders commercially available may prove more suitable from the standpoint of speed.

On the average, a cartridge (2-3/4" useful height) will hold 100 blanks. The feeding rate of the hopper is two blanks per second, hence a cartridge will be filled in about 50 seconds. Cartridges will be changed by the operator when they are full.

At least two machines will be required in order to handle the different diameter blanks.

3. Alternate Methods

Depending on the design of the blank inspection section, which will be immediately adjacent to this process, the bowl may be conveyor fed by a belt carrying the accepted blanks.

It is contemplated that the blank inspector will also supervise the cartridge loader. It may prove a convenience or necessity to provide an automatic shut-off for the loader so that the cartridges need not be changed continually.

4. Condition of Material Leaving Process

The blanks will be loaded in cartridges of two inside diameters, one for each of the two blank diameters. The average filling will be 100 blanks per cartridge.

5. Yield

The yield will be 100%.

PROCESS 26, X-RAY SORTING

1. Incoming Material

The diced blanks from Process 22, having been separated, inspected, and loaded into cartridges, are delivered to the X-ray sorting process, either directly or via intermediate (unsorted) storage. The blanks are circular and possess a flat which is perpendicular to the X-axis and parallel to the Z′ axis within ±30′ (95% are within 22′).

The cartridges are designed to receive only 0.375″ or 0.490″ diameter blanks, so that the blanks have already been segregated according to diameter in Process 25. Within each cartridge type, there may be blanks which have been diced from wafers of the following ZZ′ angles and thicknesses:

Table 26-1

Cartridge Type (Blank Diameter)	*Thickness (in. ± .003″)**	*ZZ′ Angle (±3′)**	*Frequency Range Intended (mc.)*
0.375″	0.025	35°20′	9.0—11.5
	0.025	35°22.5′	11.5—18.0
	0.025	35°26.5′	25.0—54.0**
0.490″	0.029	35°17.5′	6.0—9.0
	0.029	35°25.′	25.0—54.0**
	0.033	35°15′	4.3—6.0

*Tolerance equal to three standard deviations (3σ)
**Third harmonic crystal (CR-23/U)

2. Process

As seen from the above table and as discussed under Processes 15 (Preposition Sections) and 16 (Saw Wafers), the spread of ZZ′ angle within each type of blank is ±3′. On the other hand, it is desired that the blanks used to make crystals of any frequency within the range of our order board should not deviate more than 3′ total from the optimum ZZ′ angle. As discussed in Appendix 15-1, the ZZ′ angle of blanks must be measured individually and they must be sorted into smaller increments ear-marked for the manufacture of crystals falling within their frequency range.

In view of the large production quantities demanded oft his plant, an automatic method of achieving this aim has been developed. Basically, the ZZ′ angle is remeasured by means of X-ray diffraction from the $01.\bar{1}$ atomic plane, using the same two-crystal method which was outlined in Process 5B. However, where Processes 5 and 15 were manual adjustments, this process is automatic and utilizes electronic circuitry for measuring the peak. Where prepositioning may be relatively slow, X-ray sorting must proceed at the highest practical speed because of the much larger quantity of blanks compared to the number of stones or sections.

In prepositioning, the end result was an adjustment of the jig, while in sorting, the objective is to arrange the blanks in an ordered sequence of batches so that they may be allocated to the correct frequency order.

In the automatic sorting machine which will be used, the cartridge containing the blanks will be merely inserted into a slot on the top of the sorter console. The blanks will be removed from the bottom of the cartridge, one by one, by means of vacuum chucks which transfer the blanks to a rotating head.

The blank is rotated between a system of rollers and a slide until the flat portion of the blank is in contact with the slide. (See Appendix 22-1.) The blank is then oriented with respect to its X-axis, and maintaining this orientation it is transferred to the measurement position. Here the blank is oscillated about its X-axis while being exposed to a collimated X-ray beam. The instantaneous angle of the blank meanwhile activates an electronic circuit which generates a series of square pulses, each equivalent in width to an increment of the sweep angle. Each pulse or increment controls a separate gate in a sorting channel. The X-ray beam reflected from the blank is detected and the peak superimposed on the angle increment pulse.

The coincidence between the two pulses serves to open one of the sorting gates. The blank is swept once through the range of angles, and then transferred to the sorting channel and ejected. Sliding down the channel, it falls through the gate opened by its reflected X-ray pulse, which gate corresponds to a certain range of ZZ′ angles, and drops into an output cartridge.

One output cartridge exists for each gate and increment, and as sorting proceeds they are filled with blanks, each of which has a ZZ′ angle within that increment (except for sorting errors; see below).

The equipment developed under this contract will measure and sort blanks at the rate of 43 per minute. The sorting increments are adjustable between one and ten minutes of arc, and there may be a maximum of eleven two-minute increments. The machine will operate continuously with no direction from the operator, aside from the removal of an empty cartridge or insertion of a full, unsorted one. Full, sorted cartridges (output) may be removed by a push-button operation and replaced without interrupting the machine operation.

The precision of the ZZ′ angle measurement is approximately ten seconds of arc (one sigma) but the accuracy of sorting is less easily expressed. Appendix 26-1 defines the meaning of sorter accuracy, and explains how it is related to the input distribution and to other parameters. In the range in which this Plant will operate, it is estimated that the sorter accuracy will be such that substantially all blanks entering any one output cartridge (increment) will have ZZ′ angles falling in a range equal to the nominal increment width plus 0.5 minutes of arc (3 sigma) on either side of the increment.

The development of sorting errors by reason of errors accumulated in the cutting processes is analyzed in Appendix 26-3. This appendix also discusses the effect of cutting errors on resolution (beam width) of the double-crystal goniometer.

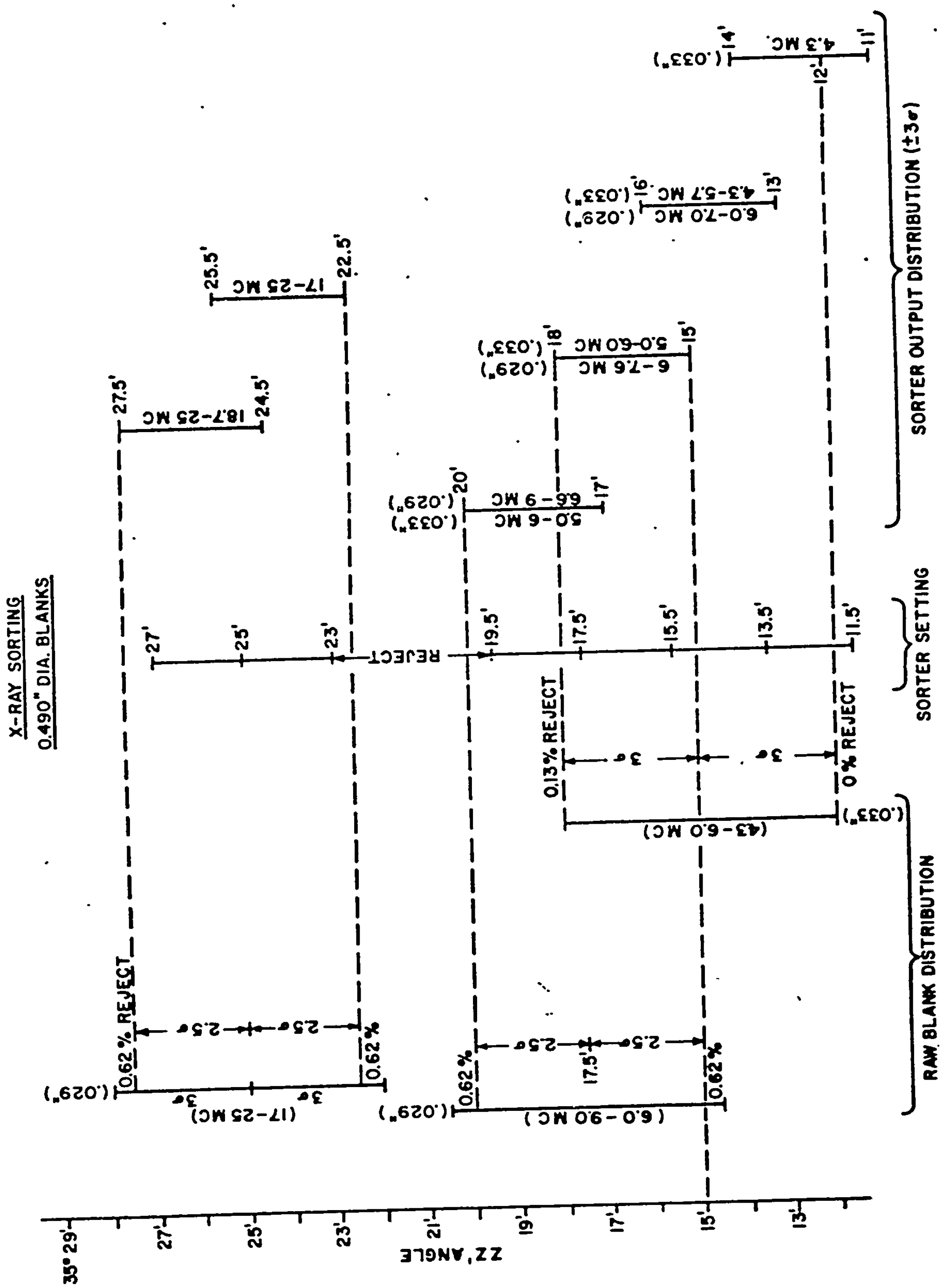

X-RAY SORTING
0.490" DIA. BLANKS
ZZ' ANGLE
35°29'
27'
25'
23'
21'
19'
17'
15'
13'
(17-25 MC)
(.029")
3σ
3σ
0.62% REJECT
2.5σ
2.5σ
0.62%
(6.0-9.0 MC)
(.029")
0.62%
2.5σ
17.5'
2.5σ
0.62%
RAW BLANK DISTRIBUTION
(4.3-6.0 MC)
(.033")
0.13% REJECT
3σ
3σ
0% REJECT
27'
25'
23'
REJECT
19.5'
17.5'
15.5'
13.5'
11.5'
SORTER SETTING
27.5'
18.7-25 MC
24.5'
25.5'
17-25 MC
22.5'
(.033")
(.029")
20'
5.0-6 MC
6.6-9 MC
17'
(.029")
(.033")
18'
6-7.6 MC
5.0-6.0 MC
15'
(.029")
(.033")
16'
6.0-7.0 MC
4.3-5.7 MC
13'
(.033")
14'
4.3 MC.
12'
11'
SORTER OUTPUT DISTRIBUTION (±3σ)

Figure 26-1.

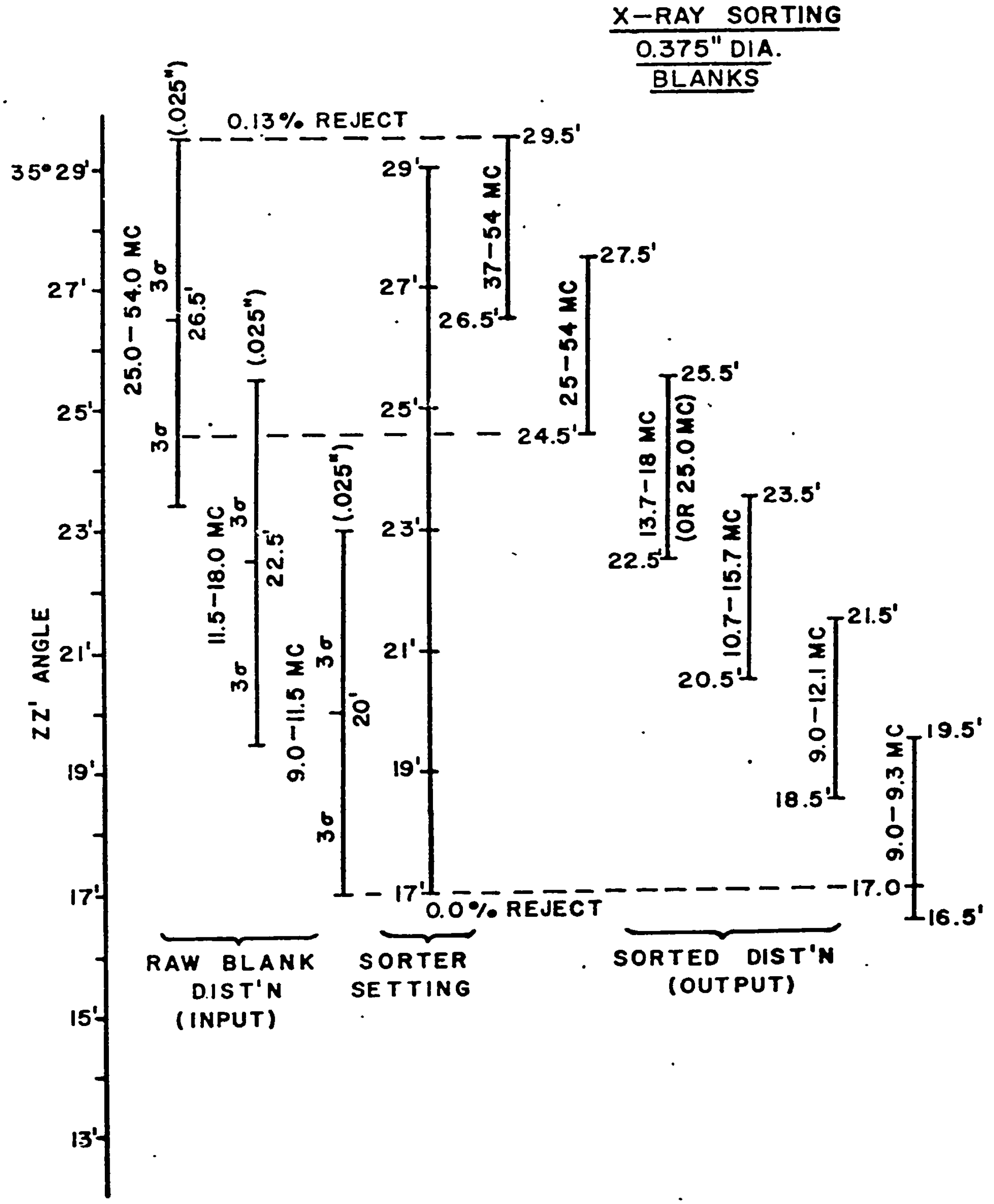

X-RAY SORTING
0.375" DIA.
BLANKS
0.13% REJECT
0.0% REJECT
ZZ' ANGLE
35°29'
27'
25'
23'
21'
19'
17'
15'
13'
(.025")
25.0-54.0 MC
3σ
26.5'
3σ
(.025")
11.5-18.0 MC
3σ
22.5'
3σ
(.025")
9.0-11.5 MC
3σ
20'
3σ
29'
27'
25'
23'
21'
19'
17'
29.5'
37-54 MC
26.5'
27.5'
25-54 MC
24.5'
25.5'
13.7-18 MC
(OR 25.0 MC)
22.5'
23.5'
10.7-15.7 MC
20.5'
21.5'
9.0-12.1 MC
18.5'
19.5'
9.0-9.3 MC
17.0
16.5'
RAW BLANK
DIST'N
(INPUT)
SORTER
SETTING
SORTED DIST'N
(OUTPUT)

Figure 26-2.

The question of how to set the sorter increments has received some study, although the machine is flexible enough so that a final decision may be deferred. The increment settings must not only meet a criterion that no blank shall deviate more than three minutes from the optimum ZZ′ angle but also be placed so as to gain the maximum yield of useful blanks without requiring too many blank types to be stocked. Figures 26-1 and 26-2 show some of the study results, and also represent one possible way of setting up the sorter. The numbers cited are based on an assumption of normal distribution of angular errors around each nominal angle set into the prepositioning equipment. The spread past the nominal increment limits due to sorter errors is taken as 0.5′ on each side. This results in an overlap of 1.0′ between two adjacent increments. Observing Figure 26-1 (settings for 0.490″ blanks), and taking the 35°25′ (nominal) blanks as an example, it is obvious that if the center 3′, e.g., 23.5′ to 26.5′ (equivalent to a sorter setting of 24′ to 26′), were taken as an increment, all the blanks sorted into this increment would be usable over the frequency range 17 to 25 mc. However, the two outer increments must be thrown away (or at best the lower increment could only be used for 17.0 mc., exactly). The two outer increments represent 13.4% of all blanks cut to that angle, because the central portion is equal to ±1.5 sigma of the normally distributed input, or 86.6%. By splitting the blanks into two increments, as is done in Fig. 26-1, only 1.24% need be sacrificed and the remainder will be within the 3′ tolerance for the frequencies noted.

Likewise, the range 35° 12′ to 35° 20.5′ (i.e. the 15′ and 17.5′ nominal cuts) can be separated into four increments with only 1.24% of the 17.5′ blanks and 0.13% of the 15′ blanks sacrificed. An even better yield can be obtained with the 0.375″ diam. blanks. The three nominal angles can be sorted into six increments, all of which are useful, with only 0.13% of the 26.5′ blanks lost. The number of blanks per day to which these percentage figures correspond will depend on the particular order board and total quantity of each type. Also the increment settings may be shifted in order to obtain a larger output of blanks useful for the more popular frequencies. (For example, the lowest increment sorted in Figure 26-1, which is 11′ to 14′, is useful only for 4.3 mc. crystals. But since these constitute 6% of the total production, as estimated by the order board, this is a satisfactory emphasis. If a somewhat higher frequency became more popular, it would be indicated to shift the sorting spectrum upward.)

Finally, the schemes outlined in the two figures show somewhat differing settings for 0.490″ and 0.375″ blanks. In the interests of operating convenience, it may be desirable to compromise yield slightly to keep the increment settings the same for all blanks.

3. Alternate Methods

Initially the question may be raised as to whether X-ray sorting is necessary. Prior to the advent of the Hoffman saw, the angle spread was very great, but the greater accuracy of the Hoffman machine made it conceivable that the sorting step could be omitted. Appendix 26-2 is a summary of an Operations Research Study designed to answer that question. The results of this study are that with X-ray sorting the yield of good crystals may be raised well over 10%, since approximately 78% of the crystals will be within tolerance without sorting but 94% may be expected to be within tolerance if sorting is used.

The question as to whether sorting should be done manually or automatically is simply answered on the basis of economics and skill required. The measurement specified cannot be made manually in less than 15 seconds, thus the machine proposed replaces at least ten operators, all of whom would be required to have more than a moderate amount of skill. If wafers were measured instead of blanks, the amount of work would be cut to perhaps as little as one-half (five operators) but the accuracy would be less owing to the variations along a wafer. Of course, if mechanization is granted desirable, the blank is easier to handle than the wafer because of the irregular size of the latter.

4. Condition of Material Leaving Process

The blanks will leave the sorter arranged in cartridges (an average of 100 blanks per cartridge), which will be divided into 12 active categories, six of these being for 0.490″ blanks and six for 0.375″. If the sorting scheme used in Figures 26-1 and 26-2 are accepted, the categories will be as follows:

Table 26-2

X-RAY SORTER OUTPUT

Blank Diam. (in.)	*Sorter Increment (min. arc)*	*ZZ′ Angle Range (min. arc)*	*Frequency Category (mc.)*
0.490	<11.5	—	Reject
	11.5-13.5	11-14	4.3
	13.5-15.5	13-16	6.0-7.0 (1) or 4.3-5.7 (2)
	15.5-17.5	15-18	6.0-7.6 (1) or 5.0-6.0 (2)
	17.5-19.5	17-20	6.6-9.0 (1) or 5.0-6.0 (2)
	19.5-23.0	—	Rejects
	23.0-25.0	22.5-25.5	17-25 (3)
	25.0-27.0	24.5-27.5	18.7-25 (3)
	>27	—	Reject
0.375	<17	—	Reject
	17-19	16.5-19.5	9.0-9.3
	19-21	18.5-21.5	9.0-12.1
	21-23	20.5-23.5	10.7-15.7
	23-25	22.5-25.5	13.7-18.0 or 25.0 (3)
	25-27	24.5-27.5	25-54 (3)
	27-29	26.5-29.5	37-54 (3)
	>29	—	Reject

(1) Thickness .029″ (nominal)
(2) Thickness .033″ (nominal)
(3) Third harmonic crystal

5. Expected Yield

In addition to the twelve active categories there will be three rejects as shown in the above table, i. e., the extremes (over and under limits) and the 19.5′-23.0′ cut of the .490″ blanks. What these will add up to in terms of numbers of blanks will depend on the relative number of each kind of wafer cut, but it will not exceed 2% and probably be less than 1.5% with the sawing process in good control. The number of twinned blanks, which will also be rejected, should be negligible if the wafer and blank inspection process remains in control.

PROCESS 27, THICKNESS SORTING

1. Incoming Material

Output cartridges from the X-Ray Sorter containing blanks divided into increments of three minutes spread, are delivered to the Thickness Sorter. As stated in Table 26-2, there are twelve of these increments, six each for 0.490″ and 0.375″ blanks. Nine of these contain blanks of only one nominal thickness (.006″ spread) and three of them contain two blank thicknesses with the same ZZ′ angle range, (.010″ spread). Table 27-1 defines the thickness sorter input.

Table 27-1

THICKNESS SORTER INPUT

Diam.	*ZZ′ Increment*	*Range of Thickness*	*Useful Freq. Range (mc.)*
.490	35°11′-35°14′	.030″-.036″	4.3
	13′-16′	.026″-.036″	4.3-5.7
	15′-18′	.026″-.036″	5.0-6.0, 6.0-7.6
	17′-20′	.026″-.036″	6.6-9.0
	22.5′-25.5′	.026″-.032″	17.0-25.0
	24.5′-27.5′	.026″-.032″	18.7-25.0
.375	16.5′-19.5′	.022″-.028″	9.0-9.3
	18.5′-21.5′	.022″-.028″	9.0-12.1
	20.5′-23.5′	.022″-.028″	10.7-15.7
	22.5′-25.5′	.022″-.028″	13.7-18.0, 25.0
	24.5′-27.5′	.022″-.028″	25.0-54.0
	26.5′-29.5′	.022″-.028″	37.0-54.0

2. Process

We find from the results of the study of the lapping process (Process 29) that a limited improvement in the thickness (or frequency) spread is to be expected in the Primary and Secondary stages. This will be discussed under the proper heading, but it suffices here to state that the thickness spread into Primary Lap should not exceed .002″. As can be seen from the Frequency Chart (Appendix IV), this will result in the desired spread into Final Etch if we assume that the improvements in the first and second lapping stages is 2:1 and that the Frequency Sorter (Process 32 to 37) results in a further 5:1 improvement after these stages.

On the other hand, the nature of the wafer sawing process does not permit us to control the raw blank thickness to better than ±.003″ or a spread of .006″. Thus we must resort to thickness sorting before entering Primary Lap.

a. THICKNESS SORTER SPECIFICATIONS: An ideal thickness sorter for this purpose would be one in which the error was zero, the coverage from .022 to .036 (.014″ total range), and the increment width .002″. Such a sorter would divide the inputs of Table 27-1 into a total of 42 separate categories (three increments for each of the inputs with .006″ spread and five for each of those with .010″ spread). Each of these categories would have a thickness spread of .002″ and an angle spread of 3′ or less. Since an ideal sorter is unobtainable, we have investigated the behavior of sorters having a finite error, with respect to number of increments, and to some extent, the loss of blanks by rejection. In general, the more accurate a sorter can be made, the fewer number of increments are required to divide a given input into lots with a maximum specified spread. Hence a compromise must be made between the desire to have a minimum number of increments to store, and the increased cost and complexity of more accurate sorters. In cases which may be in doubt, the decision may be based on the blank loss caused by sorting good blanks into a reject category (because of the finite sorter error). There is no general formula for determining this loss; it must be found by trial, fitting the proposed sorter increments to the actual output in an optimum manner.

It is not necessary to sort the entire range of inputs with one setting of the sorter, provided that the settings can be changed easily. However, the range must be sufficient to handle all blanks in the broadest input category; in the case of Table 27-1 this is 0.010″ (.026″ to .036″).

Let us assume a sorter with N increments (outputs), each of width W inches. S, the actual spread of the N increments, is more than W, because of the sorter error of standard deviation σ. The total range R of the sorter (for any one series of settings) is:

$$R = NW = 0.010 \text{ inches}$$

Because of the error of the sorter measuring device, some blanks lying near the border of two adjacent increments will fall into the wrong increment, however, only 0.3% of the blanks having a thickness as much as 3σ greater or smaller than an increment boundary will fall into the wrong increment. Hence, the actual spread of the sorter outputs is:

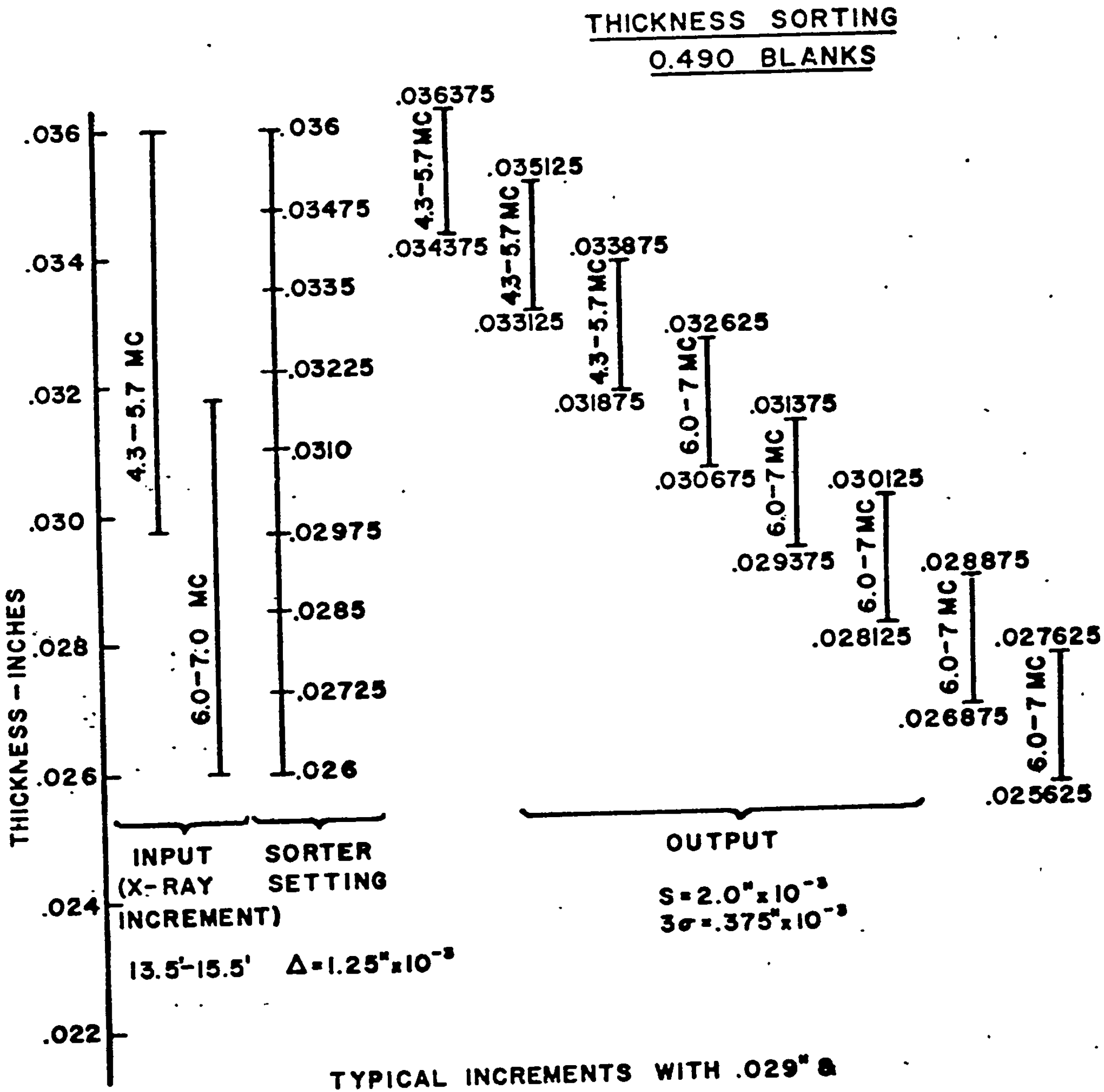
$$S = 3\sigma + W + 3\sigma = W + 6\sigma$$

Combining these two equations and putting S equal to .002″, the desired spread, we obtain

$$\sigma = \frac{S}{6} - \frac{R}{N}$$

$$\sigma = .000333 - \frac{.010}{N}$$

Hence, we obtain the following variation of σ (standard deviation of measurement) with N, the number of increments.



TYPICAL INCREMENTS WITH .029" & .033" NOMINAL INPUT (N=8)

Figure 27-1.

THICKNESS SORTING
0.375 BLANKS
(TYPICAL)

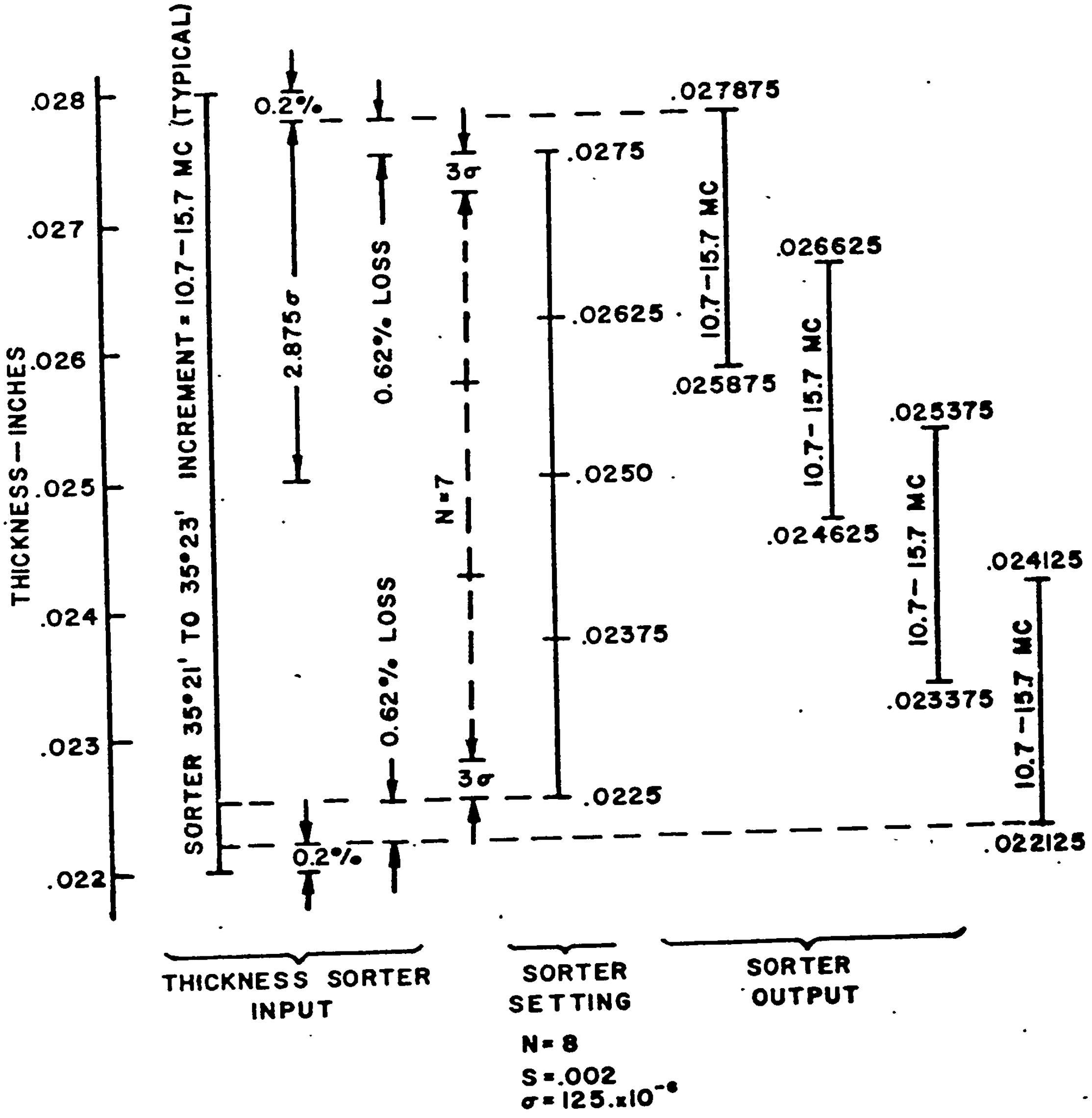


Figure 27-2.

N	σ (micro-inches)
5	0
6	55
7	95
8	125
9	148

A value of σ approximately equal to 0.0001″ should be easy to obtain by a variety of techniques, such as photoelectric gaging, air gaging, and the like A much smaller value may be difficult to instrument, particularly at high sorting speeds. Hence it appears that $N = 8$ or $N = 7$ are near the optimum values.

Figures 27-1 and 27-2 show the effect of sorting one particular 0.490″ diameter input with a 0.010″ spread, and a 0.375″ input with a .006″ spread, using a sorter of $N = 8$. Naturally, the former will divide into 8 outputs of spread .002″. The .006″ spread batch will be sorted into 4 outputs. There will be no loss incurred in sorting good blanks into reject from the 0.490″ batch because the increments overlap the total range of thickness. There will be a small loss. not exceeding 0.2% on either end of the 0.375″ batch.

With $N = 8$, the six angle-sorted input increments are sufficient to sort spreads of .006″ into those of .002″, if we accept a loss of 0.62% at either end, or a total loss of 1.24%. This would result in a total quantity of output increments equal to:

$$9 \times 3 + 3 \times 7 = 27 + 21 = 48 \text{ outputs}$$

We can reduce the number of increments going to storage by 12 but at a cost of 0.8% of blanks sorted and a slight increase (30%) of sorter accuracy. At this time it appears better to store the additional categories of blanks than to "build in" a loss of nearly 1% other than legitimate rejects.

Table 27-2

COMPARISON OF SORTER POSSIBILITIES

N =	*5* (*Perfect*)	*7*	*8*
Sorter Error (1 std. dev.)	0	0.000095″	0.000125″
Total output increments	42	48	60
Sorting loss:			
.010″ spread	0	0	0
.006″ spread	0	1.6%	0.4%

The possibilities $N = 7$ or 8 both appear to be easily instrumented at a sorter speed compatible with the X-Ray Sorter; i. e., 40 blanks per minute. Externally, the sorter could resemble the X-Ray Sorter console and could utilize the same cartridges and sorting mechanism.

3. Alternate Methods

There appears to be no reasonable alternate to thickness sorting of some kind, if we are to maintain our schedule of spreads. Frequency sorting is not considered possible because all the blanks are not "active" in the raw stage. It is possible that the blanks could be lapped unsorted until they were smooth enough to oscillate, then frequency sorted, but this would almost surely result in a great loss of time in lapping and an increase in spread to the point where many more increments would need to be separated when sorting finally occurred. It does not seem economic to defer sorting, therefore.

As far as the method of measurement is concerned, the technique has not yet been frozen, but there are many possibilities (as mentioned above) for which this range of accuracy and speed is reasonable. The most economic means will be chosen from the results of a survey of available methods.

4. Condition of Material Leaving Process

There will be 55 active categories of blanks leaving the thickness sorter, in addition to the over-and-under thickness rejects. These will all be loaded into the plastic cartridges utilized in the X-ray sorting step. A typical division of outputs will appear as follows, assuming that the sorting schemes suggested are used.

Blank Diam.	*Freq. Range*	*No. of Increments*
0.490″	4.3 mc	4
	4.3-5.7	3
	5.0-6.0	6
	6.0-7.6	5
	6.6-9.0	5
	17.0-25.0	4
	18.7-25.0	4
0.375″	9.0-9.3	4
	9.0-12.1	4
	10.7-15.7	4
	13.7-18.0	4
	25.0-54.0	4
	37.0-54.0	4
Total Categories		55

5. Expected Yield

The number of rejected blanks should be less than 1% if the most efficient sorting scheme is chosen. A fair estimate would be 0.2% of the total number of blanks from sorting errors plus 0.5% actually out of control due to sawing defects, or a total of 0.7% loss.

PROCESSES 28, 33, 38, LOAD LAP CARRIERS

1. Incoming Material

Blanks to be prepared for lapping have been previously sorted by ZZ′ angle and by thickness (see Processes 26 and 27), and are divided into a number of increments, each of which is suitable by virtue of angle of cut and spread of thickness to produce crystals of a specified range. These increments of blanks have been stored in the plastic cartridges previously mentioned by the sorting machines. They will be drawn from a central blank storage area when a production order is received. In Processes 33 and 38 the blanks will be obtained from

Frequency Sorting after one or two lapping stages. They will also be stored in these cartridges.

2. Carrier Loading Process

Depending on the process which is chosen for lapping, it is usually necessary to place the blanks in carriers made of metal or plastic, having holes large enough to receive the blanks and to allow them to rotate. In the lapping process which we will use (planetary lapping) this is certainly necessary by reason of the design of the machine. The carriers in this case possess gear teeth around their circumference, which are engaged by the planetary gears of the machine, and in turn, cause the carrier to rotate between stationary upper and lower lapping plates, carrying the blanks with them.

The use of blank carriers is common enough in the quartz crystal industry that it is hardly necessary to justify them here. The primary question has been whether to place the blanks in the carriers after the latter are in the lapping machine or to cement the blanks and carriers together and load them as an assembly.

The advantages of the latter course are obvious with respect to lapping machine loading time, and in the production quantities of this contract, the smaller number of machines required. In addition, it is possible to separate the skill required in loading from the actual operation (or supervision) of the machine.

It has been found quite feasible to pre-load the crystals into the carriers. They may be cemented with a variety of adhesives, nitrocellulose lacquer being one and a proprietary adhesive "Nu-Bond" (Solomons Laboratories, Inc.) being another. The cements dry rapidly and the carriers can be readily handled after this step. However, the cement must be removed from the blanks before the start of actual lapping, since the blanks should be free to revolve in the carriers to promote uniform lapping. Hence, the cement must be highly soluble in commercial solvents. The two adhesives mentioned are soluble in acetone and the latter may also be dissolved by solvents of lower vapor pressure which may prove more convenient in practice. When one of these solvents is introduced into the lapping machine (after the carriers are inserted and the lapping plates in place), the blanks are quickly loosened and lapping is satisfactorily accomplished without danger of crack-ups from this cause.

The actual procedure of carrier loading consists of placing the blanks in an appropriate size carrier, brushing cement over the assembly, drying, and sanding the surface slightly to remove ridges of cement which might prevent the lapping plates from contacting the blank and thus promote crack-ups. The sanded carriers are then stacked and are ready for loading into the lapping machine.

It should be mentioned that two sizes of carriers are necessary in order to hold the 0.375" and 0.490" blanks with a small clearance (a few thousandths). The carriers must be rigid so that they do not bend or warp during lapping (again promoting crack-ups). The carriers material, and hole size is therefore important. We have obtained good results with razor blade steel carriers having either three of four holes for 0.490" or 0.375" blanks, respectively. The thickness of the carriers is important—they must be thinner than the blanks, but not so thin as to cause structural weakness. Carriers used in the plant should therefore be examined periodically for wear and damage.

In practice, the skill and time required in loading the carriers is such as to justify the mechanization of this process. Hence, it is envisioned that a machine will be developed to perform the various operations described. The task of the operator will be limited primarily to feeding the machine with cartridges of blanks and in seeing that the loader carriers are delivered to the proper lapping machine or stage.

3. Alternate Methods

The various alternatives of hand-loading and loading crystals into the lapping machine directly have been discussed above.

4. Condition of Material Leaving Process

Blanks are cemented into carriers of the correct dimensions, sanded, and stacked in order of lapping machine-loads or increments of thickness and frequency.

5. Yield

No loss is assumed in the loading process; any damage to the blanks being lumped in the loss due to lapping.

PROCESSES 29, 34, 39, LAPPING

1. Incoming Material

Metal lap carriers containing three or four holes in which blanks are cemented, are delivered to the various lapping stages. The blanks in any group of carriers which are processed at one time by a machine in the first or primary lapping stage have a thickness spread not exceeding .002 inches (e. g. 99.5% of all blanks in one lot fall within this range of thickness variation.) Those entering the second stage of lapping will have a thickness range of .0002 inches (equivalent to between 33.3 and 257 kc for the nominal frequency range of 4.3 mc. fundamental to 54.0 mc. third harmonic.) Those entering the third and final lapping stage have a range of 0.15 to $0.28f^2$kc, depending on the nominal frequency, as specified in the Frequency Chart (Appendix IV).

The ZZ' angle spread will be not more than three minutes of arc for any incoming machine-load of blanks, and the angle will be not more than three minutes away from the optimum ZZ' angle for zero temperature coefficient, as defined by Appendix 15-1.

2. Lapping Process

The purpose of the lapping process in this system is to bring the blanks down in thickness to 0.55 or $0.50f^2$ above nominal frequency of the order (for CR-18/U and CR-23/U crystals, respectively), and at the same time to remove sufficient material to remove all saw marks and striations that have occured during the preparation of wafers, as well as to obtain a smooth finish appropriate to the subsequent process of etching. The spread of thickness of the blanks must also be reduced to a range of $0.2f^2$ in order that the final frequency can be adjusted easily in the finishing operations.

The lapping process is broken up into several stages, each aided by an intervening sorting process, so that the frequency spread is continually reduced rather than widened.

The theory of lapping processes is largly lacking, although a good deal of empirical data has been gathered in this project and by the crystal industry. In the first place, we find it necessary to choose a lapping process which can be mechanized to an extent where a high degree of skill is not required of the operator. In the second place, the process must be reasonably rapid and economical of machines, owing to the large quantities of crystals which must be produced. Equally important, the processing must be relatively fool-proof so that the yield of good crystals is high, since a low yield necessarily enlarges the entire plant. In particular, we must avoid crack-ups, the progressive destruction of all blanks in a lapping machine. However it is not sufficient to avoid destruction of blanks and chipped blanks of low activity, it is also necessary (in the case of high-frequency crystals) to insure that the blanks are parallel to a high degree, and in all cases to avoid unpredictable angle shift which will nullify the care taken in wafering to insure a low temperature coefficient.

So far as the mechanical aspect of lapping is concerned—production of parallel sides, spread reduction, and avoidance of crack-ups—the narrow-track planetary principle has appeared to offer the greatest advantages. The narrow track machine offers the possibility of the use of one type of machine over the complete frequency range. It can produce extremely flat blanks for high frequency and also can be used to produce medium frequency blanks which seem to require a slight surface contour. The narrow lapping plates are easier to true. The frequency spread obtained is small, possibly due to the better control of the lapping plates. Additionally, the narrow track lapping machine has a reasonable capacity which does not require the plant to have an excessive number of lapping machines. Planetary lapping involves the gear-toothed carriers previously described, which revolve about their own axes and around the axis of the machine in cycloidal fashion, carrying the loose blanks. These also revolve between a lower and upper lapping plate, the latter being loaded by an appropriate weight, the whole being flooded by an abrasive slurry. The results of such machines being attractive, we have added certain features and refinement of design, permitting mechanized raising of the upper lap for loading and unloading, mechanized wiping of blanks into a central basket after conclusion of lapping, radio-frequency monitoring of crystal oscillation and automatic shut-off at a predetermined frequency, all to permit more rapid operation and to reduce the skill needed. The design of the blanks (round) largely eliminates the chipping problem, since this most often occurs at the corners of square blanks.

We have determined by experiment and observation that three lapping stages are sufficient to produce properly finished blanks and to remove saw-marks. The minimum total removal of quartz from the raw blanks has been discussed in Appendix 16. In Figure 16-1-1 of this appendix the amount of removal which must follow lapping with a specific grit size (in order to remove marks of that grit) is specified. The grit size also determines the speed of lapping, other factors such as machine rpm and top plate weight being equal. For a certain minimum removal and a given finish at the end of the last stage, the amount of removal and hence the relative lapping time can be estimated for different numbers of stages assumed, each with a progressively smaller grit size. For example, we have found by experiment that good CR-18/U crystals can be made with a final finish of 8 microns but that CR-23/U crystals require 4 micron grit, otherwise the amount of final etch becomes excessive, causing a greater spread and loss of crystals by reason of etch pits. Also, a larger grit size in final lapping reduces the amount of control in that process. On the other hand, a much larger grit size should be used to remove the saw-marks, since 4 and 8 micron lapping is excessively slow. But again, control of 25 micron lapping, which yields sufficiently rapid results, is poor, so that an intermediate stage is advisable. More than one intermediate stage is undesirable, since it involves additional handling of the material, more machines, and greater loss of blanks. Fortunately we have found that three stages is sufficient for both crystal types; e. g., 25, 12 and 4 micron for third harmonic crystals and 25, 12, 8 micron for fundamental crystals (within the frequency range of this contract).

A tabulation of the minimum removal in each stage is found in Appendix 16-1, Table 16-1-1.

The abrasives we have found to be most satisfactory are those suspended in oil—the "permanently suspended" products of Scientific Abrasives Co. SiC and alumina Al_2O_3 are reliable and of sufficient hardness to lap quartz; diamond dust is too expensive and somewhat too hard for final lapping. The oil suspension results in a lower frequency spread and fewer cracks than water suspension, for example, although oil necessitates washing of blanks between each stage. The synthetic oil-suspended abrasives we used are the following:

SiC	25 micron
SiC	12 micron (Crystolon)
Al_2O_3	8 or 4 micron (So. African Corundum)

The amount of removal in each lapping stage is:

Primary	.0162″	(average)
Secondary	.003″	
Final	.0015″	(CR-18/U)
	.0005″	(CR-23/U)

The rate of removal in each stage is sharply dependent on such factors as top plate weight, machine rpm, and even the condition of the grit. We have not gathered sufficient data on our machine to make any firm statements. However the data on hand indicates that the lapping rate is inversely proportional to the unit area of the quartz load, for a given top plate weight, and to the square of the grit size in microns. It is not known whether or not the rate increases linearly with top plate weight (unit pressure), and it almost certainly increases less rapidly with machine rpm. Based on data for 48 blanks per load, the diameter 0.490″, 25 micron grit, 50 rpm and a weight of 16 pounds, which has averaged about .0011 inches per minute removal on a Dallons narrow-track planetary lapping machine, we have extrapolated the following rates which we expect under our own operating conditions (e. g., 48 blanks of 0.490″ and 64 of 0.375″ diameter, speed 100 rpm, top plate weight variable.)

Table 29-1

		Lapping Rate (inches per min.)	
Lapping Stage	*Grit Size (microns)*	*0.490″D.*	*0.375″D.*
Primary	25	.002	.0026
Secondary	12	.0005	.0006
Final (CR 18/U)	8	.00022	.00026
Final (CR-23/U)	4	.000055	.000067

An important objective of the lapping process is to reduce the spread in thickness (or frequency) from the range of variation to which we are capable of sawing (aided by the practical limits of thickness-sorting) to that range where finishing operations, specifically final plating, can adjust the frequency within the limits required by Military Specifications. We have found definitely that a reduction in spread is possible with narrow-track lapping and well-trued lapping plates, which reduction is most apparent using the coarser abrasives. (This spread reduction is predicted by elementary theory, but has not always been borne out in past practice.)

The spread reduction appears to have a finite limit with a specific abrasive; that is, the improvement is most noticeable when the input has a rather wide spread, (but not excessively wide), while a narrow spread input might not be improved at all, or even worsened. The absolute spread limit apparently becomes less as the grit size is decreased.

It is concluded that it is not possible to reduce the spread indefinitely in any one stage; that is, each stage has an optimum input spread which spread will improve to some extent as lapping proceeds; but after a certain degree of lapping, no further improvement is possible. Lapping in three stages is not sufficient to reduce spread to $0.2f^2$ without aid. This aid is supplied by frequency sorting between each stage; the blanks are removed from the machine, their frequency measured, and the blanks sorted into lots which have a spread optimum for the next finer grit or lapping stage. Frequency sorting can be carried as far as the accuracy of measuring instruments permit, but the complexity of production control increases with the number of sorting increments. Therefore, there is a practical limit to sorting.

We have assumed and amply confirmed by experiment that it is possible to obtain a 2 to 1 improvement in spread in the first stage of lapping (e.g., from .002″ to .001″ (6 sigma), and likewise for the second stage. After the first and second stage, we will sort to a 5 to 1 improvement. Hence, the spread after first lap and frequency sorting will be .0002″, which constitutes the input to the secondary lapping stage, and after the second lap and sorting process the spread will be $0.2f^2$, which corresponds roughly to a 10 to 1 improvement (see Table 29-2). Hence we enter the third lapping stage with the final spread which we wish to achieve, and need not assume any improvement. After the final lap, sorting is not helpful, since those blanks out of limits must be rejected or else improved in final etching or base plating. This step we do not intend to take because of the complexity added to the final etch or base plating apparatus, hence we will frequency sort after third lap only to reject out-of-limit blanks.

Table 29-2

REDUCTION IN SPREAD IN LAPPING AND SORTING

Stage (Process)	*Input Spread* (6σ)	*Output Spread* (6σ)
Thickness Sorting (No. 27)	.006″	.002″
Primary Lap (No. 29)	.002″	.001″
First Frequency Sort (No. 32)	.001″	.0002″
Secondary Lap (No. 34)	.0002″	.0001″ ($1.f^2$)
Second Frequency Sort (No. 37)	$1.f^2$	$0.2f^2$
Final Lap (No. 39)	$0.2f^2$	$0.2f^2$

Frequency sorting is described in more detail under Process 32, and is mentioned here only to show its relationship to lapping. However it is a significant point in another respect. If we did not resort to sorting, there are other means by which the spread can be kept within limits. One of these is transposition of blanks, e.g., removal of some blanks from the machine and re-insertion in a particular pattern, after which lapping is resumed. This is done by some crystal manufacturers and results in good blanks. It is almost impossibly time-consuming for large production lots, requires much skill, and is the sort of operation which this plant must avoid. Fortunately we find sorting is a good substitute. In the same way we have avoided the need for recirculation; e.g., removal of blanks after partial lapping, sorting, and returning to the same stage. This is practiced in some plants, but as can be readily seen, is equivalent in handling time to an additional stage of lapping. The quality of blanks produced by our narrow-track lapping machine has eliminated any need for this step.

Finally, one other procedure should be mentioned. It is possible to run all blanks through the various stages of lapping without sorting except at the end of the process. This is done by some manufacturers, but requires more skill on the part of the operator to maintain a narrow frequency spread. With the use of automatic frequency sorting, we can keep our overall yield at a high level without operator skill.

Two more aspects of the lapping process should be briefly mentioned. Regarding ZZ′ angle-shift, very little is known, or even if it actually occurs in narrow-track lapping. We have insufficient data to predict the amount which will occur. However, industry practice indicates that it is possible to compensate for any shift that does occur, or we could narrow the increments of our X-ray sorting procedure.

Another aspect of blank quality is the degree to which opposite sides are parallel. A certain amount of waviness can be tolerated and not effect activity or response, but non-parallel sides result in poor crystals. We know that our lapping machine is sufficiently accurate that 8 mc. crystals must be contoured slightly to give good activity; this is a strong indication of flatness and also indicates that parallel blanks will result.

To briefly summarize our lapping procedures: preloaded blank carriers will be placed in narrow-track lapping machines, the operation of which is largely automatic and controlled by radio shut-off. Three stages of lapping will be used; for CR-23/U these will utilize 25, 12 and 4 micron abrasive suspended in oil, for CR-18/U the abrasives will be 25, 12 and 8 microns.

Between each stage, blanks will be removed and sorted by frequency to reduce frequency spread. After the last lap, the spread will be $0.2f^2$. Blanks will be flat and parallel and a high yield of undamaged blanks will result. After final lap, low frequency crystals will require edging or contouring to bring up activity (which is discussed under Process 41). Between 7.5 and 10. mc. it may prove possible to produce the slight contour needed by altering the planetary gear ratio of the lap. Hence an additional operation would not be required.

3. Alternate Methods

In Report No. 1 of this System Study, mention was made of various other methods of lapping. These have been studied in sufficient detail to plan a course of action. The methods and our reasons for not choosing them are outlined below in brief.

a. BLANCHARD GRINDER—rapid diamond wheel rough cutting is experienced with this machine. However blanks must be cemented to the holder, degreased, and re-cemented; once for each side, and this is time-consuming if not mechanized. Further, it does not seem possible to hold angle shift to the required orientation. This machine is certainly limited to primary lapping.

b. DRILL-PRESS—suitable for small loads only (up to 18 pieces). Neither faster nor as precise as planetary.

c. PIN-LAP—results in a wide spread of frequency. Requires transposition.

d. WIDE-TRACK PLANETARY LAPPING—narrow-track lapping plates are trued more easily, resulting in better blanks. It is also limited to the lower frequency ranges.

Because the use of one machine type for all lapping stages results in greater efficiency in plant operations and development and also simplifies operator training procedures, this has been established as our design goal.

4. Material Leaving Process

The lapping machine design provides for sweeping the blanks from the lower lapping plate into a basket, which necessarily contains the carriers and abrasive as well. Thus, at each stage a basket containing 16 carriers and 48 or 64 blanks will be the output of the machines.

The quality of the blanks has already been discussed.

5. Yield

The yield of undamaged blanks in any stage is less important than the overall yield. The degree of mechanization incorporated into the lapping machines coupled with the loaded-carrier system leads us to believe that the overall yield will be on the order of 78% for the three stages, or an average of 92% per stage. The damaged blanks will include those broken in crack-ups (relatively few), cracked and chipped blanks, and those with scratches or other defects which prevent oscillation. These rejects will be detected visually and automatically in subsequent processes.

PROCESSES 30, 35, 40, WASH BLANKS

1. Incoming Material

Baskets removed from the lapping machines, holding lapped blanks (from the various stages), abrasive SiC or Al_2O_3 in an oil slurry, and the metal lap carriers.

2. Process

Blanks must be washed to remove abrasive, quartz dust and oil before they can be inspected and frequency-sorted. Particularly oil must be removed in order not to interfere with the frequency measurement. No abrasive grains may be carried on to the next lapping stage or the blanks will be scratched. In summary, the blanks must be washed with a liquid of sufficient density to loosen the abrasive grains, as well as dissolve the oil, such solvent being commercially available and acceptable in industrial usage. A natural choice for this solvent is trichloroethylene which is a standard industrial degreasing solvent.

The blanks and other material from the lapping machines have been purposely swept into special baskets, which can be placed without further manipulation into washers designed to accept them. The washers are envisioned as being similar to domestic dishwashers, in that the liquid will be swirled or agitated in and around the baskets, however, the action shall not be so violent as to cause damage to the blanks. The washing cycle will be automatically timed.

3. Alternate Methods

The saving in operator time achieved by automatic washing is such that manual methods, although possible, should not be considered.

4. Condition of Material Leaving Process

Blanks will be free from oil and abrasive, but will be wet. They must be separated from the baskets and carriers as well as dried.

5. Yield

Shrinkage estimated in this process has been lumped with the loss during lapping.

PROCESSES 31, 36, 42, SEPARATE, DRY AND INSPECT BLANKS, LOAD CARTRIDGES

1. Incoming Material

Blanks will be removed from the washers after each lapping stage, contained in perforated baskets.

2. Process

Several objectives will be achieved in this process. First, the carriers are removed from the baskets and set aside for return to the loading machines. Secondly, the blanks are emptied from the baskets and placed on an inspection belt which carries them past an inspector in single file. These operations can be performed manually with the assistance of some simple jigs.

The blanks, having been separated, will then be passed through a drying section which may consist of infra-red lamps above and below the traveling belt. It may be necessary to perforate the belt to achieve good drying. Finally the dry and separated blanks are passed in front of an inspector.

The blanks are best inspected by transmitted light, hence they may be illuminated from below and the belt made transparent or translucent for this purpose. Optical magnification or projection may ease the inspector's task of determining defects in the blanks. It is necessary to reject blanks that are broken or cracked, else they may jam the sorting machine. Blanks which are badly chipped or scored should also be rejected since it is expensive to process them further. However, they will be eliminated in the sorting process if the defects are serious enough to destroy their activity. Since the blanks are already separated, it is easy to load them into cartridges by letting them slide off the end of the belt. In the event that several different orders are to be processed at once in the lapping stage, different cartridge loading stations should be provided, and the belt divided into sections for the purpose of keeping orders separate.

3. Alternate Methods

There are other possible variations of this scheme, but basically the inspection and separation is a manual process, and it is necessary to provide as many aids as possible to assist the operator in making a decision as to quality of blanks.

4. Condition of Material Leaving Process

Inspected blanks will be free from visual defects and will be packaged in standardized cartridges which fit the sorter mechanism.

5. Yield

Approximately half the blanks which are considered damaged or lost in the lapping process will have visual defects and will be rejected at this point. The remaining blanks will be rejected in the frequency sorter. Since we have assumed 8% loss in the lapping stage, the shrinkage here will be about 4%.

PROCESSES 32, 37, 43, FREQUENCY SORTING

1. Incoming Material

After each of the three lapping stages, inspected blanks which are loaded into cartridges will be picked up and delivered to the Frequency Sorter. The blanks will have different spreads, depending on the lapping stage just completed. (See table below)

Table 32-1

TYPICAL INPUTS TO FREQUENCY SORTER

(SPREAD* FOLLOWING LAPPING STAGES)

		Primary Lap	*Secondary Lap*	*Final Lap*
CR-18/U	4.3 mc.	167 kc.	23 kc.	4.6 kc.
	18.0 mc.	995 kc.	250 kc.	50.0 kc.
CR-23/U	17.0 mc.	283 kc.	45 kc.	8.9 kc.
	54.0 mc.	1290 kc.	383 kc.	76.5 kc.

*Spread equals range of 6σ. All spreads refer to fundamental frequency.

2. Sorting Process

The objective of frequency sorting after each lapping stage is to reduce the spread into the next stage, or in the case of final lap, to reject out-of-limit blanks before final etch. A reduction in spread by a factor of five is necessary after the first and second stages of lapping.

Frequency sorting by hand methods is manifestly impractical for production quantities of the magnitude cited. Hence, this process will be automatic, with one operator required to load cartridges into the machine, unload those cartridges containing the increments sorted, and to change from one nominal frequency to another when input cartridges are changed.

The frequency sorter is a device to measure automatically the frequency of oscillation of the crystal blanks at various stages of lapping.

The frequency measurement and sorting equipment can be divided into three units; oscillator, frequency measurement unit and control unit. In addition various mechanisms will be needed to handle the blanks. The oscillator into which the crystal is inserted must be one that requires no tuning over at least the frequency spread expected from crystals being lapped to the same frequency. One type of oscillator that can be used is the Pierce oscillator which contains no frequency determining elements except for the crystal blank itself.

To obtain reliable results, a means must be provided for inserting the blank so as to insure oscillation at the correct frequency. The holder will consist of a slot into which the crystal blank is inserted horizontally. The blank will lie on one electrode and the other electrode will operate from above through a small air gap.

For measurement of frequency, an electronic frequency counter will be used. This unit is similar to the Berkeley Model #5570 which covers the frequency range of interest. However, this unit will be modified considerably to provide for automatic operation and provide signals which indicate the frequency increment of the crystal oscillation.

Operation of the system is as follows:

The crystal is inserted into the test oscillator. The test oscillator output is applied to the frequency counter. The frequency counter first reduces the input signal to below 2.26 mc. (This frequency is based on the magnitude of the largest frequency increment.) This is accomplished by mixing the input signal with proper harmonics of an accurate crystal-controlled 1 mc. oscillator. The mixer output is applied to the frequency counting circuits and it is counted for an accurately known period of time. The number of counts divided by this time is the frequency of the mixer output. In addition to measuring the frequency, a signal must be produced which allows the counter to be used as a preset counter. This signal is generated when the number of periods of the mixer output equals the lower frequency limit of the test crystal multiplied by the gating interval.

The preset counter operation is such as to generate an output pulse and reset itself after counting a predetermined number of periods of the input signal. The setting of the preset counter will be the frequency increment multiplied by the gating interval of the frequency counter. The number of resetting pulses, therefore, will be measure of the frequency increment in which the test crystal is oscillating. The counter output will actuate the sorting mechanism so as to properly sort the test crystal.

The control unit contains selector switches and relays which permit setting up the preset nominal frequencies and increment intervals. It also controls an automatic test feature by which the entire assembly is checked for accuracy when input cartridges are changed.

The console, or frequency measuring unit, contains the mechanical parts which remove blanks from the input cartridge, feed them through the air gap, and sort them into the correct incremental cartridge.

3. Alternate Methods

Other electronic schemes have been proposed and discussed in System Study Report No. 1 of this contract. These are based on mixing or analog methods. The digital method described was chosen primarily because of the availability of commercial designs which could readily be adapted to our use. However, the method chosen probably has advantages both in accuracy and reliability.

4. Condition of Material Leaving Process

Each of the inputs exemplified in Table 32-1 will be divided into five increments following the first and second lapping stages. These increments will be equal in width. The sorter input following final lap will be maintained as one increment of $0.2f^2$ range. Each output increment will be packaged in the same type of cartridge as it entered.

5. Yield

The sorter will reject high frequency and low frequency (or dead) blanks which are out of the preset limits, and sort them into additional cartridges. These will amount to about 4% of the input for each stage of sorting.

PROCESS 41, CONTOURING

1. Incoming Material

Blanks for CR-18/U crystals between 4.3 and 7.5 mc. will be taken from the Final Lapping Process to be contoured. Some blanks greater than 7.5 but less than 10.0 mc. may also require this processing.

2. Contouring Process

It is well-known that low frequency crystals require contouring or beveling of their edges in order to have sufficient activity and also to prevent unwanted oscillation modes in other than the desired frequency. For example, 8 mc. crystals lapped flat and parallel on our narrow-track machines require a slight surface contour in order to have high activity. Likewise, groups of blanks we have prepared between 4.3 and 5.2 mc., baseplated with aluminum and sealed in helium have occasionally shown frequency and activity dips if insufficiently contoured.

The exact degree to which we must contour to prevent these effects must be determined in later experiments. In order to fix the present state of the art, we have surveyed a number of companies producing low-frequency AT blanks and investigated their practices. This survey is summarized in Appendix 41-1.

It appears definite that we must contour to a significant depth for frequencies below 7.5 mc. and that some contouring may be required below 8 or 9 mc. A slight contour may be obtained by adjusting the gear ratio of the planetary lap, and it is suggested that this method will be adequate for blanks above 7.5 mc. Special methods will be needed below this frequency, one of which is the diopter or optical cup commonly used for this purpose.

In our range of frequencies (down to 4.3 mc.) it is not required to have a full contour. Hence the time of contouring will be small. Furthermore, coarser grits can be used in the last lapping stage since the area occupied by the plated electrode may be left untouched. Contouring may be controlled by time or by frequency monitoring. If both are equally satisfactory, the former will probably be used. Contouring times may be as low as 15 seconds per side, although the average will probably be higher.

As of our present knowledge the following contouring procedures are suitable to produce crystals according to Mil-C-3098B.

Frequency	*Abrasive*	*Procedure*
4.3-6.0 mc.	25 micron Nat. Alumin. Oxide (Scientific Abrasives)	each side of blank one minute on optical cup #2.37
6.0-7.5 mc.	25 micron Nat. Alumin. Oxide (Scientific Abrasives)	each side of blank ½ minute on optical cup #3.37
7.5-10 mc.	8 micron Nat. Alumin. Oxide (Scientific Abrasives)	achieve very slight contour by means similar to pin-lap (approx. 15 seconds) or change of gear ratio on lapping machine.

NOTE: The expression "optical cup" does not necessarily exclude other machine constructions. Actually a multiple head machine may be used, which uses a flat grinding disc (and suspended abrasive), and on which the blanks are bevelled on the tips of vacuum-chuck equipped axes.

3. Alternate Methods

The method to be used has not been firmly established, but it will not be equipment radically different from that in present use. One alternative may be a bowl-polisher holding three blanks—these may be held in place by means of vacuum chucks or suction cups. Another alternative is a flat plate against which the crystal is edged by being fixed to a rotating shaft held at an angle to the plate (see Note, above). Any method used must be capable of rapid loading of crystals.

A very attractive contouring method from the standpoint of mechanization is tumbling. Union Thermoelectric Corp. is experimenting with tumbling of blanks in jars and drums, and obtaining promising control of frequency and spread. However, at this writing, not enough is known of production methods to utilize this process, and the contouring rates at present are extremely slow.

4. Condition of Material Leaving Process

Crystals above 4.3 mc. and below 7.5 or 9.0 mc. will leave this process with a bevel or contour so as to produce high activity without dips.

5. Yields

Any loss which may occur in this process has been lumped with the lapping shrinkage.

PROCESS 44, ETCH HOLDER LOADING

1. Incoming Material

Blanks emerging from the Frequency Sorting process following Final Lap are loaded in cartridges. They will be stored until needed for final etching.

2. Process

To prepare for the Final Etching process the blanks must be loaded into holders so that the hydrofluoric acid can attack them evenly. The blanks should be arranged vertically in slots, each blank well separated from the other, for best results in the etching bath. The holder is made of Teflon and should contain about 100 slots for blanks.

Owing to the number of blanks to be handled, and to the fact that they may be as thin as .003" after Final Lap, the task of manually loading them is difficult, as is their removal from the cartridge. Hence, a mechanized method will be used which will require no skill on the part of the operator. The machine will extract blanks from the cartridges by some mechanism similar to that used in the Frequency Sorter, and place them in the etch holder slots.

3. Alternate Methods

No firm design has been specified for the loading machine. It is obvious that this task should not be performed manually, from the standpoint of time and blank loss.

4. Condition of Material Leaving Process

Blanks will be loaded in etch holders.

5. Yield Expected

Although breakage will be far less than would occur using tweezer methods, some loss (less than 1%) will be allowed.

PROCESS 45A, DEGREASE ETCH HOLDERS

1. Incoming Material

Final etch holders loaded with blanks.

2. Process

After loading, the blanks should be degreased to insure that all traces of oily material that may interfere with the action of the HF acid are removed from the surface.

A standard trichloroethylene degreasing process has proven adequate for this step.

3. Alternate Methods

None applicable.

4. Condition of Material Leaving Process

Etch holder and blanks will be free from oil or greasy material.

5. Yield Expected

No loss will be experienced.

PROCESSES 45B, C, FINAL ETCHING AND BLANK DRYING

1. Incoming Material

The lapped quartz blanks are taken from the degreaser 45A, still loaded in their Teflon holders, and brought to the loading station of the Final Etching Machine. The Teflon holders each contain 100 slots to hold an individual blank edgewise. The blanks are lapped to $0.55f^2$ or $0.50f^2$ ($\pm 0.1f^2$) greater than their final frequency for CR-23/U and CR-18/U blanks, respectively; finished with 8 micron abrasive for CR-18/U or 4 micron for CR-23/U blanks; and are thoroughly degreased from process 45A.

2. Final Etching Process

The purpose of the final etching process is to remove the rough surface of the quartz (the "disturbed layer") resulting from the finite grain size of the abrasive used in the final lapping process. Removal of the disturbed layer is necessary to obtain satisfactory aging characteristics of the final plated crystal.

A series of tests made in conjunction with this System Study have shown that the optimum amount of etching to achieve good activity is a function of the grain size in the last lapping process. The results of these tests are shown in the "Special Report, Final Etching and Cleaning of Quartz Blanks", issued by the Bulova R & D laboratories on 11 September 1956.

In the case of the plant, final lapping is performed with 8 and 4 micron grains, hence the amount of etching is $0.38f^2 \pm 0.06$ and $0.21f^2 \pm .05$, equivalent to 4.5 and 1.6 minutes, respectively, using 16% hydrofloric acid at 25°C. In the process of etching, the resonant frequency is raised by these amounts owing to the reduction in thickness of the blank.

In order to achieve uniform etching and maximum smoothness, the surface of the blank must be absolutely clean. Hence, after degreasing, the blanks are subject to a further cleaning process with a 5% solution of trisodium phosphate ($Na_3PO_4 \cdot 12H_2O$) at 85°C for 2 minutes. This is followed by a treatment with 3% ammonia at 25°C, in order to disintegrate the last traces of fluosilic acid, H_2SiF_6 which may occur on the surface of the blanks.

The crystal blanks are agitated during these treatments by oscillating their holders at the rate of 40 cycles per minute.

Two rinses in continuously flowing demineralized water at 25°C precede the etching bath, in order to remove the last traces of ammonia. Demineralized water is used because the impurities of ordinary tap-water as salts and organic components would negate the previous cleaning procedure. The actual etching occurs in a triple tank of 16% HF, at an accurately (0.5°) controlled temperature of 25°C.

The total time in the etching tank is adjustable between 0 and 6 minutes. Agitation is continued at 40 oscillations/minute.

All traces of the etching bath must be removed, in order that the chemical reaction cease and no foreign material remains to react with the plating material in the next process. Hence, etching is followed by a second treatment with trisodium phosphate (2 minutes at 85°C), 2 minutes in 3% ammonia solution, and three demineralized water rinses at 25°, 85° and 85°C.

Water is removed from the surface of the crystal blanks by means of a superheated steam blast for 4 minutes. This treatment is followed by radiant heating in a separate machine for 30 minutes.

The process described above is summarized in Table 45-1.

3. Alternate Methods

Consideration has been given to cleaning the blanks with chromic acid prior to etching. It has been shown as a result of our study that chromic acid has a detrimental effect on the activity of the blank and increases the effective series resistance. These results have been confirmed by the experience of Phillips Eindthoven of Holland as described by Mr. Missel of that Company. Hence, we eliminated the chromic acid treatment.

Many methods of etching crystal blanks have been used in past and current practice, among them being

Table 45-1

PROCESS 45B—FINAL ETCH

Station	*Treatment*	*Temp.* C.	*Time* *Min.*
1, 2	Loading		4
3	5% Trisodium Phosphate	85°±2	2
4	3% Ammonia	25°±2	2
5	Demineralized water	25°±2	2
6	Demineralized water	25°±2	2
7-9	16±½% HF (3 station tank)	25°±½	6
	(For 8 micron finish, 0.32 to $0.44f^2$, time immersed = 4.5 min.)		
	(For 4 micron finish, 0.16 to $0.26f^2$, time immersed = 1.6 min.)		
10	5% Trisodium phosphate	85°±2	2
11	3% Ammonia	25°±2	2
12	Demineralized Water	25°±2	2
13	Demineralized Water	85°±2	2
14	Demineralized Water	85°±2	2
15, 16	Superheated steam	115°(Approx.)	4
	(Steps 3-16 carried out in Teflon holders, containing blanks in individual slots, oscillated at 40 cycles/minute)		
17, 18	Unloading	—	4
—	Drying	—	30

Dallons Etch, ammonium biflouride and various modifications of these. The superiority of hydrofluoric acid as an etchant has been demonstrated by the excellent control of frequency-change spread we have observed with manual control of the process variables, compared with plant results using other materials mentioned. In addition, the cost of HF will be considerably less than 1/5 that of competing etchants.

Lower concentrations of HF are to be preferred, since better surface quality is achieved and longer etching times permits better control. Figure 45B-1-1 (Appendix 45B-1) indicates the etching time required to obtain various amounts of frequency change, with HF concentration as a parameter. A constant concentration of acid in the etching tank is desired, otherwise control or machine design problems become difficult. A choice of 16% HF at 25°C permits us to achieve $0.44f^2$ in 6 minutes, the maximum etch required on 8 micron finished blanks, and also allows us at least one minute for blanks finished to 4 microns, hence, the specifications on timer precision and transfer time variations are less stringent.

ULTRASONIC AGITATION—Preliminary experiments performed under this System Study showed that benefits were to be obtained by the use of ultrasonic agitation during etching. As shown in Figure 45B-1-1, quoted above, the effect of ultrasonic agitation is to increase the etching rate a small amount. However, no improvement in frequency spread was noted. Increase of the etch rate alone was insufficient to justify use of ultrasonics, since the total time required for etching is not a critical factor in plant operation.

DRYING—Other methods of drying the etched blanks have been considered. Initially a spin-dry at 250 rpm was considered. However, it was found experimentally that superheated steam was as efficient, and reduces the complexity of the etching machine.

Infrared is not the most efficient means of final drying because of the shielding effect of the etch holders and the comparative transparency of quartz to I. R. Dry air would be more efficient, as would vacuum drying. The former cannot be considered because of the danger of blowing dust on the crystals and the consequent need for filters and frequent changes of filters. On the other hand, vacuum drying, although it would undoubtedly be faster, is expensive and complex from the equipment standpoint. Hence, we have chosen radiant heating as the optimum technique for the present time and the results have proven very satisfactory.

4. Condition of Material Leaving Process

The blanks leave the final etching machine and drier thoroughly cleaned and dry, prepared for the base plating process and still in their Teflon holders. Indications both of our experience and that of the Bulova Watch Company's Crystal Division are that blanks etched and cleaned by the process outlined have satisfactory aging properties. The blanks will be etched to a nominal increase in frequency of 0.38 $\pm 0.06f^2$ for 8 micron finish and 0.21 $\pm .05f^2$ for 4 micron finished (17.0 to 54.0 mc CR-23/U) blanks. Since the lapping spread on (sorted) incoming blanks was $\pm 0.1f^2$ for both types, the statistically combined spread is $\pm 0.12f^2$ ($0.115f^2$ for 4 micron blanks). Summarizing, the frequency and spread of the blanks are as follows:

	CR-23/U	*CR-18/U*
Frequency range	17.0-54.0 mc.	4.3-18.0 mc.
Finish lap	4 micron	8 micron
Nom. frequency increase, lapping	$0.50f^2$	$0.55f^2$
Nom. frequency increase, etching	$0.21f^2$	$0.38f^2$
f^2, above nominal	$0.71f^2$	$0.93f^2$
Spread (lapping) (3σ)	$\pm 0.10f^2$	$\pm 0.10f^2$
Spread (etching*) (3σ)	$\pm 0.05f^2$	$\pm 0.06f^2$
Total Spread (3σ)	$\pm 0.115f^2$	$\pm 0.12f^2$

*See Section 5

5. Yields

Since there will be no complete quality inspection of blanks leaving the etching process, there will be no shrinkage except for actual breakage, which, due to the design of the Teflon holders, should be nominal. However, considerable accuracy is claimed for control of the etching process (see above), with respect to results obtained in conventional practice. Since blanks over- or under-etched with respect to the established limits may not be corrected in the adjustment plating process, it is of interest to consider whether the degree of control claimed is justified.

Actually, a statistically valid answer cannot be given until experience has been obtained with the prototype etching machine. A theoretical analysis (see Appendix 45B) indicates that a reasonably high degree of confidence can be held in the etching spreads claimed. With the machine controlled within the design tolerances, the following deviations can be expected from nominal total etch.

Type	*Deviation* (3σ)
CR-23/U blanks	$\pm 0.050f^2$
CR-18/U blanks	$\pm 0.055f^2$

Hence, better than 99.7% of all blanks should be etched within the required spread.

PROCESS 46, LOAD BASE PLATE MASKS

1. Incoming Material

Etched blanks are delivered to this process after being dried.

2. Process

The blanks must be removed from the Teflon etch holders and loaded into masks in preparation for the process of base plating by evaporation of metal in vacuum. The base plating forms the electrodes for the finished crystal and also lowers the crystal resonant frequency by mass loading. The evaporated metal is blocked off everywhere on the blank except for holes in the mask, which define the spot size and placement. The spot must be placed nearly exactly in the center of the blank, otherwise the finished crystal unit will show poor activity. The masks can be designed so that the blanks will fit only in one position relative to the hole, taking advantage of the orientation flat.

The spot (or hole) size must also be defined precisely, since the plated areas, one on each side of the crystal, form a capacitor in parallel with the holder and pins. Military Specification MIL-C-3098B states that the pin to pin capacitance of the finished unit shall not exceed 7 micro-micro farads. The capacity of an HC-6/U wire spring holder, similar to the type we will use, is 1.5 mmf. Allowing 0.5 mmf. factor of safety, the capacity of the plated spots must not exceed 5.0 mmf. On the other hand, it has been established as a matter of experience that the larger spot sizes result in lower effective resistance of the crystal, so that the capacity should not be less than 4.5 mmf. for the best results.

The capacity formed by the two plated electrodes and the quartz dielectric is expressed by the formula:

$$C = \varepsilon \frac{A}{4\pi d} \qquad (1)$$

where C is the capacitance

A is the area of the plated electrode

d is the thickness of quartz dielectric

ε is the dielectric constant of quartz in the direction of the applied voltage.

The value of ε depends on the direction relative to the optic axis and as given in the literature, varies somewhat with the source, but 5.06 has been found to produce satisfactory results with AT cut crystals. This yields the standard formula

$$C = 0.402 \frac{A}{d} \text{ mmf.} \qquad (2)$$

where d and A are in cm. and $(\text{cm})^2$.

The thickness of the crystals varies according to the form-

$$d = \frac{66.6}{f} \qquad (3)$$

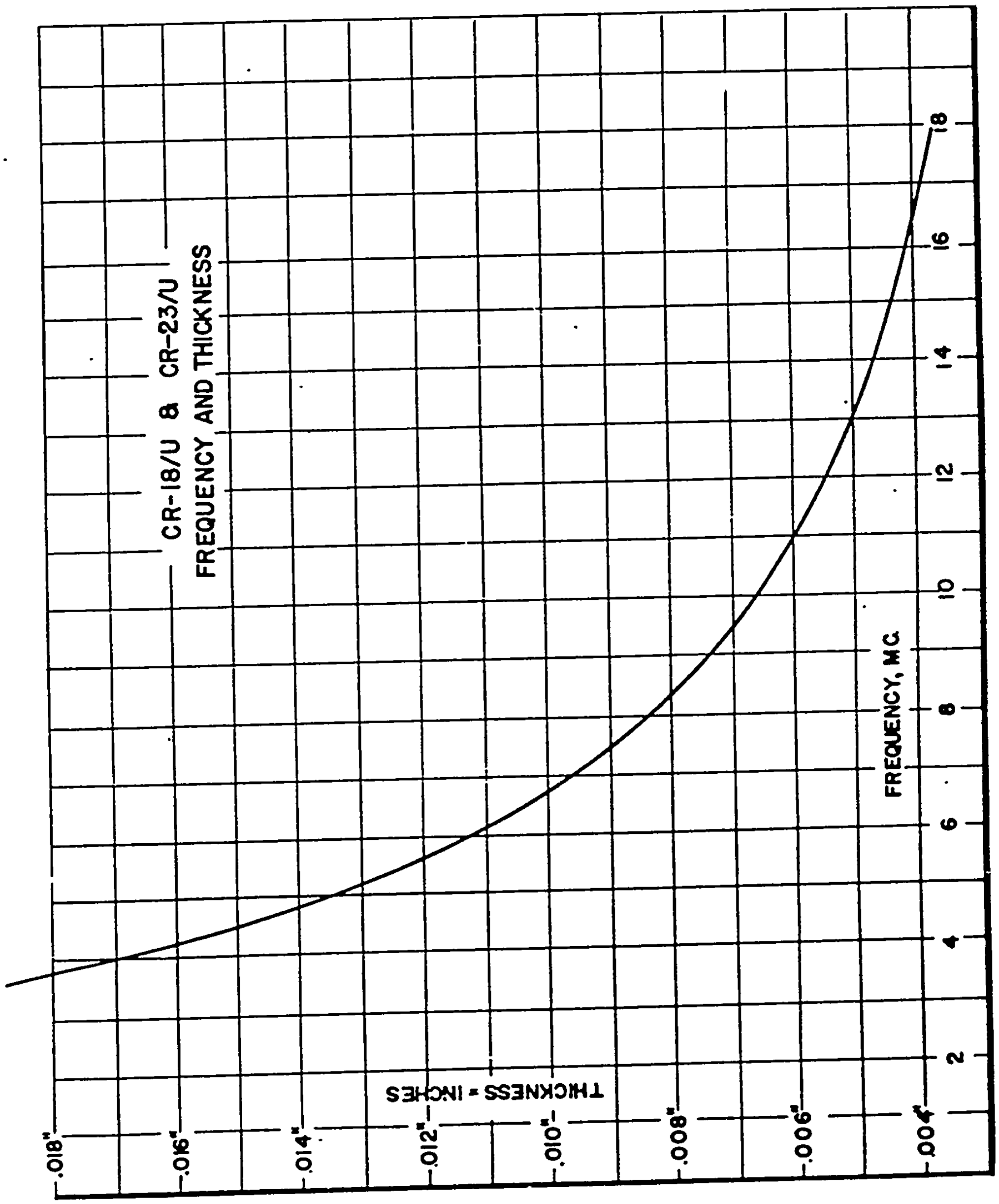

CR-18/U & CR-23/U
FREQUENCY AND THICKNESS
FREQUENCY, M.C.
2
4
6
8
10
12
14
16
18
THICKNESS - INCHES
.018"
.016"
.014"
.012"
.010"
.008"
.006"
.004"

Figure 46-1.

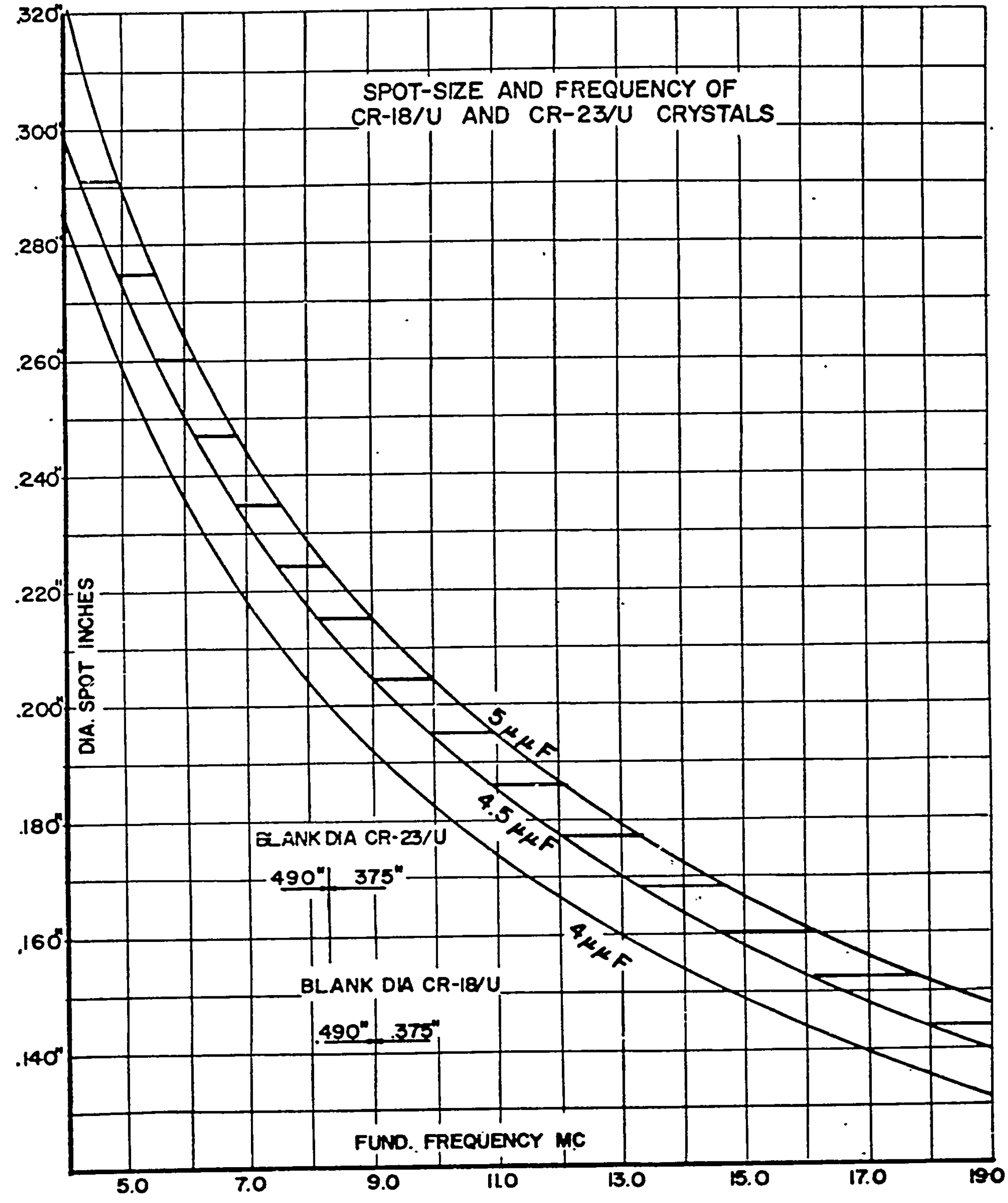

SPOT-SIZE AND FREQUENCY OF
CR-18/U AND CR-23/U CRYSTALS
.320"
.300"
.280"
.260"
.240"
.220"
.200"
.180"
.160"
.140"
DIA. SPOT INCHES
5 μμF
4.5 μμF
4 μμF
BLANK DIA CR-23/U
.490" .375"
BLANK DIA CR-18/U
.490" .375"
FUND. FREQUENCY MC
5.0
7.0
9.0
11.0
13.0
15.0
17.0
19.0

Figure 46-2.

ula where f is the fundamental frequency in kilocycles and d is in inches. This relationship is plotted in Figure 46-1 for the range of interest (4.3 to 18 mc.). For the same range, the electrode (spot) size is plotted with C as a parameter, using formula (2) above and converting to inches diameter. These results are shown in Figure 46-2. The spot sizes of interest are those diameters which cover the range of fundamental frequencies between 4.3 and 18.0 mc. and do not fall outside the values C = 4.5 to C = 5.0 mmf. It can be seen that this range is covered by 14 spot diameters, varying from .144″ to .291″ approximately.

Thus the entire range of crystal frequencies between 4.3 fundamental and 54.0 third harmonic can be covered by 14 spot diameters without exceeding the capacity limits. However the masks must be made also in two sizes, to fit 0.375″ or 0.490″ diameter blanks. All fundamental frequencies less than 8.33 mc. are to be made from 0.490″ blanks, and all above 9.0 mc. will utilize the 0.375″ size. Between 8.33 and 9.0 mc. there may be provided one mask for 0.375″ blanks (CR-23/U) and one for 0.490″ blanks, each, however having the same spot size (approximately 0.215″). It is possible, therefore to meet the requirements of the Plant with fifteen mask types, and it may be possible to produce good crystals with fewer types.

The masks, once loaded with blanks, are fitted into holders which can be inserted into the base plating machine, and which hold the masks at a precomputed distance from the source of metal vapor. The distance determines the amount of plating since the thickness of the evaporated film varies inversely with the square of the distance from the source. CR-23/U and CR-18/U units will require different amounts of plating, equal to $0.55f^2$ in the first case and $0.7f^2$ in the second. Thus, the masks must be placed in holders appropriate to the crystal type being manufactured. (The holders, it will be noted, are mechanically designed to permit mask rotation in the vacuum chamber.) The fact that it is necessary to orient the blanks in the masks makes it difficult to perform the mask loading rapidly without some mechanized aid. The exact degree of mechanization which will be optimum has not been completely determined. For example, the operator may transfer the blanks from the etch holders to the masks and have the blanks oriented mechanically before the masks are completely assembled. Or, it may prove feasible to have the entire operation performed mechanically. The mask loading aids or machine must be coordinated with the design of the mask proper, and this in turn is determined by the utilization of the mask in subsequent processes. It is desirable, for example, to have the blanks remain in the mask through base plating, pre-aging, and into mechanized unloading in the mounting and cementing machine (Station P). The high temperature of pre-aging (425°C) and the requirement of mechanized unloading will cause some restriction in design, but it appears now that at least some mechanical aid in loading will be possible.

The requirements of the overall production goal require that the blanks be loaded into masks at the rate of 30 per minute (approximately) and it appears feasible that this can be done by one operator with proper mechanization.

In any method of loading, the mask type must be coordinated with the crystal frequency as specified by the order. If completely mechanized loading is used, the operator must still select the type of mask, perhaps by stacking the type called for by the job ticket in a magazine, or by selecting the proper chute of a multiple magazine to feed into the machine.

The masks, when loaded, must be inserted in the proper holder as called for by the crystal type. This would be a manual operation. Either 40 or 50 blanks will be mounted in one holder, depending on the blank diameter.

3. Alternate Methods

Manual loading of blanks into masks would be so slow as to require several operators, since there is not only the problem of orientation but also the fragility of the blanks, and the need to keep them clean.

4. Condition of Material Leaving Process

The blanks are transferred to a preheating stage assembled in masks, which in turn are assembled to holders. Each holder totals 40 or 50 blanks.

5. Yield Expected

A small loss of the higher frequency blanks (.003″ thick) may be expected due to handling. This will amount to less than 1%.

PROCESS 47, PREHEATING AND BASE PLATING

1. Incoming Material

The crystal blanks are delivered to this process after being loaded into the base plating masks and mask holders Prior to plate-back in the base plater the blanks have the following characteristics (from Final Etch):

CR-18/U: Frequency=Nominal $+0.93f^2 \pm 0.12f^2$

CR-23/U: Frequency=Nominal $+0.71f^2 \pm 0.115f^2$

2. Base Plating Process

There are several reasons for base plating, among them being the need to provide metal electrodes on either side of the crystal so that it can be electrically excited. Base plating also serves in part to bring down the resonant frequency of the crystal so that it can be exactly adjusted to the desired nominal by means of the final or frequency adjustment plating. Finally, the base plating material forms a film which adheres strongly to the smooth quartz surface and serves as

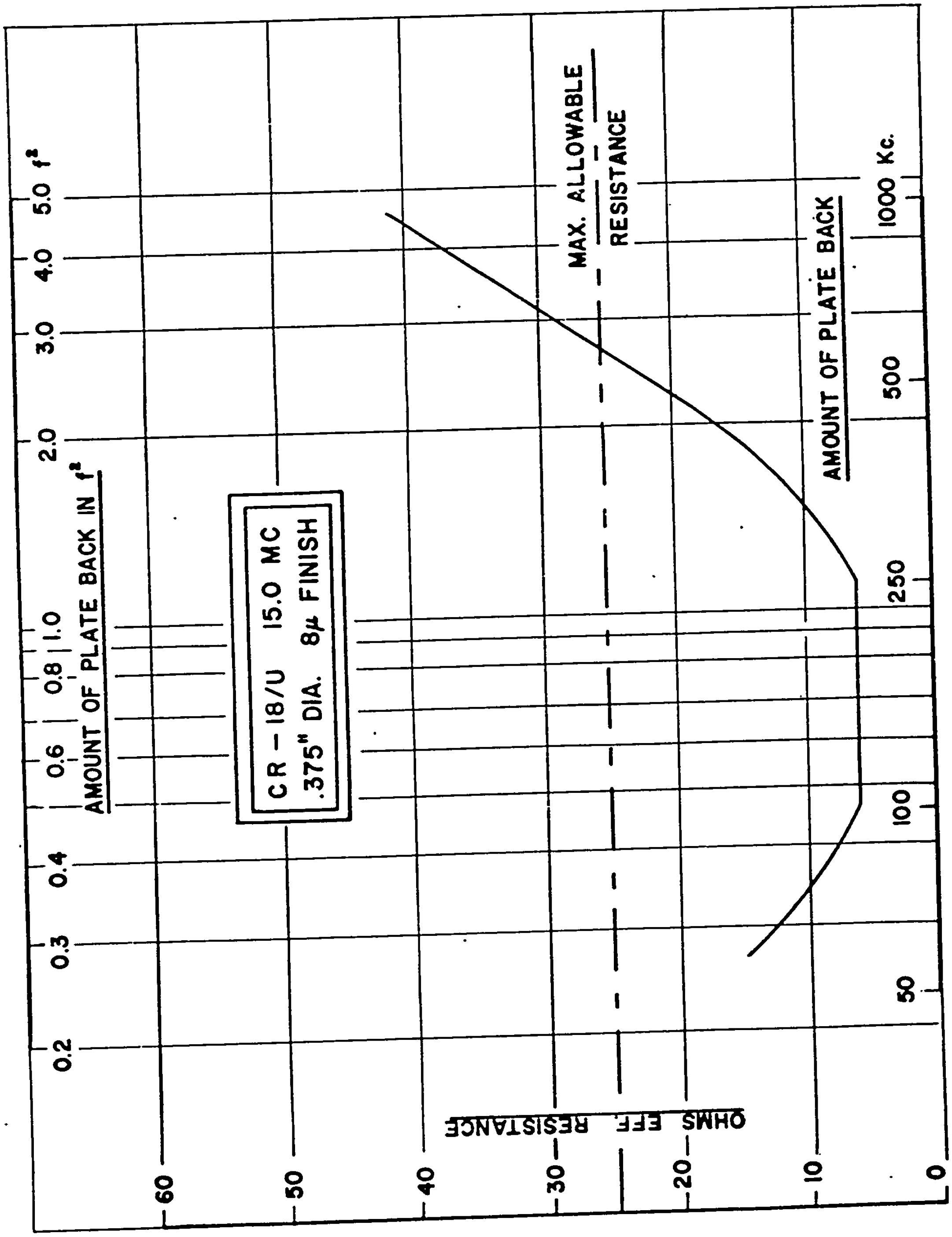

CR – 18/U 15.0 MC
.375" DIA. 8μ FINISH
AMOUNT OF PLATE BACK IN f²
0.2
0.3
0.4
0.6
0.8
1.0
2.0
3.0
4.0
5.0 f²
MAX. ALLOWABLE RESISTANCE
AMOUNT OF PLATE BACK
50
100
250
500
1000 Kc.
OHMS EFF RESISTANCE
60
50
40
30
20
10
0

Figure 47-1.

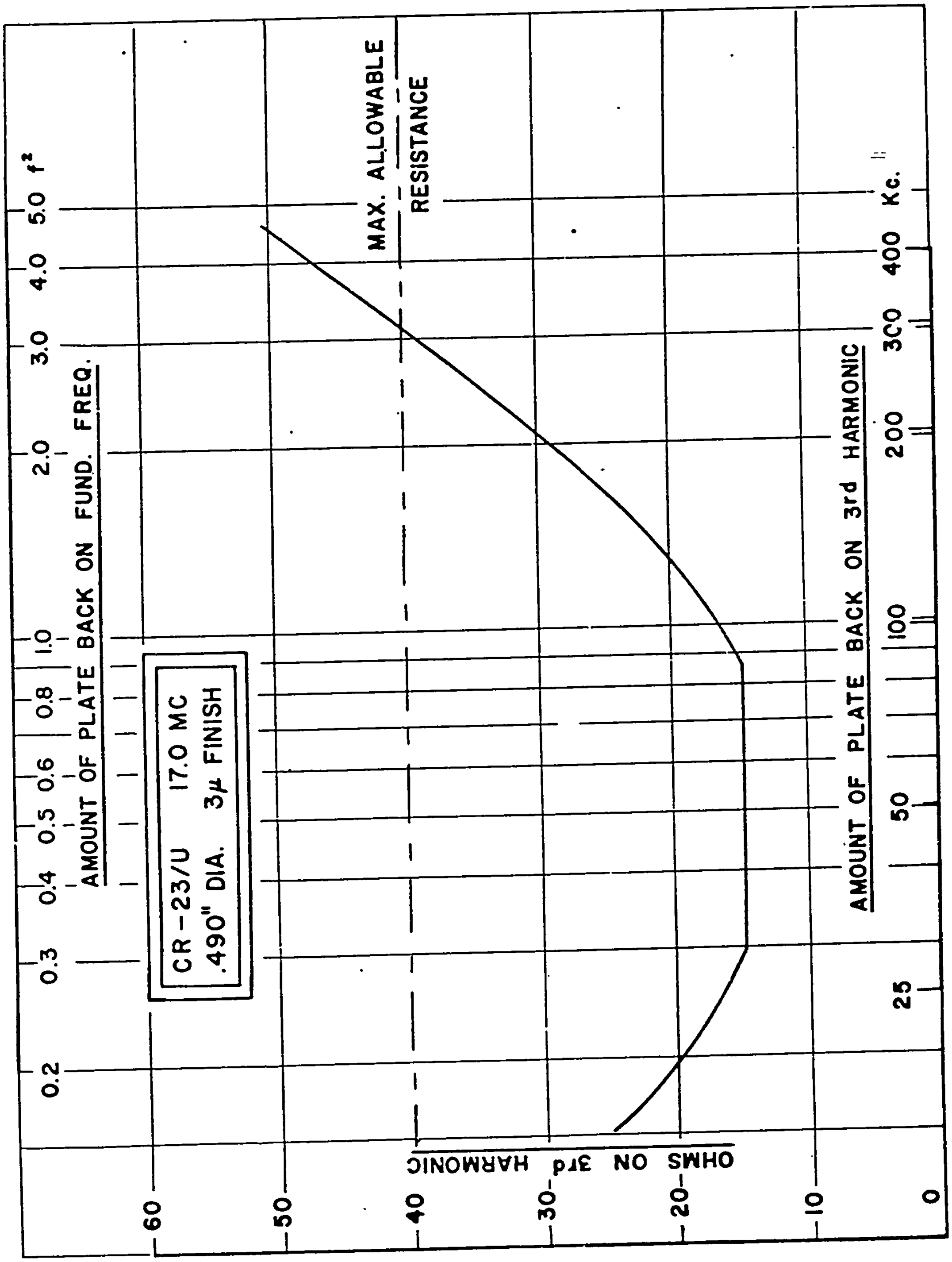

AMOUNT OF PLATE BACK ON FUND. FREQ.
0.2
0.3
0.4
0.5
0.6
0.8
1.0
2.0
3.0
4.0
5.0 f²
MAX. ALLOWABLE RESISTANCE
CR-23/U 17.0 MC
.490" DIA. 3μ FINISH
AMOUNT OF PLATE BACK ON 3rd HARMONIC
25
50
100
200
300
400
Kc.
OHMS ON 3rd HARMONIC
60
50
40
30
20
10
0

Figure 47-2.

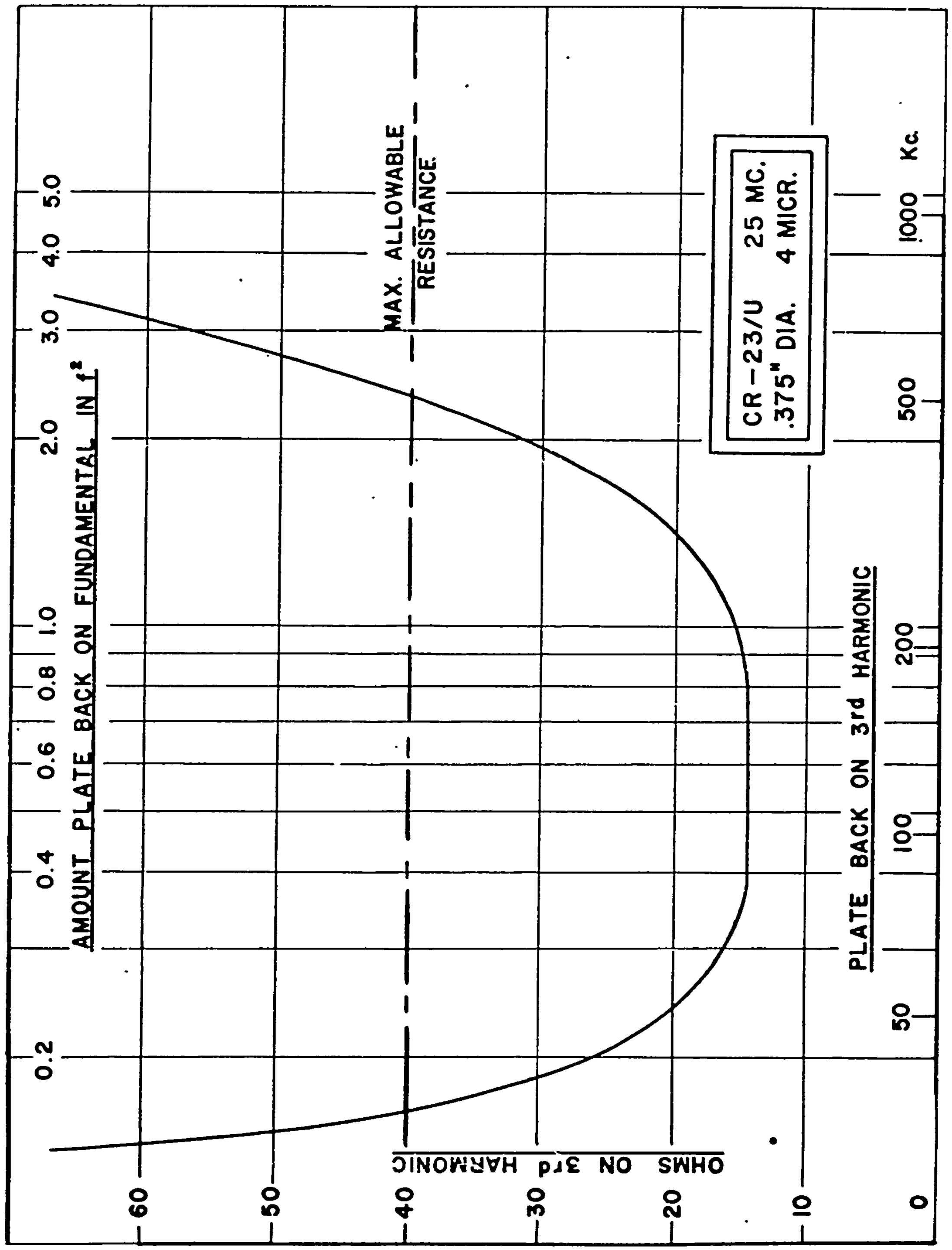

AMOUNT PLATE BACK ON FUNDAMENTAL IN f²
0.2
0.4
0.6
0.8
1.0
2.0
3.0
4.0
5.0
MAX. ALLOWABLE RESISTANCE
CR-23/U 25 MC.
.375" DIA. 4 MICR.
PLATE BACK ON 3rd HARMONIC
50
100
200
500
1000
Kc.
OHMS ON 3rd HARMONIC
60
50
40
30
20
10
0

Figure 47-3.

TOTAL PLATE BACK VS. SURFACE-FINISH
(EMPIRICAL)

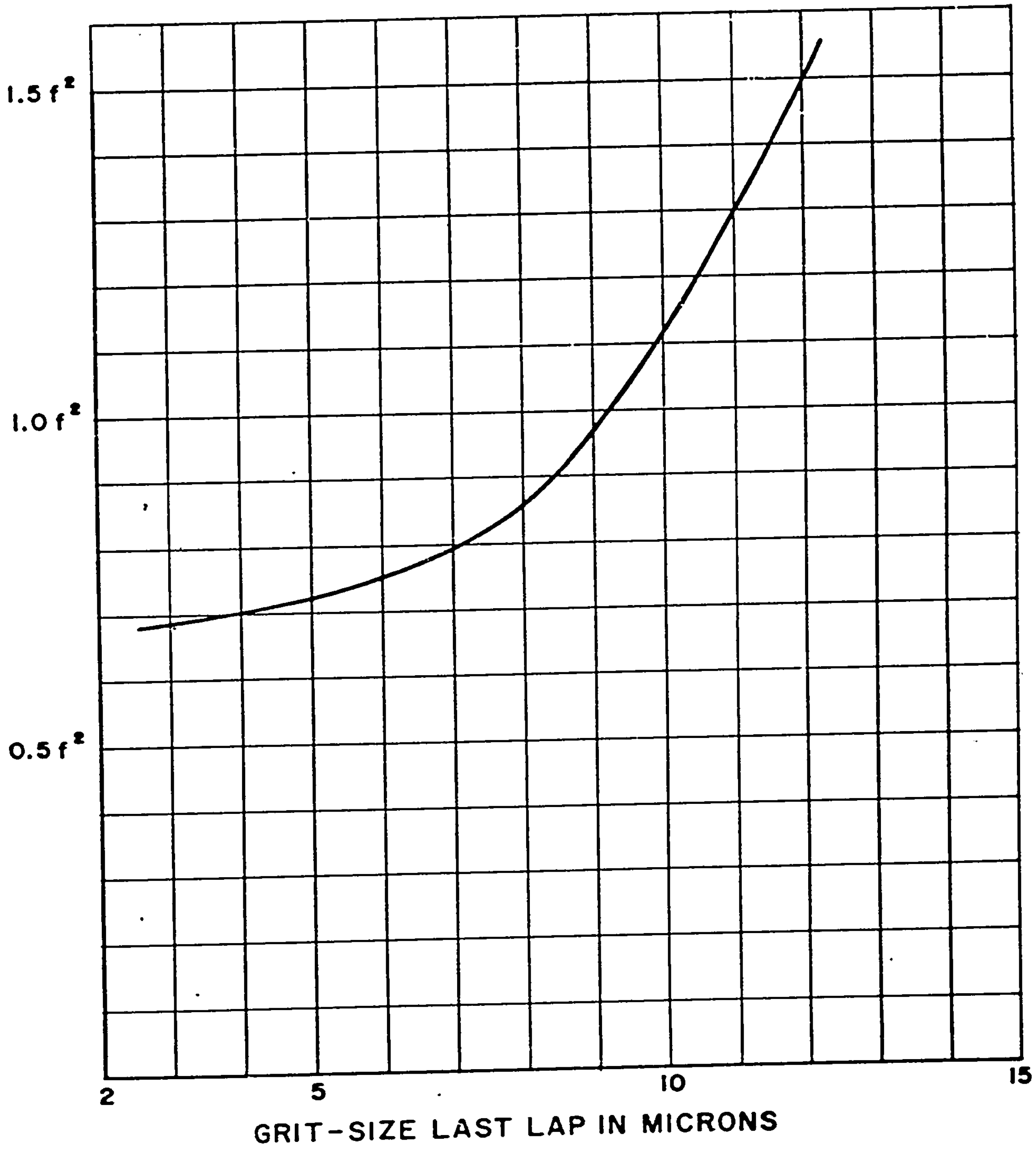


Figure 47-4.

an intermediate layer to which the final plating material will bond.

The desirable qualities of the base plating material are (1) a firm bond to quartz, (2) low ohmic resistance (a metal), (3) low density, so that the loading effect (primarily that of mass) is not too extreme and can therefore be readily controlled. The material must furthermore not have any undesirable physical or chemical characteristics which will cause excessive frequency drift or failure of the crystal on aging.

The plating process must be one which will apply the material at a high rate and distribute it evenly over the surface of all blanks treated at one time. The area to which the base plate is applied should be such that the specified capacitance is not exceeded. Furthermore, material and plating method must combine so as not to cause the allowable maximum effective resistance to be exceeded.

A comprehensive survey of base plating materials was reported in System Study Report No. 1 (3 January 1955), in which it was concluded that aluminum would make a desirable choice because of its lightness and physico-chemical properties. This choice has been amply confirmed in subsequent experiments. Hence, we have chosen aluminum in this process. Of the several means available of depositing aluminum on quartz, the method which has proven best is evaporation in a vacuum chamber. Furthermore, apparatus has been designed and tested to perform the operation automatically, so that the requirement of operator skill is reduced to a minimum.

Prior to base plating, the blanks must be thoroughly dried, so that traces of water vapor will not interfere with the evaporation process. This is accomplished by preheating the loaded masks and holders at 120°C, and leaving them at this temperature for at least one hour. It is envisioned that a mechanized conveyor will transfer the holders to the base platers, and this conveyor may include a heated section so that the blanks are dried during transfer, and delivered to a heated storage section near each base plater.

The holder will be removed from this storage heater when required and inserted into the base plater above the induction coil. Prior to this, a small tantalum crucible is inserted into the work coil. The openings in the masks (which have been selected in the prior process) are of such diameter as to maintain the capacitance of the final crystal within the desired allowance. The distance of the masks from the crucible is determined by the design of the mask holder inserted in the plater. CR-23/U blanks are to receive an amount of plating corresponding to a frequency reduction of $0.55f^2$ while CR-18/U blanks receive $0.70f^2$. These amounts have been shown to result in good activity and resistance of the final units (see Table 47-1 and Figures 47-1 to 47-4). Since the rate of plating in the evaporation process is inversely proportional to the square of the distance, preset adjustment of the height of the two types of mask permits the plating time to remain a constant.

Operating procedure for the base plater is as follows:

The operator will lift the counterbalanced chamber which raises sufficiently high to permit easy unloading and loading of crystal mask fixture and crucible. The operator removes the previously plated mask fixture and drops a new mask fixture in place with one simple motion. Angular alignment and centering with respect to the crucible is accomplished by aligning pins.

The old crucible is removed and a new crucible inserted in the load coil with a suitable tool. The operator lowers and seats the chamber, presses a start button and from this point the process is automatic. The vacuum system is then automatically valved into the roughing cycle and brought down to 200 micron pressure by a Kinney KC-15 pump. During the roughing cycle, a 2S composition aluminum ball is fed into the hemispherically shaped tantalum crucible located within the induction load coil. At 200 microns, a thermocouple gauge relay switch sequences the vacuum solenoid valves into the fine pressure cycle (a C.V.C. MC-300F Diffusion pump backed up by the Kinney KC-15 pump). When the system pressure is brought down to 0.3 microns, the induction load coil is energized. This is accomplished through appropriate circuitry between the cold cathode discharge gauge and the cycle timer which sequences the Lepel induction generator through the melt and evaporation stages of plating.

After the plating has been completed on the first side of the crystal, the load coil is deenergized and the ball loading mechanism drops a new charge into the crucible. With the same motion, the crystal masks are rotated 180°. The load coil is then energized and the second side is plated. At the end of a 15 sec. crucible cooling period, the vacuum system is sequenced to the starting or unloading position. A bright light will indicate to the operator that the cycle is complete and the machine is ready for unload/load.

The base plating cycle has been determined to require 4.5 minutes, as follows:

Operation	*Time*
Unload and load masks	15 sec.
Change crucible	10 sec.
Pump down to 0.3 micron	80 sec.
Plate one side	75 sec.
Plate second side	75 sec.
Cool crucible	15 sec.
	270 sec. =4.5 min.

3. Alternate Methods

Other materials that have been used in the production of CR-23/U crystals or suggested for use are:

Table 47-1

BASE PLATING RESULTS WITH BULOVA HIGH FREQUENCY INDUCTION PLATER, TANTALUM CRUCIBLE AND ALUMINUM PLATING MATERIAL

Nominal Frequency mc/s	*Diam. Blank*	*Surface Finish, microns*	*Distance Mask: Crucible*	*Plating time, one side*	*mg. Alum. Evap.*	*Amount Plateback,* f^2	*Effective Resistance, ohms*	
							Measured	*Max. Allow. Mil. Spec.*
4.3	.490"	8	4"	90 sec.	78	0.74	14	120
5.0	.490"	8	4¼"	90 sec.	78	0.70	36.7	75
5.1	.490"	8	4"	90 sec.	78	0.70	12.5	75
7.5	.490"	8	4"	90 sec.	78	0.62	10.4	35
9.2	.490"	8	4"	90 sec.	78	0.70	7.6	35
15.0	.375"	8	4"	90 sec.	68	0.67	10.9	25
15.0	.375"	8	4¼"	90 sec.	60	0.46	13.7	25
15.0	.375"	8	4"	90 sec.	69	0.68	13.6	25
15.0	.375"	8	4¼"	90 sec.	78	0.52	10.8	25

RESULTS WITH RCA PLATER, TANTALUM CRUCIBLE AND ALUMINUM PLATING MATERIAL

Nominal Frequency mc/s	*Diam. Blank*	*Surface Finish, microns*	*Amount Plateback,* f^2	*Effective Resistance, ohms*	
				Measured	*Max. Allow. Mil. Spec.*
		—CR-18/U—			
4.3	.490"	8(1)	0.71	17	120
6.2	.490"	8	0.52	34	50
8.775	.375"	8	0.66	13	35
10.0	.375"	8	0.64	12	25
12.0	.375"	8	0.50	6	25
15.0	.375"	8	0.42	7.9	25
		—CR-23/U—			
17.0	.490"	4	0.51	17	40
25.0	.375"	4	0.55	16.7	40
30.0	.375"	4	0.47	20.1	40
44.5	.375"	4	0.52	20	40
50.0	.375"	4	0.65	22	40

(1) blanks are edge-contoured

gold (evaporation)
gold (sputtering)
silver (evaporation)
silver (chemical deposition)
copper

As mentioned in the above reference, gold is so heavy as to make the film thickness very critical for high frequencies, also it has poor adhesion to polished quartz. Silver is better on both counts but not the equal of aluminum since aluminum forms a chemical bond with quartz. Both gold and silver are expensive and tend to recrystallize and show large frequency and activity changes on aging. A further advantage of aluminum noted is the even distribution of plating over the crystal as compared to gold. Copper has excellent adhesive properties, but its aging characteristics are doubtful.

Of the plating methods used and proposed, evaporation is common and the most applicable for aluminum. Sputtering is possible with gold and offers possibility of close control (particularly for final plating) but it is difficult with aluminum because of the oxide layer. An additional difficulty with sputtering at high rates is the heat developed, which, while it insures a clean surface, may cause quartz modification and twinning above 570°C.

Electrolytic deposition, although it has been used for final plating, is not possible for base plating since a metallic layer must already exist. In common with chemical deposition it has the disadvantage of requiring treatment with chemicals which may cause serious aging effects unless completely removed.

With the evaporation method, several variations are possible. We have chosen induction heating, but resistance heating is possible. However, this requires a larger, more complex crucible which costs from 10 to 20 times as much as one which can be designed for induction heating. Also, the problem of clamping a resistance-heating crucible into electrodes would complicate the operator task or the mechanism. Since the crucible life is limited (one cycle in our process), this is a serious consideration in high production. Instead of tantalum crucibles, tungsten and molybdenum have both been tried since the melting point of each (4000°C) is sufficiently high. Molybdenum has proven to have insufficient chemical resistance to molten aluminum. Tungsten, on the other hand, has not been obtainable except in sintered form. Sintered crucibles tested have proven too porous, and hence easily attacked by the aluminum.

4. Condition of Material Leaving Process

The error expected in base plating is $\pm 0.10f^2$ (3 sigma), which will combine with the Final Etch frequency error to yield the following:

CR-18/U: $\text{Frequency} = \text{Nominal} + 0.23f^2 \pm 0.16f^2$
CR-23/U: $\text{Frequency} = \text{Nominal} + 0.16f^2 \pm 0.155f^2$

5. Yield Expected

No significant loss of blanks is to be expected in this stage.

PROCESS 48, PRE-AGING

1. Incoming Material

Unmounted crystals are conveyed to this process in the masks used for base plating.

2. Pre-Aging Process

Quartz crystals manufactured by any process are subject to drifts in frequency and changes in activity or resistance with age. These effects are mainly due to the following reasons:

> Properties of thin metal layers, which were deposited at temperatures below the recrystallization temperature of the metal;
>
> Properties of the quartz itself, which occurs in various crystallographic modifications;
>
> More or less unknown factors, connected with chemical impurities adsorbed on the surface of the plated units.

The aging effect is greatly accelerated with temperature, and the crystal reaches a state of comparative stability after a time. The purpose of pre-aging is to accelerate aging which would occur normally, by heating the crystals prior to the final plating adjustment. In this way the crystal will stabilize and a greater yield of satisfactory crystals will be obtained, since any frequency drifts can be adjusted in final plating.

Richard B. Belser (Georgia Institute of Technology, Atlanta, Ga.) and E. M. Washburn (Radio Corporation of America, Camden, N. J.) have prepared extended aging studies under contracts with the Signal Corps.

In tests with approximately 19 different plating metals, these studies have demonstrated that units with low aging rates can be obtained by heating quartz plates with electrodes to temperatures which are at least 200°C higher than the plating temperature of the electrode metal. The temperature which is considered to secure a sufficient pre-aging range is between 400—600°C. In these tests, the finished crystals were sealed in helium instead of air.

Since it is known that the Curie-point of quartz (conversion of β quartz into α quartz) is 575°C and that application of too high temperatures in pre-aging may yield changes of the crystallographic structure of the quartz or destruction of the metal electrodes by undesired aggregation (as shown by R. Belser), 425°C has been selected as a safe pre-aging temperature. A period of ¼ to ½ hour seems to be sufficient to obtain stable units.

Mechanized transfer to the Mounting and Cementing machine (Process 49) is envisioned, since it appears most convenient to convey the masks through a tunnel oven. In this way, variations in heating cycle can be obtained by adjustment of conveyor speed and temperature along the oven.

3. Alternate Methods

Other combinations of time and temperature are possible as shown in the investigations cited above. The optimum combination, therefore, will be determined for the particular oven which we shall use, when the final design is established.

4. Condition of Material Leaving Process

Having been aged, the crystals will be comparatively stable in frequency and will have shifted slightly from the values specified in Process 47.

5. Yield Expected

No loss is expected during pre-aging.

PROCESS 49A, CLEAN BASES

1. Incoming Material

Bases of the HC-6/U type will be purchased or fabricated for the plant, and will be delivered from the stock room.

2. Process

Bases must be inspected for leakage on a continuous or sampled basis, and cleaned for subsequent processing. The bases will be identical to the standard HC-6/U type except that they will have stiff mounts rather than the wire type.

Inspection will be part of the quality control procedure and therefore not considered in this report.

The purpose of cleaning the bases will be to remove traces of oil or dirt which may interfere with the subsequent vacuum processing (frequency plating) or soldering (in the sealing stage) or contaminate the crystal. A standard degreasing treatment, such as trichloroethylene, should be adequate. The base preparation procedure will then be as follows. Bases (inspected by lot samples) will be delivered from storage and assembled to small ceramic blocks, fitted with electrical contacts from the base pins to points on the outside of the block. (These blocks will be used to support and locate the bases during insertion, and will be used also in final plating and base sealing.) The assembly will be manually performed, with some mechanical aids, such as automatic feeding of blocks into a jig. The bases and contact blocks will be degreased by passing through trichloroethylene. This will serve not only to clean the bases, but to remove traces of flux from the blocks which have been recirculated from the subsequent sealing operation, and may adhere to them and cause difficulty in final plating.

The blocks and bases will be taken out of the degreaser and fed directly into the insertion machine.

3. Alternate Methods

Other possible methods include cleaning of bases at the source and packaging in strip form for easier mechanization. This possibility is outside the scope of this report, however, since it involves the problems of procurement and perhaps development by the vendor.

4. Condition of Material Leaving Process

Clean bases will be conveyed to the insertion machine assembled to individual ceramic blocks.

5. Yield

(Not applicable)

PROCESS 49B, MOUNTING AND CEMENTING BLANKS

1. Incoming Material

The crystal blanks coming from the Base Plating process have been plated with aluminum electrodes on both sides, and have been pre-aged at high temperature in order to decrease subsequent frequency drift. The aluminum electrodes are circular with one rectangular tab extending radially, parallel to the orientation flat, on either face of the blank. The two tabs, which make continuous electrical contact with the electrodes, are on opposite ends of a diameter of the blank. The blanks will still be loaded in the base plating masks.

2. Process

The masks will emerge from the aging oven and feed directly into a mechanism which will extract the blanks. The blanks are oriented in the mask, and they will drop one by one, still retaining their orientation, into a mechanism which will push them into a waiting base. The angular error of mounting with respect to the X-axis of the blank should not substantially exceed 5° (owing to possible damping). The flat error may be ±30′, hence the target mounting tolerance should be on the order of ±4.5°. The base, held in its ceramic block, will meanwhile have been moved under the blank chute and the contract fingers of the stiff mount spread apart to receive the blank.

The contact points of the mount will then be allowed to spring back, and since the blank has been dropped into the mount with the correct orientation, the fingers will make electrical contact with the tabs of the plated aluminum electrodes. The ceramic block holding the base and blank will then be moved to another station. At this point cement will be applied. This could be accomplished by two small injector tubes that press against the mount contacts where they touch the aluminum tabs. The contacts would be drilled at these points. A small drop of electrically conducting cement would be injected into the holes in the contacts.

The cement used will be an epoxy-silver compound similar to DuPont formulation #5605 or #5604.

The mounted and cemented crystals will be ejected from the machine at this point and go on to the next process, which is to dry and cure the cement.

3. Alternate Methods

Current methods, using bench jigs and wire spring mounts seldom exceed a rate of 1200 per day per operator. Even these rates require skilled operators, particularly for thin crystals. The development of the stiff mount has opened the possibility of mechanization, which is clearly justified. The mount design may well improve crystal performance as a by-product, owing to the lesser strain on the crystal blank.

A choice exists between two available kinds of conducting cement used to insure reliable electrical connection between base plate coating and mount electrodes. Epoxy-silver is superior from the standpoint of thermal, mechanical and chemical stability, but requires a longer drying and curing time than the more common silver-Bakelite. The advantages in performance appear to be worth the additional difficulty.

Other methods of connection, such as soldering and spot-welding, have not proven practical so far.

4. Condition of Material Leaving Process

Crystals are assembled in the base mounts and have a spot of cement at each electrode contact.

5. Expected Yield

A nominal loss of about 1% may be expected in handling crystals in and out of the masks.

PROCESS 50, AIR DRY AND CURE CEMENT

1. Incoming Material

Crystals assembled to bases and with epoxy-silver cement applied to the electrode contacts, enter this process. The bases are inserted in the ceramic blocks previously described.

2. Process

The epoxy cement must be cured for 5 hours at 150°C. Before entering the curing oven it must be air-dried for ½ hour to prevent the cement from swelling.

Ceramic blocks holding the mounted crystals will emerge from the mounting machine and be ejected onto a conveyor track. The length of this track can be made sufficiently long to result in the required air-drying time.

At the end of the air-drying time, the cement will be rigid enough so that the blocks may be handled and placed into racks that will hold ten blocks each. These racks will be used as part of the mechanization of the next process (Adjustment Plating). The operation may be semi-automatic; that is, the blocks may be pushed into the racks by action of the conveying mechanism and the racks removed manually when filled, or the entire operation may be manual. In either event, the racks will be assembled in easily-handled groups and loaded into a curing oven held at 150°C and left there for five hours. One method of timing various batches would be to have separate compartments in the oven, each with an individual timer and a signaling arrangement, so that the operator will be notified when each batch has completed its cure.

3. Alternate Methods

Although a completely conveyorized cure would result in some labor saving (e.g., transfer to the batch oven), the requirement of five hours curing time means that a substantial amount of a day's production must be kept moving through the oven. This may be expensive to mechanize. In addition, the demands of the next process (Adjustment Plating) are variable owing to the variation in adjustment between batches of crystals. It is better to combine the take-up storage with the oven than to have a continuous output from the oven and a comparatively long dwelling time where the crystals will cool and pick up moisture or contamination.

4. Condition of Material Leaving Process

On leaving the curing oven, the epoxy cement will be completely polymerized, and the crystals as well as the holder blocks will be free from moisture. The blocks are assembled in slotted racks ready for final plating.

5. Expected Yield

No loss of blanks is expected to occur in this process owing to the method of handling.

PROCESS 51, ADJUSTMENT PLATE

1. Incoming Material

Mounted and cemented crystals are removed from the curing oven of the previous process in a clean, dry state.

As a result of base plating, the crystals have the following specifications with respect to the nominal frequency.

Table 51-1

Type	*Frequency*	*Range (3 Sigma)*	*Required Adjustment*
CR-18/U	Nominal $+0.23f^2$	$\pm 0.16f^2$	$0.07\text{-}0.39f^2$
CR-23/U	Nominal $+0.16f^2$	$\pm 0.155f^2$	$0.005\text{-}0.315f^2$

2. Process

In the final plating procedure the crystals are to be adjusted to their desired frequency as specified in the individual job orders. Since the crystals have a considerable variation, the adjustment must be made on an individual basis. The accuracy of the adjustment must be sufficient so that the final crystal will meet the tolerance specifications of the heat run (−55°C to +90°C), which is ±0.005% of the nominal (job order) frequency. Some frequency shift occurs during sealing and in aging, apart from the excursion which results from a non-zero temperature coefficient. Hence at this stage, before sealing, the nominal must be approached with considerable precision. We have set a tolerance of ±0.001% of nominal, which corresponds to deviations of ±0.043 kc. (fundamental) to ±0.540 kc. (third harmonic) or from $\pm.0023f^2$ to $\pm.0006f^2$ between the nominal frequencies ranges of 4.3 to 18 mc. fundamental or 17 mc. to 54 mc. third harmonic.

Thus two of the important requirements of the adjustment plating process are (1) accuracy and (2) speed. In addition, the process must not contaminate the crystal surface with any material which will affect its activity on aging, the added material must adhere strongly to the aluminum base plate, and it should ideally be evenly distributed over the base coat surface so as to minimize undesirable loading effects (damping, unwanted modes or decrease in activity).

These requirements have been met to a high degree by the method of evaporation of gold in a high vacuum (1 micron or less). As a result of these studies we have developed apparatus which will evaporate gold from a hot filament while the crystal is in oscillation. Both the rate of evaporation (e.g., the filament temperature) and the amount of gold reaching the crystal are controlled by the difference between the measured frequency of the crystal and a reference standard. The filament temperature is controlled by a frequency-sensitive magnetic amplifier circuit reading from the difference frequency. In addition a shutter is caused to oscillate between the crystal and filament, intercepting the evaporated gold molecules when the difference frequency drops below a predetermined value. As the difference is decreased, the shutter cycle is altered so that the crystal is exposed less to the gold. When the frequency difference reaches zero, a separate circuit stops the shutter oscillation completely and shuts off the filament.

The above apparatus, after some experimentation, has been refined to a point where the required accuracy is met. One difficulty has been the unavoidable heating of the crystal due to radiation from the filament. This causes the crystal to oscillate at a different value from that which it would have at room temperature, and so causes a drift after shut-off. The combination of shutter duty cycle variation and filament temperature reduction has reduced this error to that of the specification. The speed of plating has been lowered to some extent, but it appears probable that the plating can be accomplished in 20 seconds in the final machine.

The other factor which determines speed is the time to pull down an adequate vacuum. Vacuum plating with gold can be accomplished with pressures as high as 100 microns, which is equal to the vapor pressure of gold at about 1450°-1500°C. With lower pressures the evaporation temperature is reduced, but more important, the gold films obtained at higher pressures tend to peel. With pressures on the order of 0.1 to 0.2 microns, good adherent gold films have been achieved.

A rough vacuum can be readily achieved by a mechanical pump of moderate size, for example the Hypervac 20 at 422 rpm has a pumping speed of about 3 liters per second at 100 microns, but the speed drops off to less than one half at about 0.5 microns. A Kinney pump is even faster; their type CVM556 being rated at 5.4 liters/sec. above 100 microns. With pressure differentials less than a few hundred microns, diffusion pumps become enormously efficient. In our system, we will use the above-mentioned Kinney pump down to 100 microns and then valve in a diffusion pump having a rated speed of 375 liters/sec. from 100 to 1 microns and practically the same speed down to 0.1 micron.

If the final pressure for a pumping system is substantially above the so-called limiting pressure (about 10^{-3} microns for an oil diffusion pump) the pumping time can be expressed as

$$t_2 - t_1 = \frac{V}{S} \ln \frac{P_1}{P_2}$$

where V is the volume of the system in liters, S the pumping speed in liters/sec., P_1 the initial pressure and P_2 the final pressure. If V is about 1 liter, P_1 equals 760 mm. (one atmosphere), P^2, the cut-in pressure for the diffusion pump, 0.1 mm. and S, the rough pumping speed, 5.4 liters/sec., then the rough pumping time is:

$$(t_2 - t_1)_{\text{Rough}} = \frac{1}{5.4} \ln 7600 = 1.2 \text{ sec.}$$

The fine pumping time, from 100 to 0.1 microns with S = 375 liters/sec. is:

$$(t_2 - t_1)_{\text{Fine}} = \frac{1}{375} \ln 1000 = 0.02 \text{ sec.}$$

Therefore, neglecting leakage, out-gassing and conductance of the pump connections, the total pumping time in theory should be less than 2 seconds. Practically, the pumping time should be less than 10 seconds for a tight system. The time to transfer crystals in the machine, including raising and lowering of the bell-jar, should be very small, on the order of 2 seconds. Hence the entire operation of adjustment plating may not take more than 30 seconds.

In plating from one side only as called for by this process, it is desirable from the standpoint of crystal loading to make the size of the gold spot nearly equal to that of the base electrode. Hence a separate size mask is required for each frequency range; as many sizes as are required by the base plate. It will also be necessary to alter the setting of the electronic shut-off circuit each time a machine is changed to a different frequency order.

3. Alternate Method

A previous survey of manufacturers who have produced CR-23/U crystal units in quantity has revealed that silver and nickel electroplating is the most common method of reaching final frequency. Other methods of plating are cathode sputtering and "burning on" or firing of colloidal metal. Other possibilities are deposition from solutions of gases (e.g., carbonyl compounds) and torch deposition.

The electroplating method is objectionable in large scale production because the crystal frequency cannot be measured in the plating bath, therefore the crystal must be removed, rinsed, dried and measured several times to achieve the desired accuracy. Estimates of cycle time run between 5 and 10 minutes for this process, besides requiring skill on the part of the operator. Also the strong chemical treatment may well cause undesirable aging effects.

Chemical reduction from solutions of metal compounds is open to the same objections and seems to offer no advantage. Reduction from gases has been ruled out owing to the poor adherence expected of the fine powders deposited and the toxic nature of carbonyl compounds. The Schoop or torch process appears more likely to be successful, but insufficient data has been obtained to justify experiments along this line.

"Burning on" is a common means of producing optical mirrors. Its major fault in this instance is the fact that the metallic salt to be applied and reduced is suspended in an oily solution, which may easily contaminate the crystal surface. The film after burning must be compacted by heating and rubbing, thus requiring another operation. Finally, it is doubtful that frequency control could be applied to this process.

In contrast to the above, cathode sputtering shows much promise as a plating means, and has advantages (such as control of the areas of metal application) over evaporation. Two difficulties have prevented its use here. First, the process is slow, even with gold which is one of the most rapidly sputtered of all metals. Optical practice in sputtering (gold or silver in 1. to .01 mm. N_2, A or air using 1-20,000 volts) requires as much as 1 hour to achieve an opaque coat. Conventional quartz crystal practice (gold, 2000 volts, 0.1 mm.) requires 35 to 40 minutes, the rate being approximately .01 microns per minute and a total of .25 microns (approximately $.15f^2$) being plated. It has been found possible to speed this cycle considerably, using small chambers and improved electrode design. However we have not been able to reduce the time for plating below 1 minute for a significant correction. Hence the evaporation method has better than a 2 to 1 advantage in plating time alone. In addition to this fault, sputtering causes a considerable amount of heating of the crystal, which heating shifts its frequency and tends to make automatic shut-off inaccurate. The heating effect is greater than that of evaporation, which latter we have been at considerable pains to minimize.

4. Condition of Material Leaving Process

Both types of crystals (CR-18/U and CR-23/U) will leave this process with their frequency adjusted to within ± .001% of the nominal value called for on the job ticket, and with an adjustment (gold spot) on one side, of a thickness equivalent to between $.005f^2$ and $.39f^2$ per Table 51-1.

5. Expected Yield

If adjustment plating and the processes leading up to it are in control, there should be no significant number of crystals which require a negative adjustment; that is, none that are already below the nominal frequency. A small number, less than 1/4%, will require less than $0.005f^2$ adjustment, and an equal amount will require more than $0.39f^2$; these latter crystals will only require slightly more time to plate and will not be lost.

A small number, about 1%, are expected to be lost in handling.

PROCESS 52, ASSEMBLE CANS TO BASES & SOLDER PREFORMS

1. Incoming Material

Clean cans are received from the hydrogen firing process (No. 49A). Crystals cemented to bases, adjusted to final frequency, and plugged into ceramic blocks which are assembled in racks, enter from Process 51.

2. Process

Cans are to be sealed to bases by means of a subsequent soldering process. At this stage they must be assembled to solder preforms and fluxed so that the actual sealing process may be mechanized.

Present methods (e.g., those developed by UTC) call for a preform of 63-37 tin-lead alloy to be fitted around the can after being dipped in flux and dried (the can being assembled to the base), additional flux to be added and the assembly clamped in preparation for soldering. The solder is purchased in ribbon form and is preformed by special tools.

This is normally a manual operation requiring skill and care, and would be unsuitable for the specified production rates unless mechanized.

At present, it appears that the steps of assembling cans to bases, preforming solder, and fluxing, could be accomplished more easily in one step than in attempting to separate preforming and fluxing on the one hand and assembly to bases on the other. The major danger in this operation is that flux will enter the cans and cause poor aging characteristics after sealing. Unfortunately the flux appears to be required to form a good seal. We have experimented with ultrasonic soldering in an attempt to eliminate flux but without complete success.

On the positive side, the bases received from the final plating operation are already assembled in racks and are in a form convenient for mechanized assembly to the cans.

It is therefore envisioned that the entire series of operations will be mechanized with exception of can loading, and if a suitable handling mechanism is available for the can stamping press it may be possible to mechanize this step also. Lacking this refinement, the operation would be somewhat as follows.

An operator will select cans with the required frequency stamping from trays of annealed pieces and feed them to the machine. Racks of mounted crystals will also be fed to the machine either by an operator or from a conveyor. The cans will be engirdled by solder preforms which will be fabricated in the machine from a solder spool, and then placed on top of the bases. The cans will be held in place while liquid flux is applied and dried, during which time a spring-loaded clamping bar will be inserted on top of all cans in a rack. The clamped assembly would then be ejected from the machine.

3. Alternate Methods

There are many variations of this concept which are possible, but some similar scheme must be implemented if metal cans and holders are to be used. Glass holders would, of course, present an entirely different set of problems.

One point which might be raised is the automatic assembly of the clamping bars. This operation might be performed manually after the racks are ejected, but it is feared that the cans would move out of place on the bases after fluxing, making it difficult to assemble the clamps properly, and presenting a danger of flux entering the can. Also the cans might be assembled to the solder preforms automatically and placed on the crystal bases, either manually or in the same machine, the clamps manually put on, and the clamped assembly sent through a second machine which will apply flux. In view of the additional labor required, this scheme will not be tried unless it results in considerable simplification of the mechanisms.

Placing the unsoldered cans directly on the bases by hand before feeding the racks to the solder-forming machine would seem at first to offer some simplification, but on further investigation it is seen that it is difficult to place the solder ring on the can without danger of malalignment, so that no substantial saving in complexity results.

4. Condition of Material Leaving Process

The assemblies leaving this process will consist of the crystals mounted in ceramic blocks, assembled in racks, and clamped to the HC-6/U cans complete with solder preforms and flux.

5. Yield

Owing to the clearance between can and crystal, no loss through breakage of the blank is anticipated.

PROCESS 53, BASE SEALING

1. Incoming Material

Can and base assemblies (HC-6/U) are obtained from Process 52 complete with solder preform in place and fluxed, the unsealed crystal units being joined together in racks, while the cans are held against the bases by means of a spring-loaded clamping bar. The spring exerts a force of approximately one pound against the cans.

2. Sealing Process

Sealing of the crystal units is an important step in assuring good aging qualities. A hermetic seal free from the smallest leaks must be obtained after a controlled atmosphere of dry gas is introduced. The sealed unit must be capable of passing military tests (e.g., hot water immersion).

In contrast to methods previously used with HC-6/U mounts, the process to be described is largely automatic. The incoming assemblies are prepared in all respects for sealing and need only be flushed with the proper gases and heated.

The sealing process which will be used is accomplished without a pin-hole in the can, thus eliminating several operations.

In order to permit a larger quantity of crystals to be more readily handled, the racks of units will first be arranged in special trays which will hold 400 crystals in the sealing machine. The latter consists of a large chamber which can be evacuated and flushed with dry gas, and in addition, is equipped with an induction heating coil and mechanisms for feeding the units through the coil.

When the crystals are in place in the machine, it will be pumped down to 10 microns, at which point a valve will open to admit dry helium or nitrogen and the vacuum valve closed. When gas pressure equals atmospheric, the unit will again be pumped down to 10 microns and gas re-admitted until the pressure reaches 6 psig. An R.F. generator will then energize the work coil inside the machine and the handling mechanism will push the crystal carriers through the induction heater. The units, filled with gas, pass through the work coil. The fluxed solder preform will melt to accomplish hermetic sealing of can to base. Some of the chamber gas will be vented off above the work coil and additional gas admitted in order to flush out soldering vapors.

The handling mechanism in the chamber will reassemble the racks of sealed units on a tray so that they may be removed by the operator when the last one of the batch is completed, at which time the chamber will be opened to the atmosphere and a signal given to the operator.

Apart from loading and unloading, the entire operation will be automatic, the cycle being initiated by a start button.

Pumping to 10 microns will require less than 9 minutes, while admission of gas will be very rapid. The speed of the handling mechanism will be such that a crystal is passed through the sealing unit in about 1 second, and the entire batch of 400 processed in 5 minutes. Loading and unloading will require 2 to 3 minutes, for a total cycle time of 25 minutes per 400 crystals.

Helium will be used in preference to other gases (e.g., nitrogen) if available, since it offers several advantages. The loading effect on the crystal is less than heavier gases, and it provides good heat transfer. In addition, mass spectrometer tests for leakage require the use of some helium in the can. However, helium is about 10 times more expensive than N_2 (over 1/2 cent per unit), and more important, is under priority at present. Hence, it may be necessary to use N_2 with addition of He in some proportion.

3. Alternate Methods

HC-6/U holders are conventionally sealed by means of a hot plate and appropriate jigs where production quantities are small and manual methods suffice. A pinhole is left in the can and the units flushed with gas after base sealing, after which the pinhole is sealed. Experiments at Bulova R&D Labs. and at Union Thermoelectric Corp. have shown that satisfactory seals can be made without the pinhole in an apparatus similar to the one described, without bubbling of the solder or other poor results. Elimination of the breather hold significantly simplifies the entire operation.

For heating the joint, induction coils are the most convenient, compared to resistance heating, for example. Welding would necessitate redesign of the HC-6/U can. Hot plate methods, of which there are several, are satisfactory for small quantities but do not lend themselves to mechanization.

The most satisfactory method of hermetic sealing is undoubtedly an all-glass seal. Glass mounts have been developed and tested, but have not yet been approved for use with CR-18/U and CR-23/U units. Among other reasons, it has not yet been proven feasible to design a mount small enough to replace the HC-6/U directly. Furthermore, some modification of standard vacuum tube sealing machinery would be necessary to adapt it to crystal units.

Ultrasonic soldering has the possibility of giving a good seal but does not give a good appearance. It is also a non-continuous process which leads to a lower machine capacity than induction heating. On the other hand, it would eliminate all flux problems if otherwise suitable.

4. Condition of Material Leaving Process

Crystal units after sealing will be removed from the chamber and subjected to leakage tests (by immersion or mass spectrograph) on a sampled basis.

5. Yield

No loss of crystals by breakage is expected in this process. As a result of quality control procedures, some lots will be rejected in leak testing; this should not exceed 2% of the total. (Rejected crystal units may be salvaged and resealed.)

PROCESS 54, FREQUENCY AND ACTIVITY CHECKING

1. Incoming Material

Crystal units, having been sealed in the base sealing machine, will be sent to the frequency checking bench after removal from the trays used in the previous process. The crystals are plugged into the ceramic blocks used in the prior operations and the blocks are arranged in racks.

2. Process

It is necessary to check each crystal unit individually to be certain that they are within the limits of frequency and activity specified. This check will be accomplished at a temperature of 25°C ± 2°. The crystal units must also meet a frequency and activity specification at the temperature extremes of −55° to +90°C. This requirement calls for a deviation of not more than ±0.005% of the nominal frequency over the temperature extremes, an effective series resistance of less than 40 ohms for CR-23/U units, and a maximum effective resistance (anti-resonance) varying from 120 ohms at 4.3 mc. to 18 ohms at 25 mc. for CR-18/U units.

The heat run test requires a significant amount of time, a minimum of several minutes per unit using methods now available. To require a complete test on every unit would require an inordinate amount of equipment and manpower. The room temperature test, on the other hand, can be performed much more rapidly since we have already developed equipment to measure frequency and sort crystals with great rapidity. We believe that our quality control procedures in the pilot plant will be sufficiently accurate to eliminate the need for 100% sampling on the heat run. Since the temperature coefficient is a primary function of the angle of cut (ZZ′), this means that the quality procedures will emphasize close control to this parameter. Hence, shifts in the nominal frequency which are due to aging, sealing, or imperfections in final plating can be detected in the more rapid room temperature test with 100% sampling, while only a selected number of each lot of crystals will be given the heat run tests.

This number (the quality control level for heat run) should be sufficient not only to control the temperature coefficient but also to monitor activity dips adequately. These may be due to insufficient contouring or to moisture and other foreign substances in the sealed can.

The room temperature frequency check may be performed by an automatic apparatus similar to the electronic portion of the Frequency Sorter, except that it can be simplified. Only one increment need be set, an upper and lower limit, and the crystals sorted into good, high and low units. The frequency limits for each lot will be set into the apparatus by a control panel similar to that developed for the sorter, except that it will contain only two rows of selector dials, eight each for the high and low frequency. The limits for each order can be established by the job ticket and set in by the supervisory or maintenance personnel. The accuracy of the frequency check will be on the order of ±0.0002%. Effective resistance limits will be detected by resonating the crystal in a circuit similar to the standard C.I. Meter and equipped with relay contacts to signal grid currents lower than the specified value. The apparatus will be preset for effective resistance limit of each lot of crystals.

The frequency sorter operates on the principle of counting the number of cycles in a given time interval, which permits a test to be made to the desired accuracy in 0.2 sec. Another 0.1 sec. is needed to stabilize the crystal. About 2 seconds or less will be required to handle the crystals in and out of the checking unit. The effective resistance test should proceed simultaneously with the frequency check. Hence, the entire operation will be performed in better than 2.3 sec. per crystal unit.

The handling mechanism may be a variation of that developed for the Final Plater, or alternately that which will be designed in the base sealing unit. Either will be capable of the above speeds, and in addition, are adapted to the racks and ceramic carriers in which the crystal units are plugged. It will be recalled that these blocks bring out electrical connections from the base pins of the unit to the outside of the block. The added capacitance will be made small enough so that this will not destroy the accuracy of the measurements.

Since the envisioned test will be automatic, the operator will require little skill and need only feed the racks of units to be measured into the device and dispose of the sorted output.

3. Alternate Methods

Several alternate schemes for automatic frequency measurement have been discussed under Frequency Sorting (Process 32 et al). Manual frequency check using a standard C.I. Meter is possible, but is too time-consuming and requires a much higher order of skill than the contemplated method. In either case, the C.I. Meter circuit is a preferred oscillator, since it is the equipment utilized by the Signal Corps Inspection personnel. Presently available C.I. Meters have a variable drive level at high frequencies. A new meter which minimizes this difficulty is under development by the Signal Corps and should be available shortly. This equipment may prove more suitable to work into the proposed automatic test than the older types.

4. Condition of Material Leaving Process

Tested crystals will be ejected from the equipment marked according to whether they pass the test or have a high or low frequency or low activity.

5. Yield

It is anticipated that less than 3% of the crystals tested will be in the reject category.

PROCESS 55, PACKAGING

1. Incoming Material

Tested crystal units are conveyed to the packaging area assembled to the ceramic blocks used in the testing and prior finishing processes. They will be arranged according to job order.

2. Process

Crystal units are to be unplugged from the blocks in which they have been transported through the various machines, and the blocks returned to Process 49A (Clean Bases). The units will be manually packaged according to Military Specifications and the particular job order.

Packaging material will be procured from vendors or manufactured in the plant by commercially available automatic machinery.

3. Alternate Methods

Packaging methods are conventional and will be specified more closely in future studies.

4. Condition of Material Leaving Process

Crystal units will be packaged as specified by the particular order, and according to destination (domestic or overseas).

5. Yield

The yield of this process will be 100%.

PROCESS 56, FREQUENCY STAMP CANS

1. Incoming Material

Cans used to seal the crystal units will be purchased and delivered from stores.

2. Process

Duplicate job tickets of orders to be processed in final plating (Process 51) will be transmitted to this process, in order that the number and nominal frequency of crystals produced are known.

The preformed cans must be stamped on the top and sides with the code designation and nominal frequency of the order. This will be accomplished by an automatic punch carrying dies in which the digits and letters are set. Two dies striking the can simultaneously will be capable of stamping both top and sides at the same time.

The Maximum Order Board specifies a distribution of about 150 separate orders per month, equivalent to 7 or 8 changes in frequency per day. This number is small enough to enable the dies to be set by hand.

The can stamping press may be fed by an operator seated at the machine, or the cans may be stacked in a hopper and fed automatically. The latter course will require procurement of a device to orient the cans. In either case, it is envisioned that the machine will operate at a rate of 25 per minute or better. A resettable counter will be incorporated in order to inform the operator of the number of cans stamped with a given frequency, or in a machine feeding automatically, it may be arranged to stop the flow of cans.

3. Alternate Methods

From a standpoint of production control, it may be more convenient to label the cans after sealing them to the crystal units, but it would not be feasible to stamp them at this stage. It is doubtful that a stenciling or other marking process would meet military requirements of permanence and legibility. The remaining question of importance is the degree to which the stamping machine would be mechanized.

4. Condition of Material Leaving Process

Stamped cans will be assembled in batches, each of which contains a number of cans stamped with the same frequency.

5. Yield

Not applicable.

PROCESS 57, DEGREASE CANS

1. Incoming Material

Stamped cans assembled in batches of the same frequency marking.

2. Process

Cleaning of cans is an important step in order to assure freedom from oils or other material which may cause poor aging qualities after sealing. The lubricant from the deep-drawing method of forming the cans, plus any traces of grease which may come from the stamping machine are possible sources of contamination.

There are several methods used in the industry for cleaning, depending on whether or not the cans will be hydrogen annealed in subsequent steps. For example, the Bulova Watch Co. Quartz Crystal Division prepares cans by washing in detergent, ammonia water, rinsing in demineralized water several times, and finally with alcohol. Hydrogen annealing is not used after this process. These steps occur after pretinning, so that some flux also must be removed. The Union Thermoelectric Co. uses a process prior to hydrogen annealing which consists of a trichloroethylene degreasing step, a detergent wash, and several rinses in tap and distilled water.

Since it is proposed to use hydrogen annealing, a washing process similar to the Union Thermoelectric Company's will be used. This will be comprised of the following steps:

DEGREASE: Stamped cans will be loaded into baskets and thence into a trichloroethylene degreaser. The baskets will remain in the degreaser for 15 minutes.

WASH: Baskets removed from the degreaser will be placed in a washer which will agitate them with hot detergent. The washer will require four minutes per cycle.

RINSE: Baskets as removed from the washer will be placed in a continuous rinser. The cans will be rinsed in several sprays of tap and demineralized water. The rinsing process will require 10 minutes.

DRY: Baskets removed from the rinser will be emptied into trays, which in turn will be loaded into a drying oven. They will be dried for 30 minutes in a normal atmosphere.

3. Alternate Methods

Whether or not this method will prove satisfactory will depend on the results of aging tests. Some modification may be required as a result of these tests.

4. Condition of Material Leaving Process

Cans will be free from oily residue, and dry.

5. Yield

Not applicable.

PROCESS 58, HYDROGEN ANNEAL CANS

1. Incoming Material

Clean and dry cans stacked in trays.

2. Process

Hydrogen annealing is a continuation of the degreasing process, with the objective of removing all material from the inside of the can which may cause poor results in aging. Experimental evidence indicates that the hydrogen treatment results in a very clean surface and removes any traces of oily lubricant which may adhere to microscopic crevices in the metal.

Existing methods of hydrogen annealing involve sealing batches of cans into a high vacuum system, baking, and flushing with H_2 several times before firing in that atmosphere. This method is quite complex and would no doubt prove difficult and costly to mechanize. On the other hand, it would require much skill and operator time to perform these operations manually.

It is believed that the major benefits of hydrogen annealing can be obtained by firing at normal pressures without the requirement of prior vacuum baking. Whether or not this will be justified will depend on the results of aging tests performed on crystals prepared by this method.

Consequently, we propose to load the trays of washed and dried cans directly into a conventional controlled atmosphere oven and to fire them at 450°C or other appropriate temperature. This treatment should require approximately 1-1/4 hour. The oven will be equipped with the necessary controls to flush the chamber with hydrogen and to maintain the correct temperature cycle automatically.

3. Alternate Methods

A recent study has concluded that H_2 treatment is responsible in some cases for poor aging properties of the crystal, rather than prevent them. Therefore, it will be necessary to conduct adequate aging tests to prove out this process before it can be firmly fixed.

4. Condition of Material Leaving Process

Cans will be unloaded from the oven held in trays, and will be free from material which may contaminate the quartz crystals.

5. Yield

Not applicable.

PART III

Man-Machine System for Mechanized Crystal Unit Manufacture

DESIGN PARAMETERS

The man-machine system herein described is designed for the manufacture of Crystal Units, types CR-18/U (4.3-18 mc.) and CR-23/U (17.0-54.0 mc.). The design goal is 200,000 units per month. The distribution of frequencies to be considered typical is summarized in Appendix I. Ten thousand units per 8-hour day (one shift) are to be produced for 20 working days per month. The plant is designed to be capable of at least doubled production rates with the addition of extra shifts.

A *process* is defined in this report as a unit operation on quartz or other material used in crystal units. Processes are *continuous* or *batch*, depending on whether the operation can or cannot be performed without interrupting material flow. An *automatic* process requires no operator attention except for loading, unloading or adjustment of the machine. A *manual* process requires continual operator attention other than standby. The *process unit* is the container in which the material is processed or the equivalent average number of quartz blanks or pieces contained (e.g., "basket" or "cartridge"). *Process time* is the time to process one blank or unit. *Machine or process capacity* is the number of blanks or units processed at one time.

Efficiency or percent utilization as used herein is the number of minutes per shift in which a machine or operator is usefully occupied (e.g., utilization in minutes divided by 480, or in hours divided by 8).

A *Station* is a group of machines or operators performing related operations on quartz.

The Stations may be divided into the following groups:

Rough Cutting:	A, (Mount Stones) to F, (Dicing).
Intermediate:	G, (X-ray and Thickness Sorting) to K, (Frequency Sorting), including Lapping (I, L, M) and Contouring (M').
Finishing:	N, (Final Etch) to U, (Packaging).

Sixteen operators are required to rough-cut 175 stones per day, for a yield of 14,900 inspected blanks. 14,600 blanks enter Primary Lap (after X-ray and Thickness Sorting), and 11,300 are delivered to Final Etch; lapped to frequency and, if required, contoured. The number of operators in Intermediate Operations is nineteen. The total shrinkage in Finishing Operations is estimated as 700 crystals or crystal units, so that 10,600 pass Frequency Check; however an additional allowance of 600 crystals is provided for defective lots in quality control. The final operations will require fifteen operators.

STATION A, MOUNT STONES AND ORIENTATION CUT

Includes Process 1, Inspect and Heat Stones
Process 2, Mount and Orient Z Axis
Process 3, X-Ray Orientation Cut.

1. Material Entering Station

175 stones averaging 250 grams each (for a total of 96.5 lbs. quartz) will enter this Station in an average day's production. The stones will be clean Grade A quartz with at least one natural face as specified in Process 1.

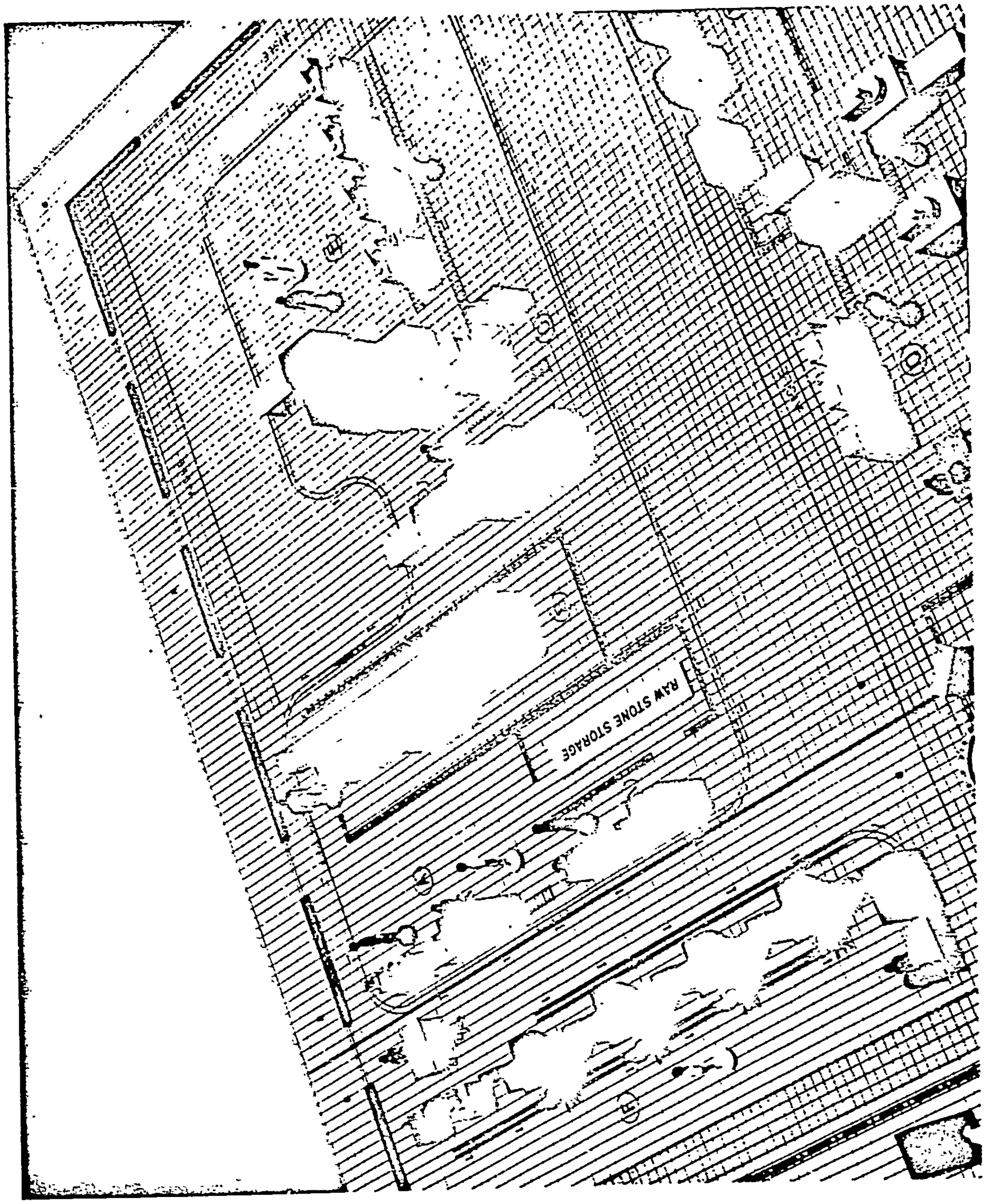
The requirement of 175 stones/day (average) to produce 200,000 crystal units per month, is based on the overall yield of the plant. Appendix V gives the estimates for each process involved.

2. Station Description

The Station is adjacent to the Raw Stone Storage area and to the Initial Etch machine. Its purpose is to mount the stones and orient them for eventual prepositioning and section sawing.

The station includes an oven, capable of reaching 155°C (311°F) and of holding at least 200 medium weight stones and 200 ceramic plates roughly 2½ x 3½ x ⅜ inch. The oven is equipped with a timer so that it will be up to temperature prior to the start of work, also with thermostatic controls, all of which suggests an electric oven of modest size. A table is provided to lay out and separate stones into large ones, suitable for cutting 0.490 inch diameter blanks, and small stones for 0.375 inch blanks. The table may be located either in the Storage area or in the Station proper, but most conveniently the former.

Next to the oven is a table of standing height, having a hot plate sufficiently large to hold three stones and plates, and having a photoelectric polariscope (light source, filters, detecting photocell and meter) built into its surface and covered with a light-shield hood open in front. A continuation of the workbench



Rough Cutting Area, Mechanized Quartz Crystal Plant Model is provided for a cooling area; this portion may include shelves to hold up to 200 mounted stones.

Separated from the cooling table, but within reach, is a plunge-cutting diamond wheel saw equipped with a special holding jig which accepts the ceramic mounting plates. Another table is located on the other side of the operator position, so that mounted stones can be taken from the cooling table, locked in the jig, cut, and placed on the second table without excessive operator motion. The table for cut stones is accessible to the operator of the initial etch machine.

A single operator will handle the work in this Station and will be allocated duties per the following table.

3. Operator Tasks

INSPECT, MOUNT, ORIENT AND X-RAY CUT
175 STONES/DAY

Operation	*Unit Time (min.)*	*Daily Total (hrs.)*
1. Inspect, separate stones, load oven	0.33	0.94
2. Remove hot stone, mount and orient	0.67	1.96
3. Cut X-ray orientation flat	1.35	3.90
	2.35	6.80
Operators required	1	
Operator efficiency	85%	

4. Quantity of Material Leaving Station

175 stones (average) per day

5. Transfer to Next Station

Cut stones are conveyed to the Initial Etch Machine.

6. Machine Specifications

a. STONES/MOUNTING PLATE PREHEAT OVEN

Purpose: To preheat stones and ceramic mounting cement plates to 155°C (315°F) and permit mounting cement application.

Requirements: Thermostatically controlled at 155°C, equipped with 24 hour timer for delayed start of heating cycle, capacity of approximately 200 stones and plates.

Visualization: A floor-mounted electric oven approximately 3 x 3 x 6 ft., equipped with shelves to separate stones and plates.

b. PHOTOELECTRIC POLARISCOPE

Purpose: To orient hot stones on ceramic plates so that the Z axis is aligned with the plate edge and the stone overhangs the plate sufficiently to allow a plunge cut and clearance for the X-ray beam in Prepositioning.

Requirements: The accuracy of the orientation means must be within ±2°. An alignment jig for the plates must be designed so that plates are easily slid in and out while hot (operator wearing gloves). The arrangement of the nulling meter and jig must be such that it is possible to observe the meter while simultaneously rotating the stone and aligning it laterally. A lateral stop for the stone must permit it to be aligned with respect to the plate edge so that it will extend a predetermined amount beyond the sawblade when finally mounted on the saw.

It must be possible to remove the oriented and aligned stone to the cooling section without disturbing the stone.

Visualization: A photoelectric polariscope has been built in accordance with U. T. C. designs, and will be used substantially unchanged. A convenient location for the meter and a lateral stop for the stone will be added, in addition to a light-shielding hood.

c. X-RAY FLAT SAW

Purpose: To cut a small flat (X-cut) on the stone preparatory to etching and X-ray orientation for sectioning.

Requirements: Rapid, rough cut of pre-oriented stone to an accuracy of ±3°.

Visualization: A plunge-cutting saw, similar or equal to the Felker type, and equipped with a heavy gauge diamond wheel, will be used. A quick-locking jig will permit rapid insertion and removal of the ceramic plate-mounted stones.

STATION A', MOUNT SECTIONS, SENSE CODE AND SAW X-RAY FLAT

This Station is adjacent to and a continuation of Station A, mount stones and saw X-ray flat. The following processes are included:

Process 10, Heat Sections and Plates
Process 11, Orient Sections for Mounting Side, Inspect for twinning
Process 12, Mount Sections, Orient AT line and Cool
Process 13, Score Sense Code and Saw X-ray Flat

1. Material Entering Station

An average of 450 sections per day will enter this station from the Initial Etch area, Station B. The sections will be conveyed in baskets or in similar loose form. An equal number of ceramic plates will enter, either new plates or recirculated from the wafering process.

2. Station Description

The Station is part of the stone mounting area, Station A, and is laid out in a similar manner. It consists of a conveyorized oven, capable of heating the sections and ceramic plates to 155°C., a work-table containing an orioscope and a photoelectric polariscope, and a cooling table. Next to the cooling table will be a gang-bladed fixed-position saw and a single-blade plunge-cut saw, beneath both of which will run a saw table equipped with clamps for the ceramic plates and a turn-table.

The incoming sections and plates will be fed separately into the oven on adjacent tracks. They will be conveyed through the oven and delivered hot to the operator's station. The sections will be picked up by the operator and examined for mounting side and twinning per Process 11, using the orioscope, and marked. One of the ceramic plates is smeared with mounting cement and transfered to the polariscope along with the section. The operator will then orient the Z-axis and locate the section on the plate, using polariscope, and transfer the assembly to the cooling table. Stones with excessive twinning, averaging 30 per day, will be rejected at this stage, leaving 420 per day to be mounted.

When cool, the sections will be picked up by the saw operator and clamped to the sliding saw table. They will pass first under the sense-code scoring saw, the table rotated 90°, and passed through the X-ray flat saw. They will then be unclamped and sent to the Initial Etch machine.

Assuming a ganged assembly of sense-code scoring and X-ray flat saw, it is estimated that approximately 0.5 minutes are required to clamp and sense-code, and another 0.5 minutes to saw X-ray flat and unclamp, or a total of 1.0 minute for the entire operation.

420 stones could be processed in 7 hours with this set-up. Thus one combined machine will be sufficient.

As an alternate the scoring and X-ray flat saws may be separated, both operating at the same time but with automatic feed. Under these conditions twice as many operations need be performed by the operator (840 clamping and 840 unloading operations). However, almost twice as much sawing time will be available, so that one saw of each type can still handle the load, even if the time to take an X-ray flat cut exceeds 0.5 minutes.

3. Operator Tasks

MOUNTING OPERATOR—INSPECT, MOUNT 450 SECTIONS/DAY

	Operation	*Unit Time (min.)*	*Daily Total (hrs.)*
1.	Unload sections, feed to oven	---	0.45
2.	Orient mounting side, inspect 450 sections	0.5	3.75
3.	Mount and orient Z-axis (420 sections)	0.4	2.8
		0.9	7.0

Operators Required 1
Operator Efficiency 87.5%

SAW OPERATOR—SENSE CODE AND SAW X-RAY FLAT, 420 SECTIONS/DAY

	Operation	*Unit Time (min.)*	*Daily Total (hrs.)*
1.	Saw sense code	0.5	3.5
2.	Saw X-ray flat	0.5	3.5
		1.0	7.0

Operators Required 1
Operator Efficiency 87.5%

4. Quantity of Material Leaving Station—Yield

420 mounted sections/day, average output.
Yield (based on sections entering) = 93.5%

5. Transfer to Next Station

The mounted sections will be placed on a mechanical conveyor, preferably in a detachable etch tray, for transfer to the Initial Etch area.

6. Machine Specifications

a. SECTION, MOUNTING PLATE PREHEAT OVEN

Purpose: to preheat sections and mounting plates to 155°C. (315°F.) and allow application of mounting cement.

Requirements: Same as Stone Preheat oven, except that it shall be conveyor fed.

Visualization: A tunnel oven, probably electrical, with a conveyor traveling through the oven and extended past the operator's position. Some means of hopper-feeding sections and plates may be included.

b. ORIOSCOPE

Purpose: to detect etch-figures and twinning of etched sections.

Requirements: Three illuminated pinholes to form etch-figures; a heat-resistant top to permit examination of hot sections.

Visualization: The pinholes should be flush-mounted in the operator's bench to eliminate unecessary manipulation of the hot sections.

c. PHOTOELECTRIC POLARISCOPE
Same as described in Station A

d. SCORING AND X-RAY FLAT SAWS

Purpose: a) to score sense-code marks on one surface of the section, approximately 1/32" wide by 1/32" deep.

b) to saw the X-ray flat from the section.

Requirements: Two saws are required, one a multi-blade saw to take a narrow scoring cut at right angles to the AT line, and the other a single-blade saw to cut the X-ray flat parallel to the AT line.

Visualization: Two saws, one a fixed-blade gang saw and the other a single-blade saw will be mounted together. A carriage and turntable, capable of 90° rotation and equipped with clamps to hold the mounted section will run beneath both saws. The scoring cuts will be made by passing the carriage underneath the first saw; the turntable rotated, and the carriage moved under the second saw where the plunge cut can be made, forming the X-ray flat. The two saws will be similar to the Felker type and equipped with diamond blades. The carriage and turntable could be power-operated, and returned, so that the operator need only inserts and remove the sections. On the return stroke of the carriage, the saw blades could also be automatically lifted so as to prevent damage to the section or equipment.

STATION B, INITIAL ETCH

Includes Process 4, Etch Mounted Stones
Process 9, Etch Unmounted Sections
Process 14, Etch Mounted Sections
Process 19, Etch Wafers

1. Material Entering Process

From Process 3: (average)	175 mounted stones/day
From Process 8: (average)	450 unmounted sections/day
From Process 13: (average)	420 mounted sections/day
From Process 18:	8,400 wafers/day (average)

2. Station Description

This work station is conceived as being a single, continuous, automatic machine which will carry out the basic operations of wash, rinse, etch, rinse and dry as specified in Processes 4 and 9. The machine will be centrally located in the rough cutting area so as to be accessible to the various processes which are followed by etching (i.e., X-ray flat saws, section saws, wafer saws). The machine will probably be located at a junction of a continuous conveyor which will connect it to all these areas, although the subject of conveyance is not covered by this report. The machine will be loaded and unloaded from one end, which will be the operator position, and will presumably be located at this conveyor terminal.

The Initial Etching Machine itself will consist of a number of tanks, containing the various solutions, the tanks being heated and thermostatically controlled where needed, and requiring no attention from the operator.

The tanks and the drying, loading and unloading stations will be connected by an internal conveyor which will have the function of carrying baskets of quartz material from one station to another, and to hold them at these stations for the proper length of time. This conveyor and the baskets, will be made of material resistant to the action of 48% HF acid; e.g., monel, copper, plastic, plastic coated steel.

The function of the operator will be to gather the various kinds of quartz and to transfer them to the Etch Machine conveyor, to remove them from the machine, and to route or carry them to the next processing area. No adjustment will be made to the machine by the operator, with one exception—the remaining adjustments being the function of maintenance personnel.

It will be noted that two etching times are specified in the referenced process descriptions, one for X-ray cuts and another for visual inspection. It is contemplated that the process time variation can be handled by means of a two-speed conveyor drive, the ratios of the two speeds being that of the total process times, or approximately 5.5 to 1. The shift from high to low speed or vice versa can be handled by the operator since it may be merely a push-button operation. The shift will take place at a time determined by the relative backlog of each kind of material to be etched.

A study of commercial types of apparatus used for similar purposes (such as electroplating) indicates that the baskets loaded into the etch machine conveyor could have the following capacities without being excessively heavy or unwieldy:

Mounted Stones and Sections — 5 per basket
Unmounted Sections — 15 per basket
Wafers — 1000 per basket

Two or more of these baskets could be processed together in each tank of the etching machine.

A particular type of automatic plating machine, the Udylite Junior Hydraulic Return Type Plating Conveyor (The Udylite Corp.) has been suggested as one which can easily be adapted to initial etching service. This machine has the following characteristics:

Rack spaces in process section (neglecting load/unload)	20
Rack size, inches	12 x 10 x 24
Process time at slow speed, hrs.	2.2 (9.1 racks/hr.)
Process time at high speed, hrs.	0.4 (53 racks/hr.)
Space between rack centers, feet	1.5
Dwell time of rack in "up" position, sec. (This can be neglected in computing the process time)	8
Overall machine size (approx.), feet	30 x 7 x 8

The number of baskets which must be processed per day, according to paragraph (1.) of this section, and the basket capacity above, is:

Mounted Stones	35
Mounted Sections	84
Unmounted Sections	30
Wafers	9

The first two items, totaling 119 baskets, or 60 racks, are to be processed at high speed. A rack will traverse the 20 rack spaces in the process section in 0.4 hrs. Assuming two baskets per rack, the time to load the mounted items is:

$$60 \times \frac{0.4}{20} = 1.2 \text{ hrs.}$$

The time required to empty the machine at high speed is 0.4 hrs.

The sections and wafers can also be processed two baskets to the rack. The time to traverse the 20 rack spaces in the process section is 2.2 hrs. Hence, the time to etch the 39 baskets (or 20 racks) at slow speed is:

$$\frac{20 \times 2.2}{20} = 2.2 \text{ hrs.}$$

and the time to empty the machine is another 2.2 hrs.

Therefore, the average time the machine is in use per day is the total of these four figures, or 6.0 hrs.

One machine is required, and the efficiency is:

$$\frac{6.0}{8.0} \times 100 \text{ or } 75\%.$$

3. Operator Tasks

The operator will be required to load and unload the machine for a total of 3.4 hrs. He will handle 119 baskets at a rate of 100 baskets per hour, approximately 35 seconds per basket, for 1.2 hrs; and the remaining 39 baskets at a slower pace of 3.4 min. per basket. During this period (2.2 hrs.) and the time during which the machine is being emptied, or is idle, the operator can be utilized in transporting or gathering material in and out of the etch Station.

4. Material Leaving Station—Yield

The same quantity will leave this Station as entered, since the quartz will be unaltered in form (see Paragraph 1).

5. Transfer to Next Station

The material removed from the etching machine may be transferred to subsequent Stations (Prepositioning or Mounting) by mechanized conveyor or by manual means.

6. Machine Specifications

a. INITIAL ETCH MACHINE

Purpose: To treat saw-cut quartz surfaces with hydrofluoric acid, together with washing, rinsing and drying operations, in order to permit X-ray or visual examination.

Requirements: Preset processing time, either 11 or 60 minutes in HF, together with temperature controls in specified stations. Completely automatic operation except for loading and unloading. Enclosed tanks and precautions to prevent contact of operators with fumes or acid.

Visualization: A series of tanks, properly controlled and enclosed, fed by a two-speed intermittent conveyor and appropriate mechanism to lower and raise basket in the various tanks. The machine will be approximately 30 feet long. A modification of a commercial automatic plating machine such as the Udylite Junior will fit these requirements.

STATION C, PREPOSITION STONES AND SECTIONS

Includes Process 5, Insert Stones in Transfer Jigs and Preposition.

Process 15, Insert Sections in Transfer Jigs and Preposition.

1. Material Entering Station

175 mounted stones per day (average) enter the station from Initial Etch, Station B. 420 mounted sections per day (average) enter this Station from Initial Etch.

2. Station Description

The prepositioning area is adjacent to the initial etch machine (Station B), and to the section and wafer sawing areas, (Stations D and E). The mounted sections and stones received will be inserted in transfer jigs (manually), and fed to an X-ray diffraction apparatus, in which the jigs will be prepositioned for sawing by measurement of the reflection from the X-ray flat saw cut.

The Station therefore, will consist of two tables or work surfaces on which the jigs and stones or jigs and sections will be assembled, means for receiving stones and sections from the etch area and for storing them temporarily, and for receiving jigs and their temporary storage. It will also include X-ray detectors to receive the X-ray beams reflected from the stones or sections at the correct angle for prepositioning, and meters to read the relative intensity of the reflected beams as the jigs are adjusted. It is envisioned that one central generator will provide the source of X-rays for the two prepositioning tables. These tables, one for stones and one for sections, will be built on either side of the X-ray tube, so that they will both be accessible to one operator. Each table will have its own collimating crystal, detector, and intensity meter, as well as the necessary fixtures (reference surfaces, turntable, etc.) to facilitate jig alignment.

The prepositioning tables will be constructed and placed with reference to the jig assembly tables so that the jigs can be slid from assembly to X-ray tables without being lifted. They will also be equipped so that the jigs can be slid from the X-ray fixture to another table or conveyor where they can be transported to the saws, also without lifting. In this way, there will be no danger of damage to the jigs or of changing the accurate settings made in the X-ray fixture.

Prepositioned jigs removed from the X-ray fixtures will be stored on a table or slowly moving conveyor, where they will be transferred to the section saw (in the case of stones) or wafering saws (for the sections).

3. Operator Tasks

The duties of the prepositioning operator can be summarized in the following table:

X-RAY PREPOSITIONING OPERATOR TASKS

Operation	*Stones* (Sec.)	*Sections* (Sec.)
1. Select mounted quartz and jigs, assemble together.	10	10
2. Transfer to X-ray fixture and secure in measuring position.	5	5
3. Make first adjustment and maximize meter reading	12	15
4. Make second adjustment, maximize reading and recheck first adjustment	18	--
5. Transfer to assembled jig storage or conveyor	5	5
Total time	50 sec.	35 sec.

Time spent on stones per day: $\frac{50 \times 175}{3600} = 2.43$ hrs.

Time spent on section per day $\frac{35 \times 420}{3600} = 4.08$ hrs.

Total prepositioning time per day 6.51 hrs.

Operators required 1

Operator efficiency 81%

No time is required to change over from prepositioning stones to sections, since both X-ray fixtures will be available for use at all times.

The time required to change from one ZZ′ angle to another (in prepositioning sections) is neglected, since this will probably not be the task of the operator. Furthermore, work flow can be scheduled so that only a few changes in wafering angle will be made per day.

4. Quantity of Material Leaving Station

175 prepositioning stone jigs and 420 prepositioned section jigs will leave per day.

5. Transfer To Next Station

Jigs will be transferred by mechanical conveyor to the wafering and section areas.

6. Machine Specifications

a. X-RAY PREPOSITIONING FIXTURES

Purpose: To provide a collimated X-ray beam system to accurately align quartz stones and sections to predetermined angles by means of reflection from appropriate atomic planes.

Requirements: The system is required to align the X-axis of stones to ±5′ with respect to a reference surface on the fixture, and to align the ZZ′ axis of sections to within ±1′. The X-axis adjustments must be made in two perpendicular directions. The time to make a single adjustment shall be in the vicinity of 15 seconds.

Visualization: The machine will consist of five major functional divisions, the X-ray generator, a prepositioning fixture for stones and one for sections, and the interchangeable transfer jigs for stones and for sections.

The X-ray generator will be of conventional design, similar to commercial units, modified as required with special power supply filters or other means needed to improve the accuracy of the system. The X-ray machine will generate two beams which shall impinge on crystals, one on each prepositioning table, for further collimation.

The stone prepositioning table will have a means of holding the stone jig against a reference table, mechanisms to raise the table so that the X-ray flat cut on the stone will contact a beam locating pointer and means for detecting the intensity of the reflected beam. It shall also include chutes or other means of sliding the jigs on and off the table. The detector output will be a meter, and if required, an alarm to signal passing of the peak of intensity or to cut off motors activating the jig adjusting screws if the jig adjustments are motorized.

The stone prepositioning table will be capable of rotating the stone 90° so that two orthogonal adjustments may be made.

Stations C—D

The section prepositioning table shall be similar to the stone table, except that it will be equipped to hold and adjust section jigs, and that only one adjustment position need be provided. However, this table shall be capable of being preset to adjust the jigs for at least six different ZZ' angles (by offsetting the prepositioning table with respect to the beam) and of being changed from one angle to another.

The jigs shall be capable of clamping the stone or section mounting plates by means of a single rapid motion. The stone jigs shall have two adjustments at right angles to each other (with respect to a fixed reference point) and the section jigs shall have one adjustment. These adjustments will be capable of fine motion with respect to the required accuracy (one or five minutes of arc) without sacrificing the required speed of adjustment (15 seconds maximum).

STATION D, SAW SECTIONS FROM STONES

Includes Process 6, Saw X-sections
Process 7, Remove Plates and Degrease Transfer Jigs
Process 8, Separate Sections

1. Material Entering Station

The incoming material consists of mounted quartz stones, averaging 250g., assembled to transfer jigs, which have been prepositioned so as to adjust the stone X-axis within ±5' of a reference surface defined by the jig feet. 175 stones per day will be processed on the average.

2. Station Description

The Station consists of a storage area, into which the prepositioned stone jigs are conveyed and accumulated; a sectioning saw equipped with ganged blades in which the stones are cut into sections in one pass; a short conveying section in which the sections, still cemented to ceramic plates, are removed from the transfer jigs; a degreaser in which the jigs are cleaned before being returned to the Prepositioning Station (C); a special degreaser in which the cement binding the sections to the plates is dissolved; and an area in which the plates are separated from the sections and the latter accumulated for initial etch.

The prepositioned transfer jigs are accumulated on a table or slowly moving conveyor terminating in a storage section adjacent to the sectioning saw. The saw may be a P. R. Hoffman Sectioning Saw equipped with a moving table which passes laterally beneath a set of five ganged blades. The table is locked in the rearward position and is located with respect to the jig storage or conveyor so that a prepositioned jig can be slid onto the table. The table has a vertical reference surface against which the transfer jig presses when it is clamped to the table. When the saw operator has secured the jig, a push-button operation starts the saw drive and the operator releases the table, which is gravity-fed, into the saw blades. At the end of the table travel the saw drive automatically cuts off and the jig can be unclamped and slid onto another storage table.

The operator will return the saw table to the starting position (manually or by a push-button operation) and start sectioning another stone. During the saw-cut (approximately 2 minutes) the operator can disassemble the sectioned stone from the transfer jig and place the latter in a continuous or batch type trichloroethylene degreaser, which removes lubricant and quartz dust from the jig. He will also place the sectioned stones in another degreaser for the purpose of loosening or dissolving the cement which holds them to the ceramic plates.

The second degreaser contains warmed denatured alcohol which serves as a solvent for the mounting cement. The sections must remain in this bath for about one hour.

Also during the section sawing time, the operator will have time to remove degreased jigs and to place them on a conveyor which returns them to the Prepositioning Station, and to remove plates and sections from the separating tank and place them on a conveyor which transfers them to the Mounting and Initial Etch Stations, respectively. The layout of the Station, including mechanical conveyors, must be such that all these operations can be performed by one person.

SECTION SAW:

Load/unload time per stone	0.4 min.
Sawing time per stone	2.0 min.
Total	2.4 min.

$$\text{Average utilization} = \frac{175 \times 2.4}{60} = 7.0 \text{ hrs/day}$$

No. of saws required	1
Efficiency	87.5%

JIG DEGREASER:

The jig degreaser will be mechanized to the extent that it can be loaded and unloaded from one position, and that it requires no other attendance.

Jigs handled per day	175
Output, jigs per hour	25
Average utilization	7.0 hrs/day
No. degreasers	1
Efficiency	87.5%

SECTION SEPARATOR:

The separator may be either a continuous or batch device. In its simplest form it will be a tank holding 25 mounted stones, which may be hand-loaded and unloaded.

Process time	1.0 hr.
Stones per day	175 (450 sections)
Capacity, stones	25
Output, stones per hr.	25
Time utilized per day	7.0 hr.
No. machines required	1
Efficiency	87.5%

3. Operator Tasks

	(per stone)
Load/unload saw	0.4 min.
Disassemble jig and stone	0.2
Load/unload jig into degreaser	0.2
Load stone into separator	0.1
Remove, separate sections, plates, scrap	1.5
Total	2.4

$$\text{Total utilization} = \frac{175 \times 2.4}{60} = 7.0 \text{ hrs.}$$

No. Operators required	1
Efficiency	87.5%

4. Quantity of Material Leaving Station—Yield

The yield of this Station is approximately 2.6 sections per stone (63% based on weight of quartz entering). The output is 450 sections (separated). In addition, 175 jigs (degreased) and 175 ceramic plates will be transferred per day.

5. Transfer to Next Station

The sections will be stored in trays capable of entering the Initial Etch machine, and transferred to the Initial Etch Station by mechanical conveyor. Ceramic plates will be similarly conveyed to the mounting area (Station A′) or will be accumulated and manually transferred to that Station. Jigs will be mechanically conveyed back to the Prepositioning Station.

6. Machine Specifications

a. SECTION SAW

Purpose: to saw X-sections from stones.

Requirements: Automatic operation, except for loading and unloading. Angular accuracy, with respect to reference surface on table, of ± 10′. Thickness spread of ± .005″. (3 sigma on both specifications). Ability to gang-saw with up to five blades, and to change sets of blades in approximately 15 minutes. Section sawing time averaging not more than two minutes for 250 gram stones. Modifications to permit loading and unloading of special positioning jigs from conveyors without lifting jigs.

Visualization: The P. R. Hoffman section saw, equipped with ganged diamond blades on a removable arbor will essentially meet or exceed the specifications for accuracy. Additional mechanization of table travel and of loading means will meet our requirements.

b. JIG DEGREASER AND SECTION SEPARATOR

(These have been described in the above text.)

STATION E, SAW WAFERS FROM SECTIONS

Includes Process 16, Saw Wafers from Sections
Process 17, Remove Plates and Degrease Transfer Jigs
Process 18, Separate Wafers from Plates

1. Material Entering Station

An average of 420 sections per day enter this station. They are cemented to ceramic plates, and assembled to transfer jigs which have been prepositioned to within ±1′ of the desired ZZ′ angle. There are two thicknesses of sections which may enter, and three different ZZ′ angles associated with each thickness.

2. Station Description

The Station will be located next to the X-ray Prepositioning Station (C), and will be connected to it by means of a mechanical conveyor.

The Station will consist of a number of wafering saws, arranged in a line so as to be accessible to a conveyor carrying the prepositioned jigs at a height the same as that of the wafering saw tables. The operator should be able to slide jigs into any of the saws from the conveyor without the need for lifting them.

The sawn sections will be discharged from the opposite side of the saws onto another conveyor, which will carry the jigs to a degreasing area. An operator will remove the sawn sections from the jigs and place the jigs in a conveyorized degreaser, where they will be cleaned and discharged automatically and conveyed back to Station C. The mounted sections, now cut into wafers, will be placed in a separation tank, containing denatured ethyl alcohol, which will be similar to that described in Station D. The solvent will dissolve the cement holding the quartz to the ceramic plate in approximately one hour, after which the material may be removed and the plates separated from wafers and scrap by the operator. Wafers will be stacked in trays holding approximately 1000 wafers, and conveyed to the Initial Etch Station (B). Scrap quartz will be discarded, and ceramic plates will be conveyed to one of the mounting Stations (A) or (A′) or retained in temporary storage until picked up. The efficiency and manpower requirement of this Station depends greatly on the layout and material handling facilities.

WAFERING SAWS:

	(Per Section)
Load/Unload time	0.4 min.
Wafering time	3.1
Total	3.5 min.

$$\text{Total machine utilization} = \frac{420 \times 3.5}{60} = 24.5 \text{ hrs./day}$$

Station E

No. machines required	4
Average machine utilization	6.1 hrs./day
Machine efficiency	77%

JIG DEGREASER:

Average jigs degreased per day	420
Output, rate, per hour	60
Utilization	7 hrs.
No. required	1
Machine efficiency	87.5%

SEPARATOR:

This machine may be a batch type or continuous output (mechanized). A batch type will be assumed.

Avg. sections input per day	420
Process time	1 hr.
Capacity of machine (batch)	60 sections
Average utilization	7 hours/day
No. required	1
Machine efficiency	87.5%

3. Operator Tasks

SAW OPERATOR:

	(Per Section)
Load/Unload time	0.4 min.
Travel between saws	0.27
Idle time (during sawing)	0.2
	0.87 min.

$$\text{Average utilization} = \frac{420 \times 8.7}{60} = 6.1 \text{ hrs}$$

No. operators required	1
Operator efficiency	77%

DEGREASER-SEPARATOR OPERATOR:

	(Per Section)
Separates plates from jigs	0.2 min.
Inserts jigs into degreaser	0.2 min.
Loads sections into separator	0.1 min.
Removes and separates wafers, plates, scrap	0.5 min.
Total	1.0 min.

$$\text{Average utilization} = \frac{420 \times 1}{60} = 7.0 \text{ hrs.}$$

No. operators	1
Operator efficiency	87.5%

4. Material Leaving Station—Yield

An average of 20 wafers will be obtained from each station, hence the number of items leaving the station is:

1. Wafers	8,400	(9 trays)
2. Ceramic plates	420	
3. Jigs (degreased)	420	

5. Transfer to Next Station

Items 1. and 2. may be conveyed to Stations B and A respectively by mechanical conveyor or by manual pick-up, depending on the desirability of continuous flow or temporary storage of these items. Item 3. will be mechanically conveyed to Station C (Prepositioning).

6. Machine Specifications

a. WAFERING SAW

Purpose: To cut AT wafers from X-sections.

Requirements: Completely automatic operation except for loading and unloading. Angular accuracy (with respect to reference bar on table) of approximately 2.5′ (3 sigma) and a thickness accuracy of 0.003″ (3 sigma) on wafers produced. Capability of producing 22 or more wafers in one pass by means of ganged blades. Ability to change and realign sets of blades (arbors) within 15 minutes in order to change thickness of wafers produced. Average sawing rate on 60 gram X sections not to exceed 3.1 minutes. To be equipped with clamping devices or other means to permit transfer jigs to be inserted and aligned within the overall accuracy requirement and removed from the saw table in 0.4 minutes total.

Visualization: The accuracy and mechanization requirements have been met by the P. R. Hoffman wafering saw, and it is visualized that this equipment, modified to the requirements of materials handling cited, will be used in the plant.

b. JIG DEGREASER

Purpose: To degrease and clean jigs utilized for wafering.

Requirements: Unattended operation, including loading, but may be manually loaded. Capacity of 60 jigs per hour for an 8 hour day.

Visualization: A commercial type of trichloroethylene degreaser with the addition of automatic unloading and internal conveying features.

c. WAFER SEPARATOR

Purpose: To dissolve the cement holding the sawn wafers to the ceramic mounting plates.

Requirements: Output of 60 sections per hour with a holding time of one hour in a warm solvent bath (alcohol).

Visualization: A batch device similar to that of Station D, but with a capacity of at least 60 mounted sections.

STATION F, DICE WAFERS

Includes Process 20, Inspect and Layout Wafers
Process 21, Mount Wafers
Process 22, Ultrasonic Dicing
Process 23, Dewax Blanks
Process 24, Inspect Blanks
Process 25, Load Blanks into Cartridges

1. Material Entering Station

A daily average of 8400 wafers will enter this station from Station B (Initial Etch). They will be conveyed in baskets or trays as received from the etching machine, approximately 1000 wafers per tray.

2. Station Description

The station includes three sub-areas; wafer inspection and mounting, dicing, and blank separation and inspection.

a. The wafer inspection and layout of defective areas is a manual operation, and will be carried out at a table equipped with lighting and marking facilities for two operators. If the wafers are mechanically conveyed from the etching machine, the operators will be seated at a position convenient to the conveyor, but in view of the small number of wafer trays per day, it may be feasible to transport them by hand and to seat the operators in any convenient location.

The inspection positions will be equipped with a simple jig in which the undefective wafer area can be compared with the position which the wafering tool will occupy in the dicer. Two such jigs will be needed at each position, one for large wafers (0.490" blanks) and the other for small wafers (0.375" blanks).

Of the 8400 wafers coming into wafer inspection approximately 1000 will be rejected as undersized or for having too much twinned area. (See Process 20).

b. The wafer mounting section will be immediately adjacent to the inspection and layout bench and will consist of two machines which will automatically perform the mounting operation. Generally, one machine will mount large wafers and the other small wafers, however both will be able to handle either size with only minor adjustments. As presently envisioned, wafers will be fed directly to the mounting machines by conveyors from the inspecting tables—alternately they could be loaded into hoppers and fed from them. In the former case the wafers can be placed on the conveyor with the correct mounting orientation (direction of the scored edge), or the scored edge can be used to mechanically align the wafer. The glass plates will most likely be fed from a hopper, since they must be inspected to see if they are still usable (used less than four times), and also must be fed into the machine with the unused side and edge properly oriented. The machines will heat the wafers and plates, apply wax, and feed the wafer to the waxed plate, after which the mounted wafers will pass through a cooling section and be conveyed to the dicing machines.

The mounting machines will process twelve blanks per minute. The average utilization of machine time is, therefore (per day)

$$\frac{7400}{12 \times 60} = 10.3 \text{ hrs.}$$

requiring two machines.

$$\text{Machine efficiency is } \frac{10.3}{2 \times 8} \times 100 = 65\%$$

c. The dicing machines will be located in a line fed by a mechanical conveyor from the mounting machines. Each machine will be serviced by an operator who will select mounted wafers from the conveyor and insert them into the first position of the machine (wafer alignment jig). The wafers will be diced by means of an ultrasonic-powered tool and ejected automatically.

The time to dice a wafer will average 11 seconds, according to present indications. The ultrasonic tool must be changed every 500 wafers and it will require approximately 15 minutes of machine down-time for the change. For an average day's production of 7400 wafers, the number of tool changes is hence:

$$\frac{7400}{500} = 15 \text{ (Approx.)}$$

The total machine time required per day is then:

$$\frac{7400}{60} + 15 \times 15 = 1585 \text{ minutes or } 26.4 \text{ hours.}$$

$$\text{Number of machines required} = \frac{26.4}{8} = 3.3, \text{ say } 4.$$

$$\text{Machine efficiency} = \frac{26.4}{4 \times 8} = 82.5\%.$$

Thus, the average time used per day per machine is 6.6 hours.

d. Diced wafers are ejected from the dicing machines and are conveyed to a continuous automatic dewaxing tank, containing a solvent such as trichloroethylene. In order to eliminate the need to transfer the glass plate-mounted wafers in and out of the dewaxing tank the operation must be continuous, and the throughput rate must equal the production rate of the four dicers. Hence the machine must be able to dewax in excess of 1120 blanks per hour. If used an average of 6.6 hours per day (equal to the dicing time) the machine efficiency is also 82.5%.

The dewaxing machine will be considered as completely automatic and will hence require no operator attention.

Station F

e. The dewaxing tank conveyor will eject a mixture of good and poor blanks, quartz scrap, and glass plates onto a belt passing through a blank inspection station. An operator will select good (unmarked) blanks and divert them to a cartridge loading station, which may be at the terminus of another conveyor belt. The remaining material will pass over a screening section where the rejected blanks and scrap will be segregated, leaving the glass plates. These will be conveyed directly or through an intermediate storage back to the mounting machines.

The total number of blanks entering this inspection position per day will be 18,500 on the average. The number of good blanks sorted out will average 14,900 per day.

f. Sorted blanks will be fed to a vibratory hopper which will load them into cartridges, with an average of 100 blanks per cartridge. Such a machine can load blanks at the rate of 120 per minute. Hence 50 seconds will suffice to fill a cartridge. The total number of cartridges loaded per day is 149, and the average loading time per day is $\frac{149 \times 50}{3600} = 2.1$ hrs.

However, two machines will probably be required since the construction of the hopper will be different for the two blank sizes, 0.490" and 0.375". Since the two sizes of blanks are roughly equal in numbers (see Order Board, Appendix I), the loading time for each machine will be approximately 1.1 hrs. per day.

Table F-1

SUMMARY OF MACHINE REQUIREMENTS, STATION F

Operation	*Input (Wafers/day)*	*Machine Rate (Wafers/min.)*	*No. Machines*	*Efficiency*
Wafer Mounting	7400	12	2	65%
Ultrasonic Dicing	7400	5.5	4	82.5%
Dewaxing	7400	19 approx.	1	82.5%
Cartridge Loading	(14,500 blanks)	(120 blanks)	2	13%

3. Operator Tasks

a. INSPECTION AND LAYOUT OF WAFERS

No. of wafers processed per day	8400
Inspection and Layout rate	10 per min. per operator
Total inspection time	$= \frac{8400}{10 \times 60} = 14$ hrs. per day
No. operators required	2
Operator efficiency	87.5%

b. WAFER MOUNTING OPERATOR

Machine operating time (2 machines)	5.2 hrs. per day
Sorting/loading glass plates (7400/day at rate of 60/min)	2.1 hrs.
Total time	7.3 hrs. per day
No. operators required	1
Operator efficiency	90%

c. DICING OPERATORS

Machine operating time (4 machines)	22.7 hrs. per day
Standby for tool change	3.8 hrs.
Total time	25.5 hrs. per day
No. operators required	4
Operator efficiency	83%

d. BLANK INSPECTOR

Blanks inspected per day	= 7400 x 2.5 = 18,500
Sorting rate	1 sec. per blank
Total sorting time	$= \frac{18,500}{3000} = 5.2$ hrs.
Cartridge loading time (2 machines) =	1.1
Total time	6.3 hrs. per day
No. operators	1
Operator efficiency	79%

Table F-2

SUMMARY OF OPERATOR REQUIREMENT, STATION F

Operation	*No. Operators*	*Efficiency*
1. Inspection/layout	2	87.5%
2. Wafer mounting	1	91
3. Dicing	4	83
4. Blank inspection	1	79
Total	8	

4. Material Leaving Station—Yield

The number of blanks passing inspection per day = 14,900. (The yield of good blanks is approximately 80% based on total blanks diced, or 2 blanks per diced wafer.)

5. Transfer To Next Station

The blanks are sent to the next Station, X-ray and Thickness Sorting, loaded into cartridges averaging 100 blanks each. The daily output is approximately 150 cartridges per day. These can be easily conveyed manually.

6. Machine Specifications

a. WAFER MOUNTING MACHINE

Purpose: to mount wafers on glass plates.

Requirements: The machine will heat glass plates and wafers and apply a film of wax, position wafers on the plates, and eject the mounted assembly at a minimum rate of 12 per minute.

Visualization: The machine will consist of a magazine in which glass plates will be manually loaded and oriented, a means of heating the plates and feeding them under a wax-film applicator, a conveyor to transport inspected and heated wafers, and an assembly section where the plates and wafers are positioned and joined together. This section will be followed by a storage conveyor in which the plates are cooled before being transported to the dicers.

b. ULTRASONIC DICER

Purpose: to dice round blanks (with an orientation flat) from quartz wafers.

Requirements: The machine will be manually loaded with wafers mounted on glass plates, and will be required to dice at least four round blanks with an orientation flat from the wafers. The accuracy of the machine must be such that the orientation flat of each blank is parallel to the alignment edge (unscored) of the original wafer with a total error not exceeding ±15′. The machine must automatically perform the dicing operation on signal from the operator and eject the mounted blanks in a cycle time not exceeding 11 seconds. A means of permitting the operator to judge the position of the best blank yield must also be provided. The design of the tool and generator must insure economical tool life. The tuning of the machine to resonance must be sufficiently stable to obviate frequent re-tuning.

Visualization: The machine as presently conceived will include the following features:

A 4-position rotary index table with a precision of .001″ (equivalent to ±1 minute of arc at the cutting position). The table will index 90 degrees in one second with pneumatic power actuation and electrical control. The unit will be equipped with a Skip-Hydro-check unit for cushioning.

The four positions will be utilized as follows:

Position (a) — Load and preposition glass-mounted wafer, and clamp in position.

Position (b) — Dice blanks using Cavitron transducer head and multiple tools.

Position (c) — Eject glass plate with diced blanks.

Position (d) — Wash work position.

The above operations all occur simultaneously.

At the loading position (a), the operator will be aided in positioning the wafer by two fixed contact points which permit the wafer to be positioned accurately in angle. An optical template locates the relative tool position, so that the wafer can also be shifted laterally for the best yield.

The ultrasonic tools at position (b) will dice 4 or 5 blanks (with the required flat) from the wafer. The tool will be lowered, slurry will be fed to the work piece, blanks will be diced, and retraction of the tool will take place automatically. The time to dice a quartz wafer of average thickness will be between 10 and 11 seconds. This will establish the cycle time. In the next position (c), the diced wafer on its glass plate will be ejected onto a conveyor. In the fourth station, the prepositioning clamp will be scrubbed and washed to remove slurry particles.

Actual operation of a test model of this apparatus has shown that an operator with a few day's training is capable of holding the overall angular error to approximately 5′, which betters the target specifications.

c. DEWAXER

Purpose: to remove the wax bond holding the diced blanks to the glass plate.

Requirements: The machine must process at least 19 glass plates per minute without attendance by an operator. It must be capable of being conveyor-fed and to eject its output on a conveyor, without the requirement of operator loading or unloading time. The solvent must completely dewax and degrease the glass plates and quartz without removing the paint or ink used to mark defects. The material must be processed through the machine with no damage to the quartz blanks.

Visualization: A degreaser of conventional design, using liquid trichloroethylene, should be capable of performing this task. The machine will be conveyorized and continuously operating, with provisions for transfer of material to other conveyors on input and output ends.

d. CARTRIDGE LOADER

Purpose: To load blanks into special rigid plastic cartridges (open on one end).

Requirements: The machine must load blanks at the rate of 50 per minute or better. It must be so designed as to make rapid interchange of cartridges possible.

Visualization: A vibrating hopper or parts-feeding device will handle one size of blank at a time at the required rate. A cartridge holder is readily added. Another possibility is a simple feeding chute at the end of a transport belt, since the blanks to be loaded may already be separated on such a conveyor.

STATION G., ZZ' ANGLE (X-RAY) AND THICKNESS SORTING

Includes Process 26, X-Ray Sorting
Process 27, Thickness Sorting

1. Material Entering Station

An average of 14,900 diced blanks per day will be received from Station F, Ultrasonic Dicing. These will be cleaned, and loaded in plastic cartridges, of which there will be between 150 and 200 per day on the average.

2. Station Description

The Station will consist of two sorters, X-ray and Thickness, including the associated electronic racks. It will be located in some convenient area between the diced blank inspection loading table and the sorted blank storage area.

The working positions of the sorters are desk-type consoles at which the operators are seated. Cartridges containing unsorted blanks will be delivered to the X-ray Sorter operator in racks conveniently placed. When blanks of either 0.490" or 0.375" diameter are available in sufficient quantities, the machine will be set to take the appropriate size and the cartridges inserted into the machine.

The blanks will be sorted automatically, falling into similar cartridges at the output of the console. A random batch of blanks of either diameter will be sorted into increments of ZZ' angle, each increment having a spread of three minutes of arc. When the cartridges of any output increment are filled, as can be observed by the operator through the transparent plastic case, the cartridge can be removed and an empty one substituted without stopping the machine. When the input cartridge has been emptied, it can be rapidly replaced by a full one.

The output cartridges containing the angle-sorted blanks will be kept in order of angle increment and passed to the thickness sorter operator, seated at a similar type of console.

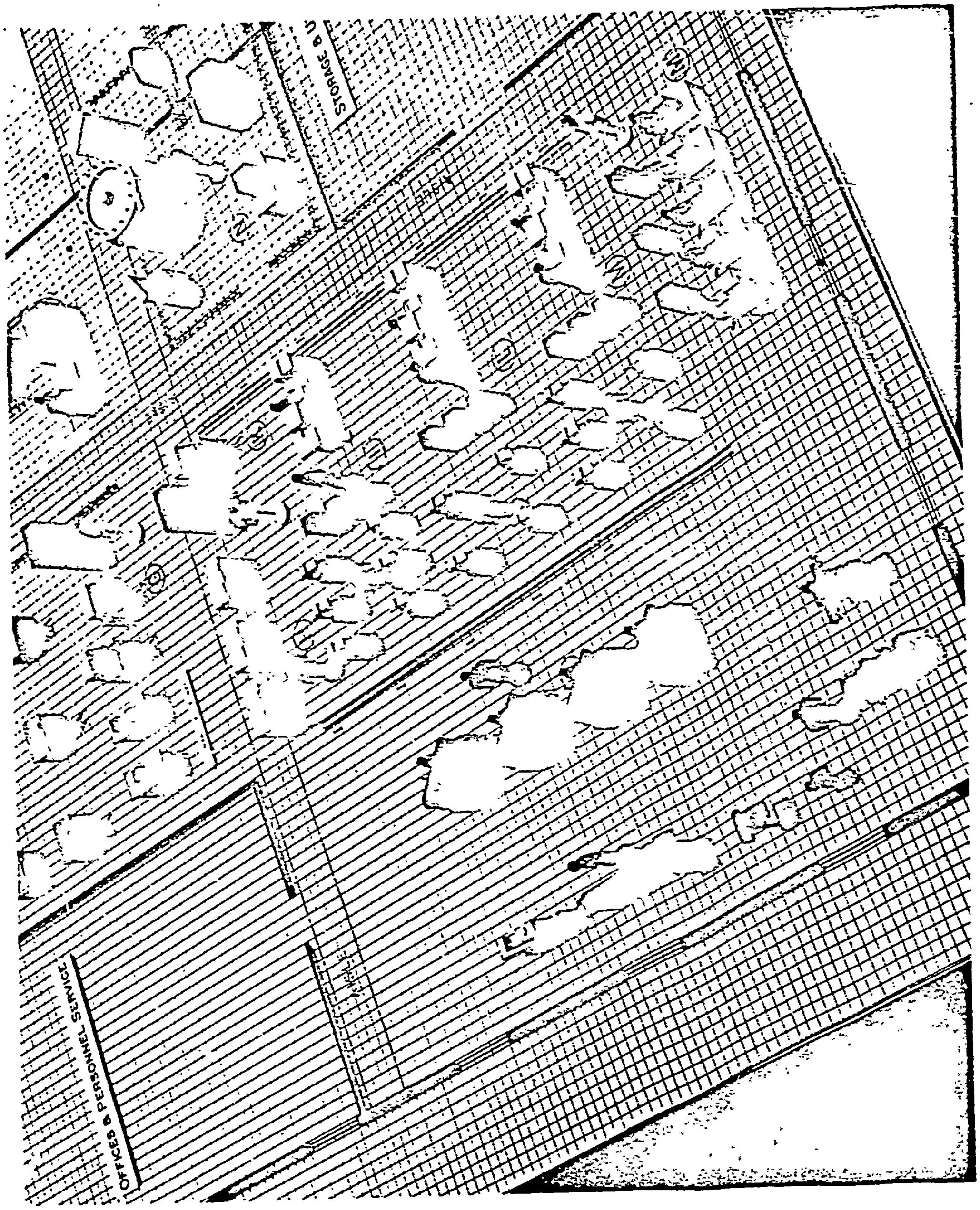
The thickness sorter will be capable of being set to handle at least three ranges of thickness, each range corresponding to one or more of the angle increments. When a sufficient number of blanks in any range is accumulated, the machine may be set to sort that range. The thickness sorter operator will then proceed to sort the blanks in the same way as the X-ray sorter operator. Two of the preset ranges of the sorter will cover a thickness spread of .006", either from .022" to .028" or from .030" to .036". The remaining range will cover .026" to .036" or a spread of .010". (See Process No. 27.) The machine will sort the .006" spread inputs into four output increments, each having a spread of .002", and the inputs of .010" spread will be sorted into eight outputs, also having a spread of .002".

Altogether, there will be 55 types of output cartridges, apart from rejected categories. A system shall be provided for the thickness sorter operator to keep the full output cartridges arranged in the proper order as they are removed from the sorter. The various outputs, now sorted into ZZ' angle increments of 3' and thickness increments of .002", will be sent to a storage area as accumulated. Each of the 55 increments is suitable for producing a specific frequency range of CR-23/U or CR-18/U crystals, and they may be so labeled in the storage area.

The speed of the X-ray sorting machine is 43 blanks per minute. Hence 14,900 blanks (average daily input) can be sorted in 347 minutes. The input will be contained in 150 or 200 cartridges, depending on the height to which they are filled in the prior operation. Assuming the larger number, and allowing 15 seconds to select and replace the cartridge, another 50 minutes will be added for a total of 397 minutes per day. Hence one X-ray sorter will suffice for the entire plant production. The thickness sorters will operate at the rate of 40 blanks per minute. Approximately 200 blanks per day will be rejected in the X-ray sorter so that an average of 14,700 will be delivered to the thickness sorter. 368 minutes plus another 50 minutes for input cartridge replacement, or a total of 418 minutes will be required to sort these. One thickness sorter will be required.

3. Operator Tasks

The two sorter operators will be required to observe their machines while they are operating and to change input and output cartridges. The time consumed will be equal to the machine time. Hence one operator will be required to supervise each machine, or



Intermediate Operations, Mechanized Quartz Crystal Plant Model

a total of two for the Station. Changing machine settings will be presumed to be the task of the maintenance personnel, and pickup of sorted cartridges will be handled by storage room personnel. Hence these tasks will not be charged to the sorter operators or deducted from the available machine time.

Summary:

		Min./day
X-ray Sorter	Machine time (1 sorter)	397
	Operator time (1 operator)	397
Thickness Sorter	Machine Time (1 sorter)	418
	Operator Time (1 operator)	418
X-ray Sorter and operator efficiency		83%
Thickness Sorter and operator efficiency		87%

4. Quantity of Material Leaving Station

14,600 sorted blanks will leave per day, packaged in approximately 150 cartridges.

200 blanks per day are rejected in X-ray sorting.

100 blanks per day are rejected in thickness sorting.

5. Machine Specifications

a. X-RAY SORTER

Purpose: To sort quartz blanks (round with an orientation flat) into increments of ZZ' angle not exceeding 3' spread.

Requirements: A range of at least 35° 10' to 35° 30' (20 minutes of arc), speed of 43 blanks per minute (either 0.375" or 0.490" diam.), increment width adjustable to 2 minutes of arc. Precision of measurement approximately equal to 10 seconds of arc (one sigma), assuming an error of up to 30' on flat orientation. (see Appendix 26-3.) Ability to handle blanks in and out of special blank cartridges.

Visualization: The X-Ray Sorter developed under this contract meets these specifications.

b. THICKNESS SORTER

Purpose: To sort quartz blanks into increments of .002".

Requirements: There is a wide range of specifications which will meet the requirements, depending on the number of increments or accuracy desired. Only one is specified here. Range of .002" to .036" in no more than three settings. Precision of measurement of 125 micro-inches (one sigma), giving an output range of .002" in each increment. (See Process 27.) Ability to sort into not less than eight increments of nominal width .000125", plus two reject categories. Speed of 40 blanks per minute, and ability to sort either 0.375" or 0.490" blanks (but not simultaneously).

Visualization: The external appearance and handling mechanism of the sorter will be similar to the X-Ray Sorter console. The machine may have specifications similar to the above, except that accuracy may be traded for number of increments or spread (see above). A photoelectric, air gage, electro-mechanical (e.g. differential transformer probe) radiation or other conventional measuring system will be able to accomplish this task.

STATION H, LOAD LAP CARRIERS

Includes Processes 28, 33, 38, Load Lap Carriers

1. Material Entering Station

The incoming material is drawn from the Sorted Blank Storage Area and from Station J, Frequency Sorting, and consists of blanks stored in plastic cartridges. The average quantity of blanks and corresponding cartridges entering each day are as follows:

Table H-1

From	*Blanks*	*Cartridges*	*To*
Sorted Blank Storage	14,600	146	Primary Lap
Frequency Sorting (after Primary Lap)	13,400	74	Secondary Lap
Frequency Sorting (after Secondary Lap)	12,300	66	Final Lap
Totals	40,300	286	

2. Station Description

In this Station, quartz crystal blanks which are to be lapped to frequency in any of the three lapping stages are first loaded into lap carriers, as the carriers (rather than the small, fragile blanks) are more easily handled and inserted into the lapping machines.

The lap carriers are thin metal plates containing three or four holes (into which, respectively, 0.490 or 0.375 inch diam. blanks fit loosely) and equipped around their circumference with teeth meshing with the lapping machine planetary gears. In this Station, the blanks which have been previously sorted into plastic cartridges are removed from them one by one, inserted into the holes in the carriers, and fixed in place with a thin film of soluble cement. After the film dries, the carriers can be easily handled, stacked in accordance with job order, and delivered to the appropriate lapping stage.

Basically, the Station as presently envisioned consists of three machines to perform the above loading tasks automatically, together with the necessary racks and facilities for temporary storage of cartridges and carriers. A single operator will be required to set up and supervise the machines, insert cartridges, and to keep separate and deliver the output to the correct lapping substations. During the loading cycle, however, the blanks will be handled from cartridge to carrier without need for operator attention.

The Station will be located adjacent to the Frequency Sorter, and in the vicinity of the three lapping stations.

From the Yield Table (see Appendix V) and the discussion of Frequency Sorting (Station J), the number of blanks and cartridges to be processed in an average day's production are in accordance with Table H-1 (above). Carriers for .375" blanks have four holes and those for .490" blanks have three holes. Using the quantities stated in the Order Board for a monthly production of 200,000 crystals (45.8% with a diameter of 0.375 in. and 54.2 of 0.490 in.) the average number of blanks and cartridges to be processed in an average of carriers to be filled per day is:

$$\frac{40,300}{3.46} = 11,650 \text{ carriers.}$$

A practical machine to perform the tasks outlined will operate at the rate of one carrier per 5 seconds or 12 per minute. The active loading time of the machine would then be:

$$\frac{11,650}{12} = 970 \text{ minutes.}$$

In addition, some dead time must be allowed from the time a cartridge is emptied to the time when it is replaced by a full one. At ten seconds per cartridge, the dead time from this cause would be

$$285 \times \frac{10}{60} = 48 \text{ minutes (approx.)}$$

Although the machine contemplated would be able to load either three blank (0.490) or four blank (0.375) carriers, the change-over from one type to another would require some adjustment time. This time can be minimized by so scheduling work as to load all of one type for a day's production at one time, before switching to the other type. This implies a certain amount of backlog (averaging one-half day's production), but is consistent with the operation of other stations, principally Frequency Sorting (Station K).

The total machine time required is then 970 + 48 = 1018 minutes per day and the theoretical number of machines required:

$$\frac{1018}{480} = 2.1$$

With three machines, each will have an efficiency of 70%.

3. Operator Tasks

A single operator will be able to tend three of these machines, since the only direct time required is the 48 minutes of cartridge loading time. The remainder of the operator's time would be spent picking up empty carriers from the lapping stations, inspecting them and feeding to the machine; delivering loaded carriers to the lapping station operators, together with similar tasks relating to the handling and distribution of blanks to be lapped.

Hence, his productive time can be taken as 420 minutes per day and his efficiency 88%.

4. Material Leaving Station—Yield

With proper machine design, there should be no breakage of blanks, hence the yield is 100%.

The average number of lap carriers delivered to each lapping stage per day is as follows:

To Primary Lap	4220
To Secondary Lap	3870
To Final Lap	3560
Total	11,650

5. Transfer to Next Station

Stacked carriers arranged in sequence of orders and by machine load (16 carriers) and properly identified as to lapping stage and order, could be delivered by any convenient means, such as hand-truck or conveyor. Tote boxes or special fixtures to hold stacks of 16 carriers together with identification means are envisioned. These may well incorporate features so as to make them an aid to loading the lapping machines, analogous to the plastic blank cartridges used throughout the plant.

6. Machine Specifications

a. CARRIER LOADING MACHINE:

Purpose: Remove blanks from cartridges and load them into lap carriers.

Requirements: Automatic feed of blanks and carriers, accurate positioning of blanks in carrier holes and indexing of carriers to fill all holes.

Ability to index either 3 or 4 hole carriers and handle .375 or .490 blanks; switching from one type to the other in a minimum of time (not more than 5 minutes).

Automatic transfer of filled carriers to cement application head, even application of thin film of cement, transfer to drying area or conveyor.

Output rate averaging 10 carriers per minute. Automatic stacking of dried, loaded carriers.

Visualization: Vacuum chuck handling of blanks similar to frequency sorting mechanism, indexing table for carriers, conventional conveying and stacking mechanism per "Requirements". A machine requiring no operator attention except for cartridge and carrier insertion and selection of 3 or 4 hole carrier operation is visualized. Operating speed should easily achieve the required 10 carriers per minute.

STATION I, PRIMARY LAP
STATION L. SECONDARY LAP
STATION M, FINAL LAP

Includes Processes 29, 34, 39, Lapping
Processes 30, 35, 40, Wash Blanks
Processes 31, 36, 42, Separate, Dry, Inspect Blanks and Load Cartridges.

1. Incoming Material

The material entering each lapping station consists of lap carriers loaded with blanks and stacked in machine loads (16 carriers), together with order tags or other information indicating the degree to which they are to be processed in that stage.

The average number of carriers entering each station (at an average of 3.46 blanks per carrier) and the number of corresponding blanks, (per day) are:

Table ILM-1

	Carriers	*Blanks*
Entering Primary Lap	4220	14,600
Entering Secondary Lap	3870	13,400
Entering Final Lap	3560	12,300

2. Station Description

a. PRIMARY LAP: This Station consists of six lapping machines, three blank washing machines, and a blank separation, inspection and loading area. The lapping machines are a planetary, narrow-track type, mechanized so as to reduce loading and unloading time to a minimum. They are arranged so as to be easily serviced by an operator who has no other task except to load the machines with carriers and occasionally change lapping plates. They may be assigned singly or in groups to work on different orders or may all work on the same order, depending on production requirements. The washing machines and blank separation are handled by a second operator, and the inspection and loading into cartridges by a third.

b. SECONDARY LAP: This Station is identical to primary lap except that only four lapping machines are required.

c. FINAL LAP: Final Lap is also identical to the other two stations except that five lapping machines are required.

d. LAPPING MACHINES REQUIRED:

Let:

N = the number of lapping machines required in any stage of lapping
N' = theoretical number of machines (at 100% efficiency)
e = efficiency level of machines (allowing for operator personal time, maintenance, etc.)
C = total number of machine cycles required per shift
T = average cycle time at any stage of lapping (minutes)
S = maximum working time per shift (480 minutes)
R = average thickness of quartz removed in a lapping stage (inches)
L_1 = rate of quartz removal when lapping 0.490" dia. blanks in any stage (inches/min.)
L_2 = rate of quartz removal when lapping 0.375" dia. blanks in any stage (inches/min.)
F_1 = fraction of .490" blanks processed in any stage
F_2 = fraction of .375 blanks processed in any stage
F_3 = fraction of blanks lapped with 8 micron grit in final lap
F_4 = fraction of blanks lapped with 4 micron grit in final lap
B = number of blanks processed per shift in a stage
D = dead time per lapping cycle = $u + p$
u = time to load and unload lapping machine per cycle (min.)
p = average time to change lapping plates per cycle (min.)
c = number of lap carriers processed in one lapping machine cycle
b = average number of blanks per carrier

The number of lapping machines required per stage:

$$N = \frac{N'}{e} = \frac{CT}{eS}$$

and the number of machine cycles required per shift

$$C = \frac{B}{bc} = \frac{B}{(3F_1 + 4F_2)\,c}$$

(since there are three blanks in a 0.490" carrier and four in a 0.375" carrier).

In the machine being considered, 16 carriers will be processed per cycle, hence:

$$C = \frac{B}{16\,(3F_1, + 4F_2)}$$

A single abrasive grit size is to be used for all blanks in the first lapping stage. This is also true of the second stage. Thus the average lapping time for either of these stages is:

$$T = \frac{R\,F_1}{L_1} + \frac{R\,F_2}{L_2} + D$$

where L_1, L_2, T and R are different for first and second stages. For the third lapping stage, two abrasive sizes

(8 or 4 micron) are used, depending on whether the blanks are for CR-18/U or CR-23/U crystals.

The average lapping time for the entire third stage is:

$$T = \left(\frac{R\,F_1}{L_1} + \frac{R\,F_2}{L_2}\right)_{8\mu} F_3 + \left(\frac{R\,F_1}{L_1} + \frac{R\,F_2}{L_2}\right)_{4\mu} F_4 + D$$

where the quantities in the first parenthesis apply to 8 micron and those in the second to 4 micron abrasive.

The number of machines for the first and second stages of lapping can be expressed as:

$$N_{1,2} = \frac{B}{16eS\ (3F_1 + 4F_2)} \left[\left(\frac{F_1}{L_1} + \frac{F_2}{L_2}\right) R + D\right]$$

and for the third lapping stage:

$$N_x = \frac{B}{16eS\ (3F_1 + 4F_2)} \left[\left(\frac{F_1}{L_1} + \frac{F_2}{L_2}\right)_{8\mu} RF_3 + \left(\frac{F_1}{L_1} + \frac{F_2}{L_2}\right)_{4\mu} RF_4 + D\right]$$

where the appropriate values of L_1, L_2, and R are used for the abrasive size.

In the section on Process 29, 34 and 39, the relation between rate of quartz removal and abrasive size for a given top plate weight and machine speed (rpm.) is discussed. The values for F_1, F_2, F_3, and F_4 are derived from the Order Board in the Appendix. B for each stage is stated in paragraph 1. above, and is repeated in the table below. The shift duration S is taken as 8 working hours or 480 minutes throughout this report. The value of D, the cycle dead time is estimated as follows:

$$D = u + p = 1.33$$

where u = load/unload time, taken as 1.0 minute

$$p = \frac{\text{time to change a set of lapping plates}}{\text{number of cycles before conditioning}}$$

$$= \frac{2\text{ min}}{6\text{ cycles}} = 0.33\text{ minutes}$$

Finally, a trial value of e, the lapping machine utilization efficiency, is taken as 0.85.

Substituting in the above equations, the values for the appropriate stage and abrasive grit size (given below) and for e, S and D:

Table ILM-2

	Primary	*Secondary*	*Final*		
Abrasive size (Microns)	*25*	*12*	*8*	*4*	*both*
F_1 (.490")	.542	.542	.902	0	.542
F_2 (.375")	.458	.458	.098	1.00	.458
F_3 (CR-18/U)	—	—	—	—	.60
F_4 (CR-23/U)	—	—	—	—	.40
R (inches)	.0162	.0030	.0015	.0005	—
L_1 (inches/min).	.0020	.0005	.00022	.000055	—
L_2 (inches/min).	.0026	.0006	.00026	.000067	—
B	14,600	13,400	—	—	12,300

we obtain the following values of N.

For Primary Lap:

$$N_1 = \frac{14{,}600}{6528\ (3x\ .542 + 4x\ .498)} \left[\left(\frac{.542}{.0020} + \frac{.458}{.0026}\right)(.0162) + 1.33\right] = 5.55\text{, say 6 machines}$$

Secondary Lap:

$$N_2 = \frac{13{,}400}{22{,}550} \left[\left(\frac{.542}{.0005} + \frac{.458}{.0006}\right)(.0030) + 1.33\right] = 4.1\text{, say 4 machines}$$

Final Lap:

$$N_3 = \frac{12,300}{22,550} \left[\left(\frac{.902}{.00022} + \frac{.098}{.00026} \right) (.0015 \times .60) + \left(\frac{0}{.000055} + \frac{1.00}{.000067} \right) (.0005 \times .40) + 1.33 \right]$$

$$= 4.6, \text{ say 5 machines}$$

The pertinent information regarding each lapping stage is summarized in Table ILM-3 (below).

Table ILM-3

	Lapping Stage		
	Primary	*Secondary*	*Final*
Blanks lapped/day	14,600	13,400	12,300
Carriers entering stage	4,220	3,870	3,560
Machine cycles/day (16 carriers)	264	242	223
Average lapping time/cycle	7.22 min.	5.54 min.	7.02 min.
Average dead time/cycle	1.33	1.33	1.33
Average cycle time	8.55 min.	6.87 min.	8.35 min.
Theoretical (8 hr.) cycles/day/machine	56.2	69.8	57.5
Theoretical No. machines (8 hr. use)	4.7	3.5	3.9
No. machines used	6	4	5
Theoretical cycles, actual machines used	337	280	287
Machine efficiency (% utilization)	78.5%	86.5%	77.5%

The factor u, load/unload time, is somewhat arbitrarily chosen, although it appears to be within the capabilities of a briefly trained operator with the present lapping machine conception.

The effect of different values of dead time and machine efficiency is shown in Appendix ILM-1. From the graph in that Appendix, it can be seen that the total dead time (load/unload plus lapping plate replacement) in Primary and Final Lap, can rise to well over 2 minutes per cycle without affecting the number of machines chosen, nor requiring over 88% efficiency (7 hours use per shift.) In Secondary Lap the total dead time can rise to 1.5 minutes without requiring an increase in machines or over 89% efficiency.

e. BLANK WASHING MACHINES: On completion of a lapping cycle, the blanks, carriers, and abrasive are mechanically wiped into a removable basket which is located at the center of the lapping machine. This basket will be removed by the lapping machine operator, placed on a rack to one side, and a clean basket inserted for the next cycle. The blanks must be washed in trichloroethylene, separated from the carriers, dried and inspected. The carriers are returned to the Carrier Loading Station, and the baskets to the lapping operator.

The washing is envisioned as being done in an automatic machine, designed for rapid loading and unloading, and having an internally timed cycle. The machine will wash, but not dry the blanks, and the liquid will be agitated rather than the basket in order to minimize breakage of the blanks. A cycle time of four minutes appears to be practical as a result of our experiments.

The baskets containing blanks ready for washing will be picked up at intervals by an operator assigned to this task. He will insert them into one of the three washers, which will start automatically when the lid is closed. The machine will require no further attention until the cycle is completed and the lid automatically opened.

The clean baskets will be removed by the same operator, the carriers separated from the blanks, and the blanks placed by the operator on a drying and inspection conveyor. To assist in the inspection task, the washer operator will be responsible for placing the clean blanks separately on the inspection conveyor. This may be accomplished in various ways, perhaps by inverting the basket over an adjacent clean surface and sliding the blanks onto the conveyor. The task does not appear at present to be practically capable of mechanization.

The number of washing machines required is purely a function of the total machine cycles in any lapping stage. At four minutes per basket, the theoretical output per washer is:

$$\frac{480}{4} = 120 \text{ baskets per day}$$

therefore the following numbers of machines will be used for each lapping stage.

Table ILM-4

WASHERS REQUIRED

	Primary	*Secondary*	*Final*
Total baskets/day (avg.)	264	242	223
Theoretical machines required	2.20	2.01	1.86
Actual machines	3	3	3
Efficiency	73.5%	67%	62%

f. BLANK INSPECTION AND LOADING: At present, the process of inspection of blanks (for cracks and large chips) does not seem to be easily made automatic, but since inspection is a necessary measure to prevent further processing of blanks likely to cause crack-ups, some mechanization is envisioned to allow the required number of blanks to be handled. The blanks must be loaded into cartridges after inspection for delivery to the sorter. Since they must be separated from each other both for inspection and cartridge filling, this suggests a conveyor terminated by a removable cartridge into which the blanks slide. It has been found also that the blanks are most easily inspected if placed on a translucent surface illuminated from beneath. This further suggests a translucent belt on which the blanks are placed (by the washer operator), which travels through a drying station (infrared lamps), over a source of illumination placed in front of the inspector, and into a loading hopper which guides the blanks into a cartridge.

It is also necessary to see that blanks are kept separate as to job order when they are loaded into cartridges. If several orders are being processed simultaneously in a lapping station, there should be a corresponding number of cartridges which are being loaded. To relieve the inspector of the task of keeping the orders separate and to allow him to concentrate on the task of rejecting defective blanks, there should be several narrow belts, all passing in front of the inspector and each terminating in a different cartridge. Thus the washer operator, who can keep track of the lapping machine from which each basket of washed blanks originates, and hence knows which baskets correspond to the same job order, can take the responsibility of placing the blanks from these baskets on the correct belt segment.

The inspector will then examine the blanks which flow past him (over the illuminated area) and reject those defective by deflecting them from the belt. To aid him in this task the belts may be equipped with rejection gates which will slide a blank to be ejected from the belt and into a scrap container. The gates may be electrically operated by means of push-buttons at the inspector's station. As a result of further studies, other inspection aids may prove necessary, for example optical projection or magnification of the blank image to more readily reveal defects. The inspector will be responsible for removing the cartridge when full and replacing them with empty ones, also for filing full cartridges in racks according to the order ticket. When the order being inspected on any belt is changed, the inspector must also change cartridges. He can be notified of this change by the blank washer (for example by means of a colored tag placed on the belt), who in turn will receive the information from the lapping machine operator. The cartridges are considered full when the height of blanks reaches 2-3/4 inch. An automatic alarm may be incorporated to signal this event to the inspector.

3. Operator Tasks

a. LAPPING MACHINE OPERATOR: This operator has two major tasks, loading and unloading the lapping machines and changing lapping plates. The time allowed for the former was 1.0 minute and for the latter, 2.0 minutes each six cycles, for a total of 1.33 minutes per cycle. Hence the operator of each lapping stage has the following utilization .

Table ILM-5

LAPPING OPERATOR

	Lapping Station		
	Primary	*Secondary*	*Final*
No. cycles/day	264	242	223
Active time/ cycle (min.)	1.33	1.33	1.33
Total time/ day (min)	352	324	299
No. operators	1	1	1
Efficiency %	73.5	67.5	62.5

The unused time of the lapping machine operator may be partly allotted to working between machines and to possible lack of synchronism between the machines. He may also assist the washer operator by transferring dirty baskets to the washers.

b. WASHER OPERATOR: This operator has two major tasks, to pick up dirty baskets and place in the washer, and to remove clean baskets and separate the blanks and carriers. With the contemplated set-up, blanks should be removed and slid on the inspection belt at a rate of better than one per second (there is an average of 55.3 blanks per basket). Allowing 1.0 minute to remove a basket and separate blanks and carriers, and 0.6 minute to return clean baskets and pick up dirty ones, the washer operators will be used as follows.

Table ILM-6

WASHER OPERATOR

	Lapping Station		
	Primary	*Secondary*	*Final*
Baskets/day	264	242	223
Washer loading time/basket (min)	0.6	0.6	0.6
Separating time/basket (min)	1.0	1.0	1.0
Process time/basket (min)	1.6	1.6	1.6
Total time/day (min)	423	388	357
No. Operators	1	1	1
Efficiency %	88	81	74.5

Time not allocated above will be spent in stacking carriers to be returned to the carrier loader station and in miscellaneous housekeeping tasks (e.g. basket arrangement).

c. BLANK INSPECTOR: This operator inspects each blank and rejects those with defects, also changes cartridges at the cartridge loading end of the machine and keeps them arranged in racks by job order. The average time to inspect, and if necessary, reject a blank may be taken as 1.7 seconds (35 per minute). Cartridge changing and filing will require about 15 seconds. The inspectors' utilization is summarized in the table below.

Table ILM-7

BLANK INSPECTOR

	Lapping Station		
	Primary	*Secondary*	*Final*
INSPECTION			
Blanks inspected/day	14,600	13,400	12,300
Inspect-reject time/blank (sec)	1.7	1.7	1.7
Rejects/day (Note 1)	600	600	506
Inspection time/day (min)	414	380	349
CARTRIDGE LOADING			
Blanks loaded/day	14,000	12,800	11,800
Avg. blank thickness (Note 2)	.0108"	.0087"	.0075"
Blanks/cartridge (2-3/4")	250	315	360
Cartridges/day (Note 3)	60	45	35
Time to change cartridge (sec)	15	15	15
Total cartridge time/day (min)	15	11	9
Total time per operator (min)	429	391	358
No. Operators	1	1	1
Efficiency %	89.5	82	75

Notes: (1) See paragraph (4.), this section

(2) From Frequency Chart, Appendix IV

(3) Assumed 3 to 4 partially full cartridges per day owing to order changes.

Table ILM-8

SUMMARY OF LAPPING MAN-MACHINE SYSTEM

Lapping Stage	*Primary*	*Secondary*	*Final*	*All Stages (Total)*
Blanks Processed/day	14,600	13,400	12,300	40,300
Lapping Machines	6	4	5	15
Machine Efficiency %	78.5	86.5	77.5	—
Lapping Operators	1	1	1	3
Operator Efficiency %	88	81	74.5	—
Blank Washers	3	3	3	9
Washer Efficiency %	73.5	67	62	—
Washer Operators	1	1	1	3
Operator Efficiency %	88	81	74.5	3
Inspection sub-stations	1	1	1	3
Inspectors	1	1	1	3
Operator Efficiency %	89.5	82	75	—
Total Operators	3	3	3	9
Blanks produced per man-day	4866	4466	4100	4477

4. Material Leaving Station—Yield

The estimated yield of each of the Lapping Processes is 92%, of which the faulty blanks will be divided approximately as follows:

	Blanks per Day Primary	Secondary	Final
Cracked, 2%	300	300	250
Chipped, 2%	300	300	250
Dead, Not Previously Rejected, 1%	150	150	125
High or Low Frequency, 3%	450	450	375
	1200	1200	1000

Of these, only the first two categories will be rejected in Inspection. The remaining defective blanks will be rejected in the next operation, Frequency Sorting. The output of Station I is 14,000 blanks per day, Station L 12,800 blanks/day; and Station M 11,800 blanks/day; stored in cartridges according to job order.

5. Transfer to Next Station

The cartridges are temporarily stored in racks at the output of the Inspection Belt, and are picked up at intervals by the operator of the Frequency Sorter, alternately they may be mechanically conveyed to the Frequency Sorter.

6. Machine Specifications

a. LAPPING MACHINE

Purpose: Lapping of blanks to desired frequency.

Requirements: A single type of machine will be used for all lapping stages, hence the machine shall be capable of adjustment or modification to operate efficiently with all abrasive grit sizes from 25 to 4 microns and with all blank diameters to be used, and shall produce good crystals for all frequencies between 4.3 and 54 mc.

Rapid and easy separation of upper and lower lapping rings (possibly power-driven), to permit insertion of loaded carriers or change of lapping plates.

Simple means of injecting solvent for dissolving loading cement and lapping compound (possibly automatic).

Radio-frequency monitoring of crystal frequency during lapping (possibly spread also), automatic shutdown of lapping power when preset frequency is reached.

Power-driven removal of blanks and carriers by wiping them into a central basket. This to be accomplished without damage to blanks. The above functions, including insertion of the carriers, are to be mechanized so as to be accomplished within one minute by unskilled operators having no more than two weeks training.

The machine shall be constructed so as to prevent the occurrence of crack-ups, excessive thickness spread or angle shift, and shall in general produce blanks of a satisfactory quality at a high lapping rate.

Visualization: The machine will be of the planetary-lap, narrow-track type, with automatic and powered features as described under "Requirements". The planetary gear ratio shall be adjustable so as to produce convexity as needed in the final lapping stage for those frequencies which require it. A separate carrier dispenser will be provided, if necessary to meet the loading time requirements. The machine will be equipped with change-gears and adjustable top plate loading so as to permit the optimum combination for lapping speed and crystal quality in each stage.

b. BLANK WASHER

Purpose: to remove all traces of abrasive from crystal blanks, after lapping.

Requirements: The machine will accept baskets of blanks as removed from the lapping machines, and subject them to a completely automatic washing cycle of not more than 4 minutes duration.

Visualization: A floor-mounting machine, loaded from the top, with a timed washing cycle initiated by latching a spring-loaded lid. Automatic release of the lid will signify the end of washing. A liquid trichloroethylene spray is envisioned for removal of the compound.

c. INSPECTION SUB-STATION

Purpose: to provide a means of separating, drying, inspecting, and loading blanks into cartridges following washing.

Requirements: A movable conveyor belt capable of carrying blanks from loading station, through a drier, inspection station, and into a cartridge-loading terminus. Means for keeping blanks of different frequency orders separated and in different cartridges.

Visualization: A conveying belt capable of transmitting light, divided into three or more tracks, on which the blanks from different lapping machines may be loaded. The drying station is pictured as a short tunnel lined with small infrared lamps. The inspection station will consist of a section of belt illuminated so as to accentuate the blank defects. Blanks, if defective, will be rejected from the belt manually, or by gates operated by keys under the operator's control. If necessary, optical magnification shall be provided at this station to permit closer inspection of the blanks. The blanks not ejected shall be conducted to a chute terminated by a holder accommodating the standard plastic cartridges used throughout the plant.

STATION M', CONTOURING

Includes Process 41, Contouring

1. Material Entering Process

CR-18/U blanks for frequencies between 4.3 and 7.5 mc., amounting to 3690 per day on the average Order Board distribution, will be contoured after leaving the Final Lapping Process (Station M).

2. Station Description

The Contouring Station will actually be a part of the Final Lap Station (M) and will be located in the same area.

Blanks from Station M will be taken from the inspection sub-station and manually loaded into a contouring apparatus. For purposes of illustration, it will be assumed that bowl-polishers will be used, each capable of contouring three blanks at a time on one side. An equivalent type of machine may be substituted. (See Process 41.) Available data indicates that the machines may be manually loaded and blanks contoured to sufficient depth in an average of 45 seconds per side. (The time will vary according to the frequency and amount of contouring.) The equipment will be shut off automatically, either by timer or by frequency monitoring.

1.5 minutes will thus be required to contour three blanks on both sides. The machine time needed will be

$$3690 \times \frac{1.5}{3} = 1850 \text{ minutes}$$

and the theoretical number of machines for one shift is

$$\frac{1850}{480} = 3.85 \text{ machines.}$$

Five machines can be used with an efficiency of 77%. In the event that blanks over 7.5 mc. require this type of contouring, the efficiency will be greater.

3. Operator Tasks

One contouring operator will be needed for each machine envisioned, for a total of five. Operator efficiency will be the same as the machine, or 77%.

4. Material Leaving Station

3690 contoured blanks per day will leave on the average. These will probably be unloaded into baskets similar to those used in the lapping machines so that the same type of washer is applicable, several machine loads being placed in one basket.

5. Transfer to Next Station

Baskets will be manually inserted in the washers by the contouring operators.

6. Machine Specifications

(No firm specifications can be established since the contouring method is still under study. However the time limitation; e.g., 0.5 minutes per blank, will be met regardless of method.)

STATION J, CONDITION LAPPING PLATES

1. Material Entering Station

This Station is an auxiliary to Stations G, K, and L (the three stages of Lapping), with the sole purpose of reconditioning lapping plates from the machines of these Stations. Hence, no quartz enters this area for treatment.

The incoming material consists of the lapping plates from the above Stations, which have been used to an extent that they are no longer flat and smooth, or contain scratches and the like.

The number of plates requiring reconditioning depends on the number of cycles accomplished in each of the three lapping stages, which will average:

270	per day for Primary Lap
243	per day for Secondary Lap
228	per day for Final Lap
741	per day for the entire plant

It is assumed that, on the average, the plates must be reconditioned every six lapping cycles, although this figure will vary for the various stages owing to the different grit sizes, lapping time, and similar factors.

As two plates are used simultaneously in the lapping machines, the number of plates requiring reconditioning per day is

$$\frac{741}{6} \times 2 = 247 \text{ plates per day.}$$

2. Station Description

The Station consists of four conditioning machines, each capable of handling four plates simultaneously. They are located so as to be accessible to all three lapping stations.

The number of conditioning cycles required per day is

$$\frac{247}{4} = 62 \text{ (approx.)}$$

Assuming a 30 minute reconditioning cycle, the theoretical number of machines needed is

$$62 \times 30/480 = 3.9 \text{ (say 4 machines)}$$

But if the machines are used at 90% efficiency (432 minutes per 8-hr. day), the total machine time available is

4 x 480 x .90 = 1727 min.

Hence, the available time per cycle is

$$\frac{1725}{62} = 28 \text{ minutes (approx.)}$$

If two minutes are required to load and adjust the four plates (machine dead time), the actual conditioning time is reduced to 26 minutes.

Although our present practice is to recondition plates for 30 minutes, it is believed reasonable to expect a possible reduction to 26 minutes with further increase in efficiency and better technique. In this case, a total of 4 machines at 90% efficiency can perform this task.

3. Operator Tasks

To load machines 62 x 2 = 124 min.

To collect and return 247 plates
from the Lapping Stations 296

420 min/day

Operator efficiency

$$\frac{420}{480} = 88\%$$

No. operators 1

4. Transfer to Next Station

The plates will be returned to the Lapping Stations by the conditioning machine operator. (This operation and that of pick-up may be conveyorized, if required.)

5. Machine Specifications

The conditioning machine is envisioned as being similar or equal to the 36" diameter Crane Lapmaster, without significant modification.

STATION K, FREQUENCY SORTING

Includes Processes 32, 37, 43, Frequency Sorting

1. Material Entering Station

The material entering Station K consists of all of the crystal blanks which are lapped, washed, inspected and stored in cartridges in the Primary, Secondary and Final Lapping Stations (I, L, M).

Frequency sorting is a means of reducing the spread of frequency (or thickness) of blanks being lapped to a particular nominal frequency. After Primary and Secondary lapping, the plant schedule calls for a reduction in spread by a factor of five, hence the blanks from these stages are sorted into five equal frequency increments. In Final Lap, the spread of outgoing blanks is to be the same as those entering; therefore, only one increment is required. In each sorting stage there are also two reject categories; one for high and one for low frequencies. Dead blanks will be sorted into the low frequency category and so be rejected.

The following quantities of blanks constitute the average daily input:

Table K-1

INPUT TO FREQUENCY SORTER

From Station	*No. of Cartridges— (minimum)*	*No. of Blanks*
G (Primary Lap)	60	14,000
K (Secondary Lap)	45	12,800
L (Final Lap)	35	11,800
Totals	140	38,600

2. Station Description

The Station consists of a single machine and workplace—the Frequency Sorter—which is centrally located as to be accessible to the three lapping areas. The Frequency Sorter includes two electronic racks, into one of which the nominal frequency and increment values are preset, and which can be time-shared with one or more feed-sort consoles which mechanically handle and sort the blanks. Adjacent to the feed-sort console will be cartridge racks in which the sorted and unsorted blanks can be temporarily stored in accordance with job order and frequency increment.

The process of frequency measurement and sorting is automatic and proceeds at the rate of 120 blanks per minute, once the console operator has selected the nominal frequency corresponding to the job order and lapping stage and has inserted a full cartridge into the machine. The operator's subsequent task is to monitor the machine and to change the output cartridges (corresponding to the sorted frequency increments), removing a full cartridge, storing it in the proper rack, and inserting an empty one. This can be done without stopping the machine.

In addition, full input cartridges of the same nominal frequency can be substituted for empty ones with only momentary stoppage of the sorting action. On the other hand, shifting to a new nominal frequency requires that both the input and all output cartridges be changed and stored, in addition to selection of the new preset frequency and changing the sorter head air-gap width.

The Maximum Order Board (see Appendix I) calls for 49 separate orders (crystal unit frequencies) per month, or roughly, 8 orders per each of 20 working days. With each crystal unit nominal frequency there are associated three other frequencies, one for each stage of lapping. Hence, the number of frequency changes which must be preset daily into the sorter is 24. Of these, at least three (and their corresponding increments) must be stored in the electronic rack at any one time, since there are three stages. Any of these three preset frequencies (and increment widths) can be selected by the sorter operator from the console. If two or more orders are to be processed at once, more presets can be added. The preset frequencies may be changed by the foreman or maintenance technician on the completion of an order in any lapping stage without interrupting sorting action on other preset channels.

Since the Frequency Sorter output depends not only on its speed during sorting, but also on the time required to change frequency, it is necessary to have some concept of how many times the operator will be required to perform this operation. That is to say, a minimum backlog of inserted blanks will be accumulated, so the number of frequency changes will depend largely on the relation between the theoretical sorting rate and the intervals at which the various lapping stages accumulate a full cartridge. These times are given in Table K-2:

Table K-2

FREQUENCY SORT PARAMETERS

Lapping Stage	*Blanks per Cartridge*	*Avg. Output Rate Blanks/min.*	*Time to Accumulate Full Cartridge (min.)*	*Time to Sort Cartridge (min.)*
Primary	250	33.3	7.5	2.1
Secondary	315	30.5	10.6	2.6
Final	360	28.1	12.8	3.0

Computation of the number of frequency changes per day from these data is not straightforward. However, a graphical means has been devised which indicates the number of frequency changes which might be expected. Appendix K-1 is an example of such a graph which has been used to study sorting problems.

The results of several trials indicate that most cartridges sorted must be chosen from a different lapping stage than that previously sorted; in other words, the machine keeps up with production or slightly ahead of it, and the operator does not have the option of choosing between several full cartridges waiting to be sorted. This means that the nominal sorting frequency (different in each lapping stage, even though all stages work on the same order) must be changed for nearly every cartridge. Accumulating a backlog, undesirable from other standpoints, is also not very helpful, since the machine will eat up the backlog at a high rate if it is not required to change frequency. Thus, the effect of starting on a new order is not great, since in most cases the frequency must be changed anyway.

Quantitatively our results show that on the average, out of 140 cartridges sorted (an average day's production), 111 are of a different nominal frequency than the previous one. Assuming that one minute is required to make the frequency change, the total time to sort 140 cartridges or 38,600 blanks is as follows:

Actual sorting time $\frac{38,600}{120}$ =	322 min.
111 frequency changes at 1 min./change	111
29 cartridge inputs with no frequency change, at 1/6 min./input (approx.)	5
Total Time	438 min.

$$\text{The machine efficiency is } \frac{438}{480} = 91\%$$

on the basis of total time in use, and one feed-sort console is sufficient.

Note: It is also required to handle different size blanks (0.490 and 0.375 in. diam.), which necessitates changing the sorter head. Since this task is unsuitable for the sorter operator, two alternatives are possible with the present machine concept. Either two sorting consoles (time-sharing the electronic units) may be utilized (one for each blank size), or production may be scheduled so that one blank size will be sorted for at least one-half day. Since the latter course does not appear to unduly affect production rates or delivery time, it will be assumed possible.

Because the sorter operator will not have time to collect the 140 cartridges daily output of the lapping stages, either another man or a conveying system is required. Since it is clear that a conveying system is practical, the details of handling being outside the scope of this study, its use will be assumed.

3. Operator Tasks

One operator is required to insert and remove cartridges, change frequencies and keep the various orders and increments in proper sequence. The operator will be required to spend full time at the console, therefore, his utilization is the same as that of the machine:

1 Sorter Operator	438 min.
Operator Efficiency	91%

4. Quantity of Material Leaving Station

If large orders are processed, for every full cartridge entering the sorter, one full cartridge will leave, even though the incoming material is broken down into increments. If the order is not sufficiently large to reach a "steady state", more cartridges will leave than enter the sorter, since some will be partially filled.

For example, if an order consisting of only one cartridge is sorted into five increments, five partially filled cartridges will leave the sorter (assuming there is at least one blank in every increment). An inspection of the size of small orders in the Order Board indicates that for orders less than five times the cartridge capacity of the previous stage, four partially filled cartridges will leave for every one sorted. From the Order Board, there are 70 orders per month which are less than five times the primary lap cartridge capacity, and 104 per month less than five times the secondary lap cartridge capacity, or 3.5 and 4.2 daily orders respectively, based on 20 days per working month:

Output cartridges to Second Lap 60 + 4(3.5)	= 74
Output to Final Lap 45 + 4(5.2)	= 66
Output to Final Etch(1)	35
Total Output (less rejects)	175 cartridges

Note (1): Sorting is only into "good" and "reject" categories following the Final Lapping stage.

In addition, there will be two reject cartridges in each stage for every order processed, since the small number of rejects precludes filling a cartridge on one order, and because the rejects will not be mixed. There are approximately 8 orders per day (maximum), so that the number of reject cartridges is:

$$8 \times 2 \times 3 = 48$$

The sorted blanks going to each station are equal to the number from the previous station, minus the "dead", "high" and "low" frequency rejects, according to the following table:

Table K-3

DAILY OUTPUT OF FREQUENCY SORTER (AVG.)

	Sorted		*Rejects*	
	Cartridges	*Blanks*	*Cartridges*	*Blanks*
To Secondary Lap	74	13,400	16	600
To Final Lap	66	12,300	16	500
To Final Etch	35	11,300	16	500
Total	175	37,000	48	1,600

5. Transfer to Next Station

The cartridges containing good blanks (the first column of the table above) are conveyed to the indicated station manually or by conveyor.

Disposition of rejects has not been determined. However, they will probably go to storage for possible inspection and salvage.

6. Machine Specifications

a. FREQUENCY SORTER

Purpose: to measure the fundamental resonant frequency of cleaned blanks as received from various stages of lapping, and to sort them into the required number of frequency increments.

Requirements: Automatic measurement and sorting of blanks from input to output cartridges at the rate of 120 blanks per minute.

Sorting into at least five increments plus two reject categories— high and low (or dead).

Capability of storing nominal frequencies (and associated increment widths) which the operator may select from a single control at the console.

Ability to change from one stored nominal frequency and increment to another (at the console) within approximately one minute.

Ability to change between sorting of 0.375" and 0.490" diameter blanks within a reasonable time (less than ten minutes), either by means of interchangeable blank holders or by ability to switch between two feed-sort consoles.

Reliable accuracy of measurement (Δf) to $0.01f^2$ kilocycles (where f is the fundamental frequency in megacycles).

Visualization: A machine has been designed and constructed under this contract which should perform the required operations in a manner equal to or better than the above "Requirements". The machine consists of a console (Feed-Sort unit), containing an oscillator, crystal holder, feed mechanism and sorting mechanism to store crystals in increments, a Selector containing electronic equipment to measure frequency and control sorting, and a Control Panel (in a rack) to set in nominal frequency, increments, etc.

The machine also includes automatic testing, which checks unit operation whenever a cartridge is removed.

STATION N, FINAL ETCHING

Includes Process 44, Etch Holder Loading
Process 45A, Degrease Etch Holder
Process 45B, Final Etching
Process 45C, Blank Drying

1. Material Entering Station

The incoming material consists of frequency-sorted blanks stored in plastic cartridges, lapped, and sorted to a frequency spread (6 sigma) of $0.2f^2$. A total of 11,300 blanks per day will be processed on the average, equivalent to approximately 115 holders.

2. Station Description

The Station consists of an etch holder loading machine, a degreaser, the final etching machine proper, and a drier. The design and arrangement of machines will be such that only one operator will be required to transfer etch holders within the station and to operate the etching machine. The holders will be molded or machined Teflon and contain 100 slots in which the blanks can be inserted edgewise.

The blanks will be removed from the cartridges and inserted into the holders by means of a machine similar in principle to the blank handling portion of the frequency sorter.

The loaded holders will be placed in temporary storage (e. g., a wheeled cart) and conveyed in batches of ten to a degreasing machine. 115 holders per day will be handled in the degreaser and subsequent processes, it being deduced from a study of the Maximum Order Board that an average of six holders per day will be less than completely filled, owing to fractional parts of an order amounting to less than 100 blanks. The degreasing machine may be similar to a commercial type. It will have a capacity of 10 holders, a cycle of 30 minutes, plus 6 minutes load/unload time, or 133 holders/day. Trichoroethylene vapor will be used for the degreasing process. The floor space required is approximately 3 feet by 8 feet. The machine will be manually loaded and unloaded by the operator.

The Final Etch Machine is conceived as a rotary machine. It will be an intermittent transfer machine, completely automatic except for loading and unloading. The theoretical capacity will be 240 holders per day, or 3000 blanks per hour. A complete cycle will require 36 minutes (0.6 hours). The machine will have 18 positions, each basket dwelling 2 minutes at each position. Etching time will be set to one of two pre-set values for each holder, the time value being selected by the operator in accordance with the type of crystal blank (CR-23/U or CR-18/U) indicated by the job ticket. The output of the machine is one basket every 2 minutes regardless of actual etching time set. The floor space required is approximately 64 square feet (9 feet diameter). Because of the toxic nature of the etchant (HF), a ventilating system will be required. The density and temperature of the etchant solution will be monitored and adjusted by continuous automatic devices. In addition to HF, the machine will require trisodium phosphate and 3% ammonia solution. (These solutions will be monitored and brought up to strength daily.)

Rinse water must be demineralized, and will be provided by an adjacent machine similar or equivalent to commercial types manufactured by the Barnstead Still & Sterilizer Co. It will have a maximum capacity of 80 gals. per hour of which 870 gals. will be supplied to the Etching Machine. A storage tank containing 500 gals. will be provided. The demineralizer will require an additional 45" x 30" of floor space.

The drier will be a continuous device, capable of holding 15 Teflon etch holders, and may be visualized as a tunnel lined with radiant heaters, equipped with conveyor roller inside and on the input and output ends. The etch holder baskets will remain in the tunnel for thirty minutes, resulting in a maximum output of 240 baskets per day, adequate to handle the average load.

3. Operator Tasks

At the maximum machine rate of 1 holder processed every 120 seconds, the operator will have the following tasks:

	Est. Time (Sec.)
1. Select cartridge, read job ticket	10
2. Remove empty cartridge from loading machine, insert new cartridge	10
3. Remove full holder from loading machine and place in cart.	8
4. Insert empty holder from cart.	7
5. Insert degreased holder in etch machine.	10
6. Set timer to position 1 or 2.	5
7. Unload etched blanks, put holder in drier.	10
	Total 60 sec. per holder = 1.0 min.

In addition, the operator has the following tasks:

8. Load/unload degreaser (6 min per batch of 10)	=	0.6 min/holder
9. Retrieve empty holders from next station. (5 min. per batch of 10)		0.5
Total		1.1 min/holder

Total Operator Utilization 115 x (1.0 + 1.1) =	232 min.
Operators Required	1
Operator Efficiency	51%

4. Material Leaving Station—Yield

Nearly 100% of blanks may be expected to be etched within tolerance, and no loss assumed for this reason. Owing to the number of times blanks are handled, a handling loss of 100 per day may be assumed, hence the yield is 99.1%, 115 holders containing 11,200 good blanks will be delivered to the next Station (Base Plating).

5. Transfer to Next Station

A non-motorized roller conveyor will transfer the etch holders from the drier to the Base Plate Mask Loading Area.

6. Machine Specifications

a. ETCH HOLDER LOADING MACHINE

Purpose: Remove blanks from cartridges and load them in etch holders.

Requirements: Quick insertion and release of cartridges and etch holders; loading rate of at least one blank per second; automatic indexing of etch holder 3.6 degrees per blank, accurate to less than slot width; automatic shut-off when holder is filled or when cartridge is empty; no damage to blanks down to 0.003 inch thickness; handle either 0.490 or 0.375 inch dia. blanks (with flat).

Visualization: Vacuum chuck removal of blanks from cartridge, similar to frequency sorter handling mechanism. Indexing table for holders, accuracy and speed per "Requirements".

b. DEGREASER

Purpose: Degrease blanks loaded in etch holders.

Requirements: Capacity of ten holders; rapid loading and unloading; 30 minute cycle with liquid trichloroethylene; provision for vapor and fume control.

Visualization: Dishwasher—type action, provision for loading and unloading of 10 holders on removable or sliding racks to permit easy transfer to cart. Automatic cycle with 30 minute timer.

c. FINAL ETCHING AND CLEANING MACHINE

Purpose: to clean final lapped quartz blanks before etching, etch to frequency with hydrofluoric acid, clean and dry etched blanks.

Requirements:

Capacity: 30 holders or 3000 blanks per hour.

Type and Cycle Time: Continuous, automatic rotary machine; approximately 9 ft. dia., consisting of 18 positions. Holders remain at each position for 2 minutes, hence max. capacity of machine is one holder per two minutes. Three positions shall make up the etch tank, and controls provided so that the holder can be immersed any pre-set time between 0 and 6 minutes. Transfer time between stations shall be less than 8 seconds.

Agitation: Clockwise and counterclockwise agitation of each holder at a rate of 40 cycles/minute shall be provided.

Timer: A timer shall be provided to control the immersion of each etch holder in the HF acid. A choice of two times shall be available, each time capable of being pre-set between 0 and 6 minutes. The etch time selected shall apply to the holder inserted in the loading position and shall be stored until that holder reaches the etch tank. The overall timing accuracy shall be better than ± 5 sec./min.

Temperature: The etch bath shall be controlled to ± 0.5°C. All other baths shall be controlled to ± 2.0°C.

Density: The density of the HF solution shall be controlled so that the concentration does not vary more than 0.5% in the region between 12 and 24%. Any concentration within that region may be selected.

Exhaust: A suitable exhaust system shall be provided to remove ammonia and HF fumes.

Materials: Blank holders will be Teflon. Other materials as indicated in the table below:

Visualization: The Final Etch Machine developed under this contract will meet the above requirements.

Table N-1

FINAL ETCH MACHINE OPERATIONS

Positions		*Temp.*	*Material*	*Capacity*
1	loading—no tanks			
2	loading—no tanks			
3	Trisodium phosphate solution 5%	85°C	Nickel	5.4 gals.
4	Ammonia solution 3%	25°C	99.5% Alum.	5.4 gals.

Table N-1 (Continued)

Positions		*Temp.*	*Material*	*Capacity*
5	Demineralized Water 11.8 gal/hr	25°C	99.5% Alum.	5.4 gals.
6	Demineralized Water 11.8 gal/hr	25°C	99.5% Alum.	5.4 gals.
7 to 9	Hydrofluoric acid solution 16%	25°C	Monel container. Polyethylene cover with 3 holes to fit holders.	
10	Trisodium phosphate 5%	85°C	see (3)	5.4 gals.
11	Ammonia solution 3%	25°C	see (4)	5.4 gals.
12	Demineralized water (see 5)	25°C	see (5)	5.4 gals.
13	Demineralized water (see 5)	85°C	see (5)	5.4 gals.
14	Demineralized water (see 5)	85°C	see (5)	5.4 gals.
15	Superheated steam blast	115°C approx.		
16	Superheated steam blast			
17	Unloading position			
18	Unloading position			

d. BLANK DRIER

Purpose: To complete drying of blanks.

Requirements: Tunnel-type, conveyor roller floor, capacity of 15 holders. One holder per 2 minutes will be inserted for a total of 30 minutes drying time.

Visualization: The drier will consist of a tunnel lined with radiant heaters built over a non-powered roller conveyor. Pushing one holder in will advance all others and push the last holder out of the tunnel into the mask loading area.

STATION O, BASE PLATING

Includes Process 46, Base Plate Mask Loading
Process 47, Preheat Base Plate
Process 48, Pre-Aging

1. Material Entering Station

Quartz blanks enter this Station after Final Etch, loaded in Teflon etch holders. The average input is 11,200 blanks per day at this stage, and the etch holders contain a maximum of 100 blanks each.

2. Description of Station

The base plating station will be located adjacent to Station N (Final Etch), so that blanks may be processed as they are discharged from the end of the drier. The Station consists of a loading area in which the blanks are removed from the etch holders and inserted into base plating masks, a preheating oven in which the masks and blanks are freed from water vapor, and three base plating machines. From the base platers, the masks are conveyed through a tunnel oven which heats them to 425°C for a period sufficient to pre-age them.

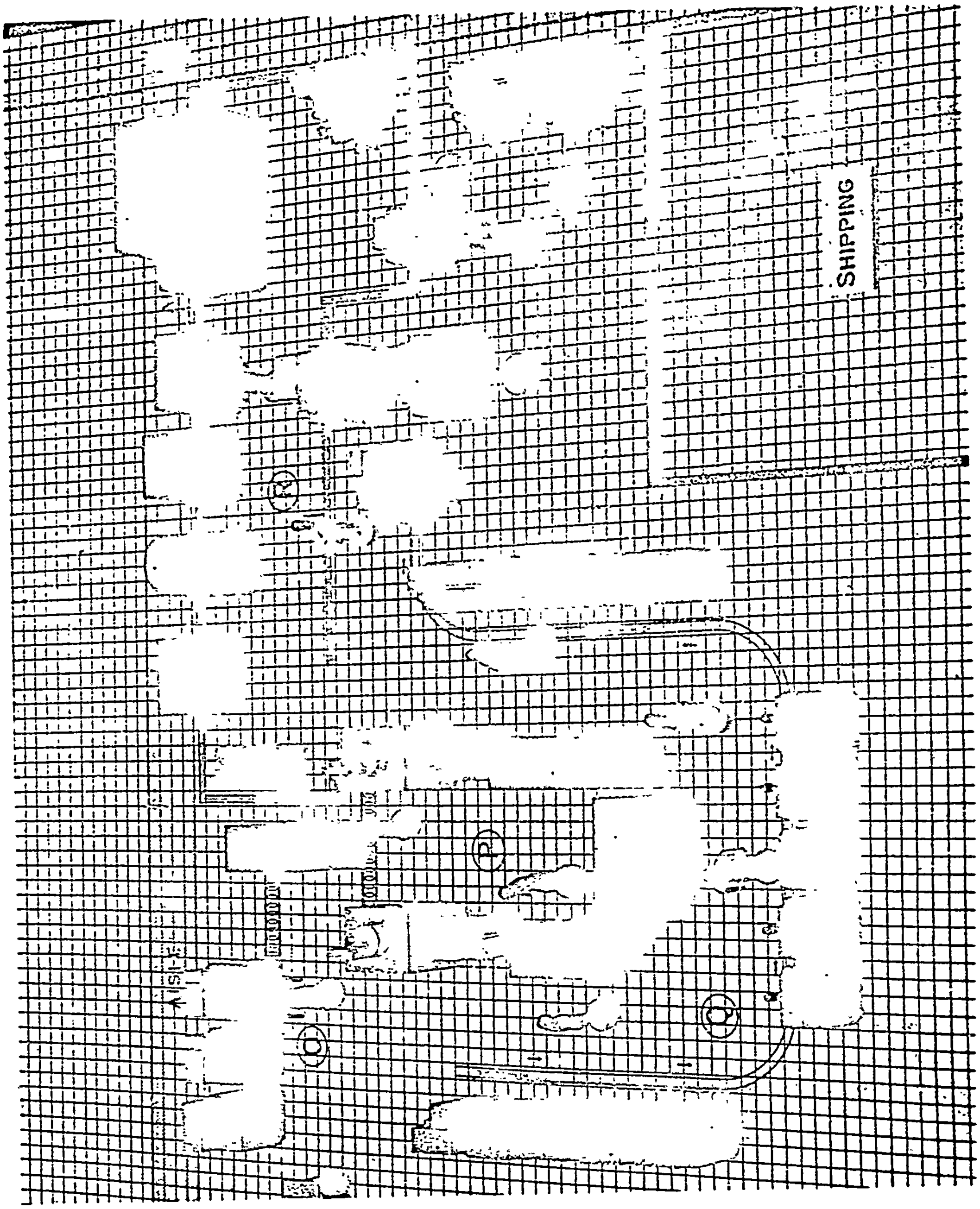
The blanks will be removed from the etch holders, either manually or by a mechanical device, and dropped into slots in a holder. The masks will then be sent through a roller or frictional device which will roll the blanks until the orientation flats mate with a similar flattened portion of the slots, and a cover containing the correct size of masking holes will be slipped over the holder.

The operator of the mechanized or semi-mechanized loader will be responsible for feeding the correct size of masks into the assembly device, and this size will be specified on the production job ticket.

The loaded masks will be delivered from the output of the assembly device, and must be assembled to holders which will support 40 to 50 blanks. Two different types of holders will be used, depending on whether the blanks are for CR-23/U or CR-18/U units. This will also be specified on the job ticket. Assembly of masks to holders will be a manual operation. 11,200 blanks per day must be loaded, and approximately 250 holders assembled. With the aid of mechanized mask loading at the rate of 40 blanks per minute, and allowing 0.5 minutes to assemble masks to holders, one operator will be able to handle this task.

Assembled holders will be placed on a conveyor which will transfer them to the base platers via a heating section, and deposit them in a heated storage point next to each plater. The holder temperature will be raised to approximately 120°C and held at this point for one hour.

The base plating machines will have a capacity of one holder of five masks (40 or 50 blanks, depending on size). The time to load and plate one batch averages 4.5 minutes of which 0.5 minutes is loading time. Hence



Finishing Operations, Mechanized Quartz Crystal Plant Model the machine time required to process 11,200 blanks or 1,272 masks is

$$\frac{1272}{5} \times 4.5 = 1146 \text{ minutes}$$

and the theoretical number of machines required is

$$\frac{1146}{480} = 2.4 \text{ machines}$$

or practically, 3 machines are required.

Their average efficiency level is $\frac{2.4}{3} = 80\%$.

On completion of the plating cycle, holders will be removed from the base platers. The masks will be detached from their holders and conveyed directly to the adjacent pre-aging oven. This will be conveyer type. If the masks are conveyed in single file and 3/4 inch is allowed for each blank, the output rate of 11,200 blanks per day or 27 per minute for seven hours operation requires an oven length for 15 minutes holding time of

$$\frac{27}{12} \times \frac{3}{4} \times 15 = 25 \text{ feet.}$$

Pasing two or more masks through the oven side by side will reduce the length directly, and undoubtedly prove more practical.

3. Operator Tasks

a. MASK LOADER

Mechanized mask loading at 40 blanks/min.

$$\frac{11,200}{40} = 280 \text{ min.}$$

Assemble 250 holders at 0.5 min./holder	125 min.
Total	405 min. per day
Operators required	1
Efficiency	85%

b. BASE PLATER OPERATOR

Loads and unloads 250 mask holder and crucibles at 0.5 minutes per set	125 min.
Return of masks and loading of aging oven	260 min.
	385 min.
Operators required	1
Efficiency	80%

4. Material Leaving—Yield

A nominal loss of 100 blanks per day due to handling is assumed in this station. Hence 11,100 blanks per day will leave, for a nominal yield of 99%.

5. Transfer to Next Station

Blanks will be mechanically conveyed out of the aging oven to the Mounting and Cementing Station.

6. Machine Specifications

a. MECHANIZED MASK LOADER

Purpose: to assist in loading masks from the etch holders.

Requirements: The device or machine must be capable of assisting the operator in loading blanks into base plating masks at the rate of 40 blanks per minute, without damage to or contamination of the blanks. The design will be such as to eliminate the need to handle blanks with tweezers.

Visualization: No firm design concept has been arrived at, but it appears that either a semi-or fully mechanized device will accomplish the desired results. The mechanization must proceed in close cooperation with design of the mask itself and with the design of the unloading device (Mounting and Cementing machine).

b. BASE PLATER

Purpose: to coat both sides of the quartz blanks with an aluminum film of specified thickness and diameter.

Requirements: The plater must deposit aluminum on both sides of the blank to a thickness equivalent to $\Delta f = 0.7 \pm 0.1 f^2$ or $0.55 \pm 0.1 f^2$ where f is the fundamental frequency in megacycles and Δf is in kilocycles. The cycle time including loading, unloading, pump-down, plating and cooling shall average 4.5 minutes. The plater shall have a capacity of 40 or 50 blanks of 0.490″ or 0.375″ diameter, respectively. Operation shall be completely automatic after loading, from the time the operator initiates the cycle to the time when the chamber opens at the end of the cooling cycle.

Visualization: A base plater meeting the above requirements has been developed under this contract. Plating is by evaporation from an inductively heated tantalum crucible containing an aluminum ball. Blanks are held in masks which define the spot size. Chamber closure, pump-down, feeding of aluminum into the crucible and plating are automatic, and at the completion of plating one side, the masks are automatically revolved 180°, another aluminum ball is automatically dropped into the crucible, and the cycle repeated on the other side.

c. PRE-AGING OVEN

Purpose: to stabilize crystal blanks by accelerated aging at high temperatures prior to final plating.

Requirements: The oven should heat the blanks to 425°C for 15 minutes at a minimum rate of 27 per minute. The heating cycle should be controlled during this period to a moderate degree, perhaps ± 10°C, and should include tapered heating and cooling at the extremes of the cycle so as to minimize thermal shock. Mechanized loading and unloading of blanks held in special containers should be provided.

Visualization: A tunnel type oven, electrically heated and controlled, with mechanized conveying of blanks through the chamber, and connection to the Mounting and Cementing machine at the output end. The oven will have controls for varying the temperature of different zones of the chamber and the conveyor speed.

STATION P, MOUNTING AND CEMENTING BLANKS

Includes Process 49A, Clean Bases
Process 49B, Mounting and Cementing
Process 50, Air-Dry and Cure Cement

1. Material Entering Station

An average of 11,100 crystal blanks per day and an equal number of bases will be processed in this station.

2. Station Description

The Station will be located adjacent to Base Plating, and connected by mechanized conveyor to the pre-aging oven of that Station. It will include two machines which will be capable of receiving base plating masks and crystal bases mounted in ceramic blocks, remove the blanks from the masks, insert them in the bases and apply epoxy resin-silver cement to the base mount where it contacts the plated electrodes of the quartz blank.

Following the Mounting and Cementing machines and receiving their output as the mounted blanks are ejected will be a drying table. It may consist of a maze of conveying tracks of such length as to allow the cemented blanks the required 30 minutes of drying time. An operator will receive the output of this air-dry table and slide the ceramic blocks holding the blanks into slotted racks. He will accumulate the racks in batches of perhaps ten, each rack containing ten crystals, and load these into a curing oven equipped with batch timers.

The Station will also include a work table where the ceramic blocks (returned from the Frequency Check, Station T) are assembled to new bases and a degreaser where the assemblies can be cleaned. One operator will attend to the assembling and cleaning operation.

The design concept of the Mounting and Cementing machine is still in an elementary state, but it appears reasonable to expect a fully automatic machine to handle the blank mounting at the rate of at least 15 per minute, or 7,200 per 8-hour shift. Thus two machines should be adequate to handle the average input at an efficiency of

$$\frac{11,100}{14,400} \times 100 = 77\%$$ which is equivalent to 6.2 hours per machine per day.

The air-drying table must provide for a drying time of 30 minutes, approximately. The blocks ejected from the Mounting and Cementing machines can be pushed directly onto tracks on the table. At an input rate of 15 per minute, the blocks being one inch long, the track length required for 30 minutes drying time is

$$\frac{15 \times 30}{12} = 37.5 \text{ feet.}$$

Assuming a 3" radius is feasible, this length of track could be accommodated in a space 5 x 3 feet. Two of these tables will be needed, one for each insertion machine.

Since the blocks will develop a high degree of friction against the sides of an unpowered track, it will be necessary to provide some mechanical means of conveying them, such as a chain or belt drive.

An operator will be stationed at the output of the air drying conveyors to load the blocks into racks. Each rack will hold ten blocks, so that the racks will be loaded at the rate of 3 per minute. An assembly of perhaps 10 of these racks (100 crystals) will be loaded into trays and placed in an adjacent batch oven by the same operator. A timer will insure that the batches remain in the oven for five hours.

The oven must have a capacity equal to five hours production at the rate of 3 racks per minute or a total of 900 racks (9,000 crystals) divided into perhaps 90 trays. A feasible arrangement might be 15 sections, each with an individual door and timer, and each holding 6 trays of 10 racks or 600 crystals. Several smaller ovens of the same total capacity would serve equally well. The individual oven sections could be allocated to batches of crystals to be adjusted to the same frequency in final plating, thus one or more oven sections will correspond to each final plating machine.

One operator will be able to handle rack loading and loading of the oven.

In the base preparation area, the ceramic blocks will be conveyed in some manner to a work table and stacked in jigs so that they are conveniently dispensed to an operator. New bases will be unpacked and assembled to the blocks by inserting their pins into a pair of spring-loaded sockets. At the rate of 30 per minute one operator could handle the day's production in approximately 6 hours. The same operator can load the assembled blocks into baskets as they accumulate, say in batches of 200, and place them in a degreaser. This operation should not take longer than one minute each for a total of approximately one hour. The baskets can be unloaded and the cleaned blocks and bases inserted into the Mounting and Cementing machines by their operator.

Table P-1

SUMMARY OF MOUNTING AND CEMENTING REQUIREMENTS

Operation	*Machine*	No.	*Operators*
Assemble and clean bases and blocks	Degreaser	1	1
Insert Blanks in Bases	Mount and Cement Machine	2	1
Air Dry Cement, Assemble in Racks	Conveyorized Rack	2	0.5
Cure Cement	Oven	1	0.5
Total Operators			3

3. Operator Tasks

a. BASE ASSEMBLING AND CLEANING OPERATOR

Assemble 11,100 bases at 30/min.	370 min.
Load 56 baskets into degreaser at 1/min.	56
Total	426 min./day
No. of operators	1
Efficiency	89%

b. AIR DRY AND OVEN CURE OPERATOR

Assemble 1,100 racks (10 blocks each) at 6/min.	185 min.
Assemble, load 110 trays (10 racks) into curing oven	185
Total	370 min./day
No. operators	1
Efficiency	77%

c. MOUNTING AND CEMENTING OPERATOR

Attend two machines	370 min./day
No. operators	1
Efficiency	77%

4. Material Leaving Station—Yield

A loss of 100 blanks per day due to handling is assumed. The total number of cured, mounted crystals leaving the curing oven per day is 11,000.

5. Transfer to Next Station

Mounted crystals will remain in the batch oven until cured and required by the Adjustment Plater operator.

6. Machine Specifications

a. MOUNTING AND CEMENTING MACHINE

Purpose: To insert blanks in bases and apply cement.

Requirements: The machine must be capable of extracting blanks from the special base plating masks and of inserting them into stiff mount HC-6/U bases. The angular tolerance on mounting (with respect to the flat) is approximately ±4.5°. The machine must also apply cement onto the mount contact points. The rate of operation should be approximately 15 units per minute or better.

Visualization: A completely automatic machine which will extract blanks from plating masks and insert them into manually loaded bases is envisioned. The machine will have stations for insertion, cementing, and automatic ejection. The postulated rate will be met or exceeded, and the machine will not require more than half the attention of an operator.

b. CURING OVEN

Purpose: To cure the conducting cement applied to the crystal mount.

Requirements: The oven must have the capacity to process over 11,000 blanks per shift at 150°C for 5 hours.

Visualization: A multiple-section batch oven with thermostatic controls and individual elapsed time indicators for each of perhaps 15 sections is envisioned. The capacity will be approximately 600 crystals per section or 9,000 crystals total.

STATION Q, ADJUSTMENT PLATE

Includes Process 51, Adjustment Plate

1. Material Entering Station

The average number of crystals per day which reach the adjustment plating process is 11,000. The crystals are stored in the curing oven in mounted form, the base pins of the mounts being inserted into ceramic blocks which in turn are assembled in channel-section racks, ten blocks to a rack. The blocks have external contact springs, which make an electrical connection to the crystal electrodes through the base pins. Each rack holds ten blocks of crystals.

2. Station Description

The Station consists of a number of adjustment plating machines, each an entirely self-contained unit, *Visualization:* A tunnel type oven, electrically heated and controlled, with mechanized conveying of blanks through the chamber, and connection to the Mounting and Cementing machine at the output end. The oven will have controls for varying the temperature of different zones of the chamber and the conveyor speed.

STATION P, MOUNTING AND CEMENTING BLANKS

Includes Process 49A, Clean Bases
Process 49B, Mounting and Cementing
Process 50, Air-Dry and Cure Cement

1. Material Entering Station

An average of 11,100 crystal blanks per day and an equal number of bases will be processed in this station.

2. Station Description

The Station will be located adjacent to Base Plating, and connected by mechanized conveyor to the pre-aging oven of that Station. It will include two machines which will be capable of receiving base plating masks and crystal bases mounted in ceramic blocks, remove the blanks from the masks, insert them in the bases and apply epoxy resin-silver cement to the base mount where it contacts the plated electrodes of the quartz blank.

Following the Mounting and Cementing machines and receiving their output as the mounted blanks are ejected will be a drying table. It may consist of a maze of conveying tracks of such length as to allow the cemented blanks the required 30 minutes of drying time. An operator will receive the output of this air-dry table and slide the ceramic blocks holding the blanks into slotted racks. He will accumulate the racks in batches of perhaps ten, each rack containing ten crystals, and load these into a curing oven equipped with batch timers.

The Station will also include a work table where the ceramic blocks (returned from the Frequency Check, Station T) are assembled to new bases and a degreaser where the assemblies can be cleaned. One operator will attend to the assembling and cleaning operation.

The design concept of the Mounting and Cementing machine is still in an elementary state, but it appears reasonable to expect a fully automatic machine to handle the blank mounting at the rate of at least 15 per minute, or 7,200 per 8-hour shift. Thus two machines should be adequate to handle the average input at an efficiency of

$$\frac{11{,}100}{14{,}400} \times 100 = 77\% \text{ which is equivalent to 6.2 hours}$$

per machine per day.

The air-drying table must provide for a drying time of 30 minutes, approximately. The blocks ejected from the Mounting and Cementing machines can be pushed directly onto tracks on the table. At an input rate of 15 per minute, the blocks being one inch long, the track length required for 30 minutes drying time is

$$\frac{15 \times 30}{12} = 37.5 \text{ feet.}$$

Assuming a 3" radius is feasible, this length of track could be accommodated in a space 5 x 3 feet. Two of these tables will be needed, one for each insertion machine.

Since the blocks will develop a high degree of friction against the sides of an unpowered track, it will be necessary to provide some mechanical means of conveying them, such as a chain or belt drive.

An operator will be stationed at the output of the air drying conveyors to load the blocks into racks. Each rack will hold ten blocks, so that the racks will be loaded at the rate of 3 per minute. An assembly of perhaps 10 of these racks (100 crystals) will be loaded into trays and placed in an adjacent batch oven by the same operator. A timer will insure that the batches remain in the oven for five hours.

The oven must have a capacity equal to five hours production at the rate of 3 racks per minute or a total of 900 racks (9,000 crystals) divided into perhaps 90 trays. A feasible arrangement might be 15 sections, each with an individual door and timer, and each holding 6 trays of 10 racks or 600 crystals. Several smaller ovens of the same total capacity would serve equally well. The individual oven sections could be allocated to batches of crystals to be adjusted to the same frequency in final plating, thus one or more oven sections will correspond to each final plating machine.

One operator will be able to handle rack loading and loading of the oven.

In the base preparation area, the ceramic blocks will be conveyed in some manner to a work table and stacked in jigs so that they are conveniently dispensed to an operator. New bases will be unpacked and assembled to the blocks by inserting their pins into a pair of spring-loaded sockets. At the rate of 30 per minute one operator could handle the day's production in approximately 6 hours. The same operator can load the assembled blocks into baskets as they accumulate, say in batches of 200, and place them in a degreaser. This operation should not take longer than one minute each for a total of approximately one hour. The baskets can be unloaded and the cleaned blocks and bases inserted into the Mounting and Cementing machines by their operator.

Table P-1

SUMMARY OF MOUNTING AND CEMENTING REQUIREMENTS

Operation	*Machine*	*No.*	*Operators*
Assemble and clean bases and blocks	Degreaser	1	1
Insert Blanks in Bases	Mount and Cement Machine	2	1
Air Dry Cement, Assemble in Racks	Conveyorized Rack	2	0.5
Cure Cement	Oven	1	0.5
Total Operators			3

3. Operator Tasks

a. BASE ASSEMBLING AND CLEANING OPERATOR

Assemble 11,100 bases at 30/min.	370 min.
Load 56 baskets into degreaser at 1/min.	56
Total	426 min./day
No. of operators	1
Efficiency	89%

b. AIR DRY AND OVEN CURE OPERATOR

Assemble 1,100 racks (10 blocks each) at 6/min.	185 min.
Assemble, load 110 trays (10 racks) into curing oven	185
Total	370 min./day
No. operators	1
Efficiency	77%

c. MOUNTING AND CEMENTING OPERATOR

Attend two machines	370 min./day
No. operators	1
Efficiency	77%

4. Material Leaving Station—Yield

A loss of 100 blanks per day due to handling is assumed. The total number of cured, mounted crystals leaving the curing oven per day is 11,000.

5. Transfer to Next Station

Mounted crystals will remain in the batch oven until cured and required by the Adjustment Plater operator.

6. Machine Specifications

a. MOUNTING AND CEMENTING MACHINE

Purpose: To insert blanks in bases and apply cement.

Requirements: The machine must be capable of extracting blanks from the special base plating masks and of inserting them into stiff mount HC-6/U bases. The angular tolerance on mounting (with respect to the flat) is approximately ±4.5°. The machine must also apply cement onto the mount contact points. The rate of operation should be approximately 15 units per minute or better.

Visualization: A completely automatic machine which will extract blanks from plating masks and insert them into manually loaded bases is envisioned. The machine will have stations for insertion, cementing, and automatic ejection. The postulated rate will be met or exceeded, and the machine will not require more than half the attention of an operator.

b. CURING OVEN

Purpose: To cure the conducting cement applied to the crystal mount.

Requirements: The oven must have the capacity to process over 11,000 blanks per shift at 150°C for 5 hours.

Visualization: A multiple-section batch oven with thermostatic controls and individual elapsed time indicators for each of perhaps 15 sections is envisioned. The capacity will be approximately 600 crystals per section or 9,000 crystals total.

STATION Q, ADJUSTMENT PLATE

Includes Process 51, Adjustment Plate

1. Material Entering Station

The average number of crystals per day which reach the adjustment plating process is 11,000. The crystals are stored in the curing oven in mounted form, the base pins of the mounts being inserted into ceramic blocks which in turn are assembled in channel-section racks, ten blocks to a rack. The blocks have external contact springs, which make an electrical connection to the crystal electrodes through the base pins. Each rack holds ten blocks of crystals.

2. Station Description

The Station consists of a number of adjustment plating machines, each an entirely self-contained unit, arranged adjacent to the curing oven of the previous Station.

Each plating machine is capable of accepting a rack of unplated crystals and of performing all operations of insertion into the chamber, pump-down to vacuum, plating, shut-off, and transfer to a receiving rack, without attendance by the operator. The racks must be replaced by the operator when emptied by the machine, or once for every ten crystals adjusted.

In operation, the crystals are transferred from the input rack to the vacuum chamber, which then closes and is pumped down to vacuum. In the chamber position, the crystal electrodes are connected to an electronic circuit which resonates the crystal and compares its frequency with a standard previously set to correspond to the desired nominal fundamental frequency.

As the desired vacuum is reached, gold wire deposited on a tungsten filament is evaporated onto the crystal and its resonant frequency is lowered. At the point where the crystal and standard frequencies match, plating is stopped. Air is then readmitted to the chamber, the chamber top is lifted, and a new crystal propelled into the working position, ejecting the finished one into a receiving rack and, if required, new gold is added to the filament. This cycle continues to repeat automatically until there are no more crystals on the input side, or until the operator stops the machine.

Before the input rack is placed in position, the crystals must be covered by a mask with a hole of a size appropriate to the base plating area. These masks will be put on individually by the operator, but as they are a loose fit and self-centering, they are easily dropped in place.

The sequence of operations will be as follows. The operator will remove a certain number of racks from the curing oven, perhaps five, and take them to the machine positions. Masks which are of a hole-size corresponding to the frequency called for in the job order will be selected to cover all crystals in the rack and dropped in place on top of the blanks. As the input rack of a machine becomes empty, the operator will stop the machine (which will, however, continue the plating operation of the crystal inside the chamber), remove the empty rack, and replace it with a fresh rack containing the crystals to be plated to the frequency for which the machine is set. The rack of adjusted crystals on the opposite side of the machine is removed and the empty one used to replace it. The masks are removed by inverting the rack and the rack of adjusted crystals placed on a conveyor which will remove it to the next station.

In the discussion of Process 51 it was stated that a complete adjustment cycle should not require in excess of 30 seconds per crystal.

A single machine will theoretically be able to plate two crystals per minute or 960 per 8-hour shift. The theoretical number of machines required is

$$\frac{11{,}000}{960} = 11.5 \text{ machines.}$$

Since major troubles with the electronic or vacuum systems would require machine shut-down and minor leaks will slow down the pumping cycle, a comparatively low efficiency (about 80%) should be assumed for the machines. A total of 15 machines will require an efficiency of $\frac{11.5}{15} = 76.5\%$ and a productive operating time per machine of $76.5 \times 480 = 368$ min./day.

The machine time to load and unload has been neglected since racks may be replaced without stopping the machine.

Thus, the minimum number of machines is 15.

A plating cycle longer than 30 seconds would increase the number of machines required. However, as the operator task is a function only of the number of crystals to be plated, the number of operators required would not increase. The man-machine system would not be basically affected.

3. Operator Tasks

	per rack (=10 crystals)
1. Replace racks at machine	25 sec.
2. Remove and stock masks	5 sec.
3. Remove 5 racks from curing oven and carry to machine station (30 sec./5 racks)	6
4. Select masks and place on blanks	20
	51 sec.

For 1100 rack/day

$$\text{Operator time} = \frac{51 \times 1100}{60} = 935 \text{ min./day}$$

For 3 operators, 1 per 5 machines	
Direct productive time	312 min.
Standby time	56 min.
Total time per operator (=machine time)	368 min./day
Operator efficiency	76.5%

4. Material Leaving Station—Yield

A nominal loss of 100 crystals per day due to handling is assumed, leaving 10,900 to be transferred to the next station.

5. Transfer to Next Station

The gold-plated crystals will be placed on a mechanical conveyor which will transfer them to the next operation. The crystals will be mounted in ceramic blocks and assembled in the same type of racks (10 per rack) in which they entered the station.

6. Machine Specifications

a. ADJUSTMENT PLATER

Purpose: Automatic adjustment of the nominal crystal frequency by means of gold evaporation plating.

Requirements: the plater must be capable of measuring the instantaneous value of the crystal resonant frequency during the plating, comparing it with a standard, and adjusting the amount of gold evaporated onto the crystal with a target accuracy ±0.001% of the nominal frequency (43 cycles for a 4.3 mc. crystal). The mechanism shall be capable of handling crystals in and out of the vacuum evaporation chamber automatically, without requiring reloading by the operator more often than once for each ten crystals plated. The average time for a loading, vacuum and plating cycle shall be approximately 30 seconds. The range of adjustment shall be between zero and at least $0.39f^2$ (approximately 0.6 microns thickness of gold).

Visualization: The frequency adjustment plater developed under this contract will be designed to meet these requirements. Loading, pump-down, measurement, plating and shut-off are automatic. The plater will accept specially mounted crystals (plugged into ceramic blocks) packaged in racks of ten crystals each, and will deliver plated crystals into similar racks.

STATION R, PREPARATION OF CANS

Includes Process 56, Frequency Stamp Cans
Process 57, Degrease Cans
Process 58, Hydrogen Anneal Cans

1. Material Entering Station

Sufficient metal cans to seal HC-6/U Holder Bases will be purchased and delivered to this Station daily. The average number of cans to be processed daily is 10,000.

2. Station Description

This Station will be located near the Base Sealing Area (Station S) and will consist of the following equipment:

Stamping Press
Degreaser, Trichloroethylene
Washer
Rinser
Drying Oven
H_2 Annealing Oven

Cans will be unboxed and fed to a stamping press, which will emboss the frequency and code designation of the crystal on the top and sides of the can. The stamping machine will be a commercial design. The dies will be set up by the operator according to previously prepared job orders specifying the nominal frequency and the number of cans required A counter will be provided to signal the operator or shut off the machine when the required number of cans are stamped. Cans will be manually or hopper-fed. If they are fed manually to the anvil of the machine, it is estimated that two seconds will be required per can. One machine and one operator will be required.

Stamped cans will be ejected from the press and collected by a second operator, who will keep them in batches according to frequency order. Cans will be loaded into wire baskets, each holding about 200 cans. The baskets will be placed directly into a commercial batch degreaser having a capacity of three baskets (600 cans). Fifteen minutes will be allowed to degrease the cans.

At the end of this time they will be removed by the operator and temporarily stored near the washer. The washer will hold hot detergent, and the baskets will be immersed in this solution for four minutes and transferred to a rinser.

The rinser will consist of a rotary or tunnel type device which will tumble and spray the cans with several changes of water while the baskets are conveyed through the machine. As presently contemplated, the machine will have three stations spraying tap water and three of demineralized water. A total of ten minutes will be required to pass through the rinser.

Baskets of cans passing through the rinser will be removed by the operator and emptied into mesh or perforated trays and the trays loaded into a drier oven. When six trays or 1200 cans are in place, the oven will be closed and the cans left to dry for 30 minutes while another six trays are being assembled. Five minutes will be allowed to transfer trays in and out of the oven.

As the final step in the processing, the trays unloaded from the drier will be placed in a commercial type of controlled-atmosphere oven which is capable of being evacuated and flushed with hydrogen gas. One or more changes of H_2 will be cycled through the oven while the cans are fired at a temperature near 450°C. The oven cycle will be automatically controlled, and will require 1 hour, 15 minutes. The oven capacity will be 12 trays of 200 cans, equivalent to 2400 cans. Alternately, a continuous feed oven of the same capacity may be used. At the end of the H_2 treatment the trays will be removed and conveyed to the Base Sealing Station (S).

Table R-1
SUMMARY OF CAN CLEANING EQUIPMENT

Equipment	*Capacity (Cans)*	*Process Time (min.)*	*Load/Unload Time (min.)*	*Theo. Output (8 hrs.)*	*No. Req'd.*	*Eff.*[2]
Degreaser	600	15	2	17,000	1	65%
Washer	200	4	1	19,200	1	57%
Rinser[1]	(400)	10	1	19,200	1	57%
Drier	1200	30	5	16,500	1	66%
H_2 Oven	2400	75	10	13,500	1	80%

Note (1): The rinser is conveyorized or continuously operating; all other equipment may be batch type, for ease in procuring commercial models.

Note (2): Theoretical efficiencies of equipment supplying the annealing oven are low because of the need for phasing the manual loading operations. Graphical studies have been made which indicate that these operations can be staggered correctly with a total output equal to the required average.

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3. Operator Tasks

a. CAN STAMPING OPERATOR

Stamp cans (2.0 sec./can)	(per 10,900 cans)
$\frac{2.0 \times 10{,}900}{60} =$	365 min.
Change dies (8 changes at 5 min. each)	40
	405 min.

Number of operators 1

Efficiency $\frac{405}{480} = 85\%$

b. CLEANING and ANNEALING OPERATOR

(See Table R-1)	*(per 200 cans)*
Load/Unload degreaser	0.67 min.
Load/Unload washer	1.0
Load/Unload rinser	0.5
Load/Unload drier	0.83
Load/Unload H_2 oven	0.83
	3.83 min.

Total productive time $\frac{3.83 \times 10{,}900}{200} = 210$ min./day

Idle time (determined by Annealing Oven rate) 175

Total (equal Annealing Oven utilization) 385 min./day

Number of operators 1

Operator Efficiency 80%

4. Material Leaving Station

The number of annealed cans leaving the process is 10,900 per day or approximately 55 trays of 200 each.

5. Transfer to Next Station

Cans will be conveyed to the Base Sealing Station (S) in the trays or any other convenient containers into which the cans may be emptied and remain clean.

6. Machine Specifications

a. STAMPING MACHINE

Purpose: To stamp cans with appropriate code and frequency designations.

Requirements: The cans must be stamped on top and sides at the rate of not less than 30 per minute. Changing dies must be simple and not require more than 5 minutes per set. Provisions for automatic counting of cans stamped will be needed.

Visualization: A commercial stamping machine should be adequate, and may be manually fed or automatic loading features will be added. If automatic, action of a predetermined counter will shut off the machine at the end of a frequency run, otherwise the counter can signal the operator of this fact.

b. DEGREASER

(This will be a small commercial batch machine similar to others previously described.)

c. WASHER

(This may be a small tank holding the washing solution and one degreasing basket, equipped with agitation. No special features are needed.)

d. RINSER

Purpose: To rinse washed cans.

Requirements: The cans must be rinsed in three changes of tap water and three of demineralized or distilled water at the rate of one basket (200 cans) per five minutes.

Visualization: To provide sufficient time for rinsing, a continuous apparatus with conveying features is envisioned. Agitation of cans may be required to obtain thorough rinsing with spray heads, or the baskets may be immersed in continuously flowing water in separate tanks.

e. DRIER

(A commercial drying oven of small size will be adequate)

(Note: Items b & d or b to e may be combined in one continuous machine)

f. HYDROGEN ANNEALING OVEN

Purpose: To treat cans with hydrogen gas in order to clean inside surfaces.

Requirements: A capacity of about 2400 cans per load. Provisions for heating to at least 450°C and for automatic time and temperature cycling and control. Provisions for evacuating and flushing with hydrogen by automatic cycle. The entire oven to be capable of unattended operation through a cycle and to be equipped with all safety precautions to avoid danger of explosion.

Visualization: A commercial model with the addition of appropriate controls may be adequate.

STATION S, BASE SEALING

Includes Process 52, Assemble Cans to Bases and Solder Preforms
Process 53, Base Sealing

1. Material Entering Station

This Station will receive an average of 10,900 mounted crystal units per day from Station Q, Adjustment Plating. These crystals will be mounted in ceramic blocks and assembled in racks. An equal number of cleaned HC-6/U metal cans will be received from Station R.

2. Station Description

This Station will consist of equipment (1) to produce solder preforms and assemble precleaned HC-6/U cans to the frequency-adjusted crystal units, (2) to flux the assemblies, and (3) machines to seal the cans to the bases in a controlled atmosphere.

A single machine will be used to make the preforms from solder spools and place them around the edges of the cans, which have already been stamped with the desired frequency and code in a previous process. An operator will receive the cans from the hydrogen annealing furnace (Station R) and feed them to the machine via a hopper. The same operator will supervise input of racks of crystals adjusted to the frequency stamped on the cans, these racks being mechanically conveyed from Station Q.

Crystal units emerging from the machine will have the cans clamped to the bases, solder preforms in place, and will be fluxed and in condition to enter the base sealing machine.

The solder preform and can assembly machine will be designed to handle an average of 11,000 crystals per day with allowance for change-over from one frequency type to another. An operation time of 2 seconds per crystal will be adequate to process 17,000 crystals per day or to handle the average input of 10,900 at an efficiency of 65%. One operator will be needed to supervise the machine and to insure that the incoming crystals are matched to the correctly stamped cans.

The solder preforming and can assembly machine will produce racks of ten unsealed crystal units at a rate of one every 20 seconds or 3 per minute. These racks will be loaded into special trays by a second operator who will supervise loading and unloading of the base sealing machines. A tray of 40 racks or 400 crystals will be assembled to constitute one sealing machine load.

The sealing machines will operate on a total cycle of 25 minutes including loading and unloading (per 400 crystals), hence their output is

$$\frac{400}{25} \times 480 = 7680 \text{ units}$$

per day.

Two units will suffice to handle an average day's production, at an efficiency of

$$\frac{10,900}{2 \times 7680} = 71.3\%$$

One operator will be required to load and unload these machines.

3. Operator Tasks

a. SOLDER PREFORMING AND CAN ASSEMBLY OPERATOR

No. of operators	1
Operator efficiency	65%

b. BASE SEALING MACHINE OPERATOR

Machine load/unload time (3 min./load)

$$\frac{10,900}{400} \times 3 = \qquad 82 \text{ min.}$$

Load trays, remove clamps from racks, unload racks from trays.	260
Total time	342 min.
Operators required	1
Operator efficiency	71.3%

4. Material Leaving Station

Sealed crystal units will leave the base sealing machine assembled in racks of ten. The average output will be 10,900 crystal units per day or 1090 racks.

5. Transfer to Next Station

Racks will be propelled to the next station by means of powered or unpowered roller conveyor.

6. Machine Specifications

a. SOLDER PREFORM AND CAN ASSEMBLY MACHINE

Purpose: To assemble solder preforms to cans, assemble cans to bases, clamp and flux cans in preparation for base sealing.

Requirements: The machine shall perform the above operations at a rate of one crystal per two seconds. Special care shall be taken to prevent damage to crystal blanks when inserting the can, or in allowing flux to enter the crystal unit.

Visualization: A completely automatic machine is envisioned which is capable of forming solder around the edge of the can as it is fed from a hopper and orienting mechanism, placing the cans on a rack of crystals traveling beneath, and clamping a spring-loaded bar on ratchet guides on either side of the rack as the cans are held in place. It is visualized that the assembled rack will be inverted and the flux applied from below by a controlled spray or brush so as to reduce danger of getting the flux inside the cans.

b. BASE SEALING MACHINE

Purpose: To seal crystal units in a controlled atmosphere.

Requirements: The machine will be capable of handling 400 crystal units and passing them through an induction coil (one at a time), after evacuating and flushing them with a dry gas. The machine will be capable of mixing nitrogen and helium as the filling atmosphere or of handling either alone.

The machine cycle (for sealing 400 crystals) will be on the order of 25 minutes.

Visualization: An automatic cycling machine of these capabilities has been designed and tested in principle. The machines will be loaded with crystal units prefluxed and with solder applied, and will handle them in special racks and trays.

STATION T, FREQUENCY CHECK

Includes Process 54, Frequency Checking

1. Material Entering Station

The average number of crystals being processed in the base sealing machine will be 10,900, but of these approximately 2% or 200 per day will be rejected owing to failure to pass leakage quality control tests. If the quality control procedure is sufficiently rapid, an average of 10,700 crystal units will be available for frequency check.

2. Description of Station

The frequency and activity checking area will be immediately following the base sealing station. It will consist of a single type of machine which is equipped to indicate defective crystal units, depending on their ability to pass frequency and activity tests at room temperature.

The machine envisioned will accept the racks of crystal units as they come from the base sealer and will handle them automatically through the testing mechanisms. An operator will be required to load racks into the machine. A test will require approximately 2.3 seconds or one rack of ten units will be fed into the machine every 23 seconds. The theoretical capacity of the machine will be $480 \times \frac{60}{23} = 12{,}500$ units per 8-hour shift, and the efficiency will be $\frac{10{,}700}{12{,}500} \times 100 = 86\%$.

Hence, one machine will be required.

3. Operator Tasks

The operator will be required to feed the machine as above and to remove defective units as indicated by the machine. Only one operator will be required to keep up with the machine at the cited rates and to unplug crystals from ceramic blocks. Blocks will be placed in tote boxes for conveyance back to Mounting and Cementing (Station P)

Operators required	1
Operator efficiency	86%

4. Material Leaving Station

Approximately 300 units per day will be rejected by the frequency check unit. This will leave a total of 10,400 units. However, quality control sampling will be used to choose a given number of each lot for a final heat run, consisting of frequency and activity tests between −55° and +90°C. A certain number of lots will be expected to fail to meet Military Specifications. An average of 400 crystals per day may be rejected without compromising the rated goal of 10,000 units per day.

5. Transfer to Next Station

The crystal units will be transferred to the Packaging area in tote boxes or conveyors, arranged in lots of the same frequency and order. Rejected crystals will be scrapped or saved for later salvage of parts.

6. Machine Specifications

a. FREQUENCY AND ACTIVITY CHECKER

Purpose: To test crystal units at room temperature for conformance to frequency limits and effective-resistance.

Requirements: The accuracy of frequency and resistance tests are not firmily fixed and will be the subject of future study. However, the checking machine probably must be nearly an order of magnitude more accurate than the Military Specification (±0.005%) over the frequency range, and the resistance sensitivity perhaps within one ohm. The machine must be capable of handling crystal units automatically and testing them on a "go-no go" basis at the rate of 26 crystals per minute or better. The unit must also cover the range of frequency and activity of the crystals of this contract, and changes in limits must be made simply and without requiring excessive skill or time. The resistance of the crystal may be checked solely against an upper allowable limit without the need for actual measurement of the resistance value.

Visualization: The units as envisioned will be a desk-type machine, similar in appearance-and mechanical handling equipment to the Final Plater. The electronic equipment will consist of a modification of the C.I. Meter and of a simplification of the counting and control equipment of the Frequency Sorter or of other commercially available counting equipment. The mechanical portion will accept crystals in the same racks as used in base sealing and other processes.

STATION U, PACKAGING

Includes Process 55, Packaging

1. Material Entering Station

An average of 10,000 crystal units per day will enter from frequency check (Station T), the units being plugged into ceramic blocks.

2. Station Description

The station will be comprised of benches, jigs and mechanized equipment for handling packaging material and packing crystal units. The location of the station will be adjacent to Station T and to the shipping room. Containers for packaging the units (or machinery for fabricating the containers) will be stored in this area.

Operations will be mechanized in order to reduce the operator task. Crystal units will be kept separated according to frequency and passed to the packaging bench.

Two operators will probably be required to box an average day's output of 10,000 crystal units, together with a third utility operator who will arrange stock and assemble packaging material.

3. Operator Tasks

a. *Package Crystal Units (10,000/day)*

Estimated packaging time	12 units/min.
Units packaged per operator	5,000/day
No. of operators	2
Operator efficiency	87%

4. Material Leaving Station

10,000 packaged crystal units per day will be stored in the Shipping Room.

5. Transfer to Next Station

Manually, to Shipping Room.

6. Machine Specifications

(None established.)

APPENDIX I

Maximum Order Board
(per month)

CR-18/U

	Frequency	Quantity		Frequency	Quantity
1.	4.3000 mc.	12000	30.	8.387500 mc.	5089
2.	6.091666	2689	31.	8.516666	2689
3.	6.183333	2689	32.	8.637500	2689
4.	6.258333	2689	33.	8.775000	2689
5.	6.425000	2689	34.	8.850000	2689
6.	6.516666	2689	35.	8.887500	2689
7.	6.591666	2689	36.	9.5375	589
8.	6.758333	2689	37.	9.6375	589
9.	6.850000	2689	38.	9.7375	589
10.	6.887500	2689	39.	9.8375	589
11.	6.925000	2689	40.	9.9375	589
12.	7.091666	2689	41.	10.0000	589
13.	7.137500	2689	42.	10.0375	589
14.	7.183333	2689	43.	10.1375	589
15.	7.258333	2689	44.	10.2375	589
16.	7.385500	2689	45.	10.3375	589
17.	7.425000	5089	46.	10.4375	589
18.	7.516666	2689	47.	12.950	439
19.	7.591666	2689	48.	13.050	439
20.	7.637500	2689	49.	13.150	439
21.	7.758333	2689	50.	13.250	439
22.	7.775000	2689	51.	13.350	439
23.	7.850000	2689	52.	13.450	439
24.	7.887500	2689	53.	13.550	439
25.	7.925000	2689	54.	13.650	439
26.	8.091666	2689	55.	13.750	439
27.	8.137500	2689	56.	13.850	439
28.	8.183333	2689	57.	15.000	889

Total CR-18/U Crystals (page 99)	120,000
Total CR-23/U Crystals (page 100)	80,000
Grand Total	200,000

Maximum Order Board
(per month)

CR-23/U

Frequency	*Quantity*
1. 31.449 mc.	240
2. 32.449	240
3. 33.449	240
4. 34.449	240
5. 35.449	240
6. 36.449	240
7. 37.449	240
8. 37.85	120
9. 38.35	120
10. 38.449	240
11. 38.85	120
12. 39.35	120
13. 39.449	240
14. 39.85	120
15. 40.35	120
16. 40.449	240
17. 40.85	120
18. 41.35	120
19. 41.449	240
20. 41.85	120
21. 42.35	120
22. 42.449	240
23. 42.700	1440
24. 42.85	120
25. 42.900	1440
26. 43.100	1440
27. 43.300	1440
28. 43.35	120
29. 43.449	240
30. 43.500	1440
31. 43.700	1440
32. 43.85	120
33. 43.900	1440
34. 44.100	1440
35. 44.300	1440
36. 44.35	120
37. 44.449	240
38. 44.500	1440
39. 44.700	1440
40. 44.85	120
41. 44.900	1440
42. 45.100	1440
43. 45.300	1440
44. 45.350	120
45. 45.500	1440
46. 45.700	1440
47. 45.85 mc.	120
48. 45.900	1440
49. 46.100	1440
50. 46.300	1440
51. 46.35	120
52. 46.500	1440
53. 46.700	11960
54. 46.85	120
55. 46.900	1440
56. 47.100	1440
57. 47.300	1440
58. 47.35	120
59. 47.500	1440
60. 47.700	1440
61. 47.85	120
62. 47.900	1440
63. 48.100	1440
64. 48.300	1440
65. 48.35	120
66. 48.500	1440
67. 48.700	1440
68. 48.85	120
69. 48.900	1440
70. 49.100	1440
71. 49.300	1440
72. 49.35	120
73. 49.500	1440
74. 49.700	1440
75. 49.85	120
76. 49.900	1440
77. 50.100	1440
78. 50.300	1440
79. 50.35	120
80. 50.500	1440
81. 50.700	1440
82. 50.85	120
83. 50.900	1440
84. 51.100	1440
85. 51.35	120
86. 51.85	120
87. 52.35	120
88. 52.85	120
89. 53.35	120
90. 53.85	120
91. 54.35	120
92. 54.85	120

Appendix I

Typical Order Board

	Freq. mc.	*Quan. in M/Month*	*Type*
1.	4.3	25	CR-18/U
2.	6.18	5	
3.	6.42	5	
4.	6.59	5	
5.	6.85	5	
6.	6.92	5	
7.	7.13	5	
8.	7.25	5	
9.	7.51	10	
10.	7.63	5	
11.	7.77	5	
12.	7.88	5	
13.	8.09	5	
14.	8.18	5	
15.	8.38	10	
16.	8.63	5	
17.	8.85	5	
18.	8.88	5	
19.	42.7	2.96	CR-23/U
20.	43.1	2.96	
21.	43.5	2.96	
22.	43.9	2.96	
23.	44.3	2.96	
24.	44.7	2.96	
25.	45.1	2.96	
26.	45.5	2.96	
27.	45.9	2.96	
28.	46.3	2.96	
29.	46.6	2.96	
30.	46.7	20.80	
31.	47.1	2.96	
32.	47.5	2.96	
33.	47.9	2.96	
34.	48.3	2.96	
35.	48.7	2.96	
36.	49.1	2.96	
37.	49.5	2.96	
38.	49.9	2.96	
39.	50.3	2.96	

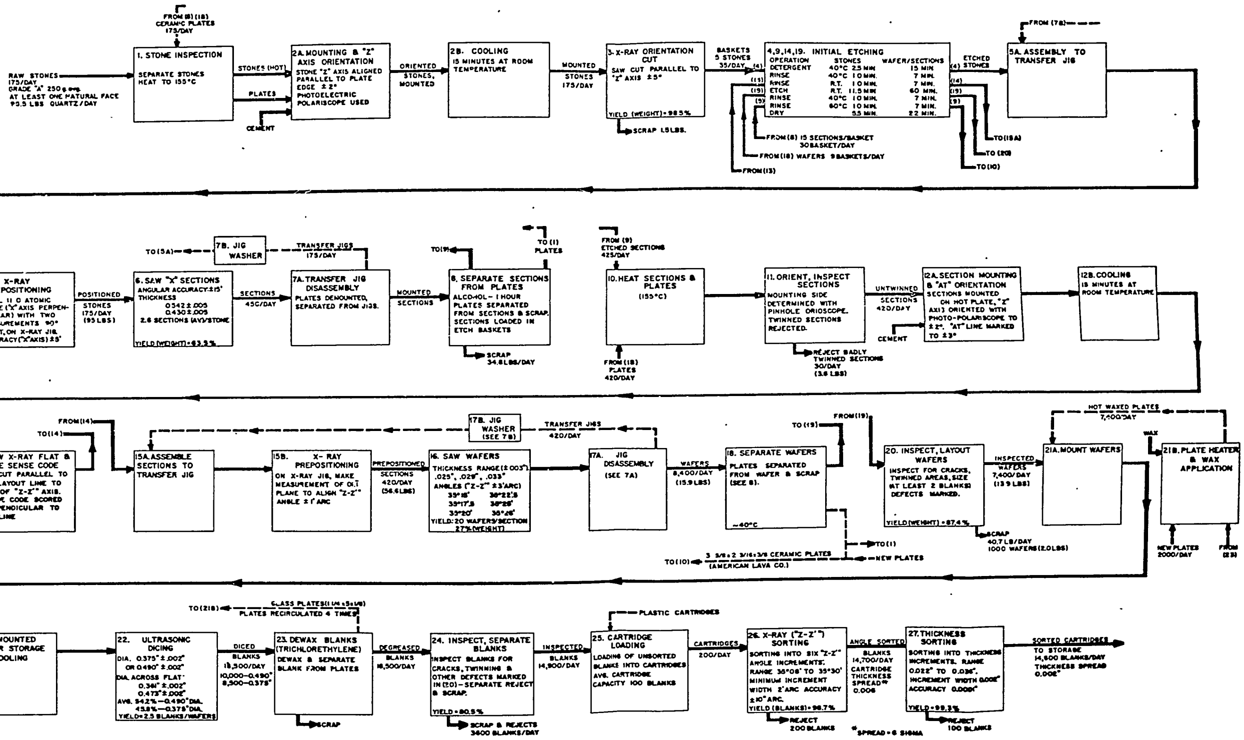
Total CR-18/U Crystals	120,000
Total CR-23/U Crystals	80,000
Grand Total	200,000

APPENDIX II

Summary of Major Equipment and Labor Requirements
(200,000 Crystal Units per Month, One Shift Operation)

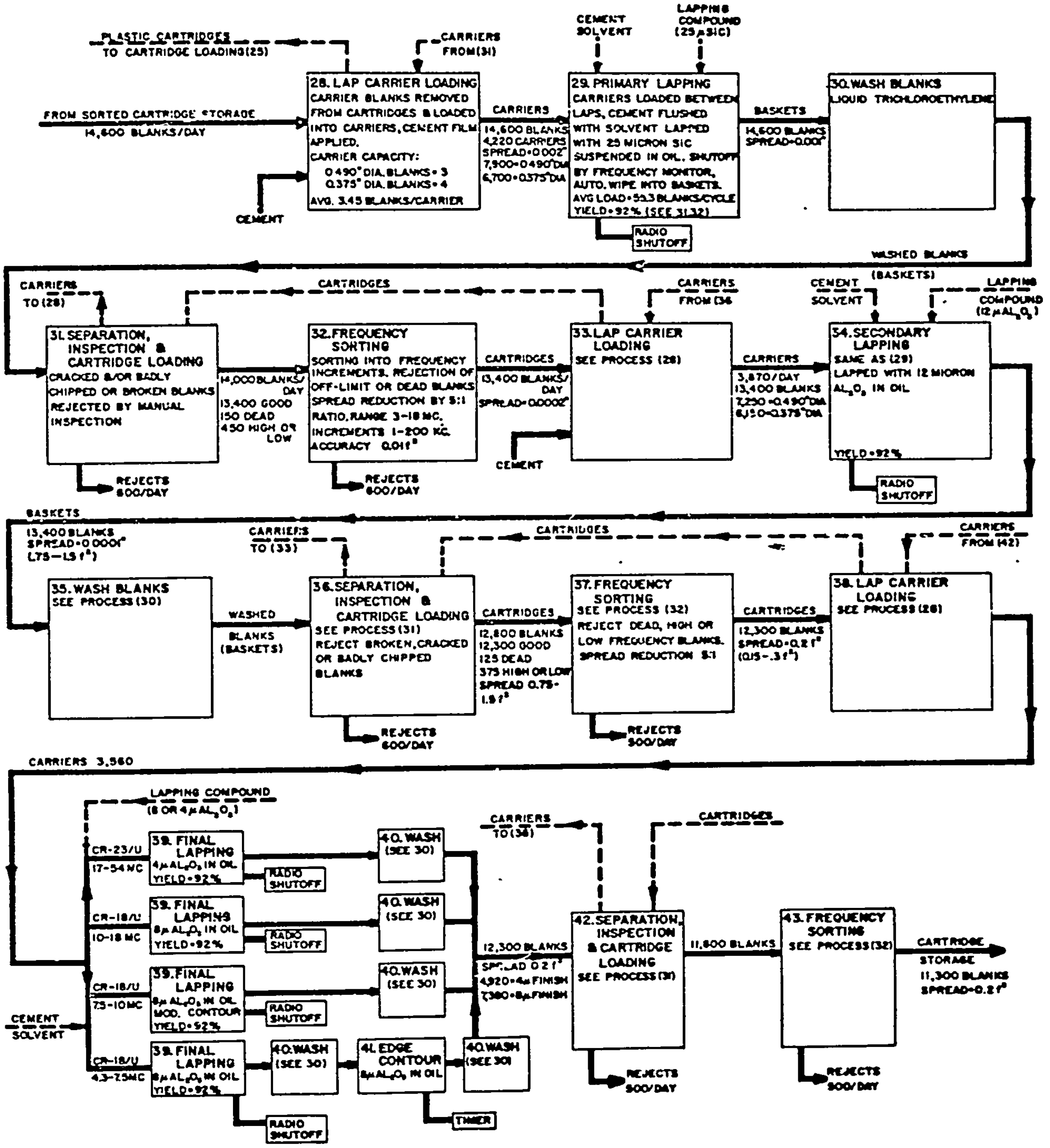
Station	*Equipment*		*Operators*
A, A′. Mount Stones, Sections Orientation Cut and Sense Codes	Stone Oven	1	3
	Section Oven	1	
	Table Saw	3	
	Photo-Polariscopes	2	
	Orioscope	1	
B. Initial Etch	Initial Etch Machine	1	1
C. Prepositioning	X-ray Prepositioner	1	1
D. Section Sawing	Section Saw	1	1
	Jig Degreaser	1	
	Section Separator	1	
E. Wafer Sawing	Wafer Saws	4	2
	Jig Degreaser	1	
	Wafer Separator	1	
F. Dicing	Wafer Mounting Machines	2	8
	Ultrasonic Dicers	4	
	Dewaxer (Separator)	1	
	Cartridge Loader	2	
G. X-ray/Thickness Sorting	X-ray Sorter	1	2
	Thickness Sorter	1	
H. Lap Carrier Loading	Carrier Loaders	3	1
I, L, M. Lapping	Lapping Machines	15	9
	Blank Washers	9	
	Inspection Stations	3	
M′. Contouring	Contouring Machines	5	5
	Blank Washers	3	
J. Condition Lapping Plates	Lapmasters (36″)	4	1
K. Frequency Sorting	Frequency Sorter	1	1
N. Final Etch	Final Etching Machine	1	1
	Degreaser	1	
	Conveyorized Drier	1	
	Etch Holder Loader	1	
O. Base Plate	Base Platers	3	2
	Mask Loader	1	
	Pre-Aging Oven	1	
P. Mounting and Cementing Blanks	Mounting & Cementing Machine	2	3
	Conveyorized Air-Dry Table	2	
	Curing Oven	1	
	Degreaser	1	
Q. Adjustment Plate	Final Platers	15	3
R. Prepare Cans	Frequency Stamping Press	1	2
	Degreaser	1	
	Washer, Rinser	1	
	Drying Oven	1	
	H_2 Annealing Oven	1	
S. Base Sealing	Base Sealer	2	2
	Solder Preform and Assy.	1	
T. Frequency Check	Frequency Checker	1	1
U. Packaging			2
	Totals	112	51

APPENDIX IIIa
ROUGH CUTTING AND SORTING PROCESSES

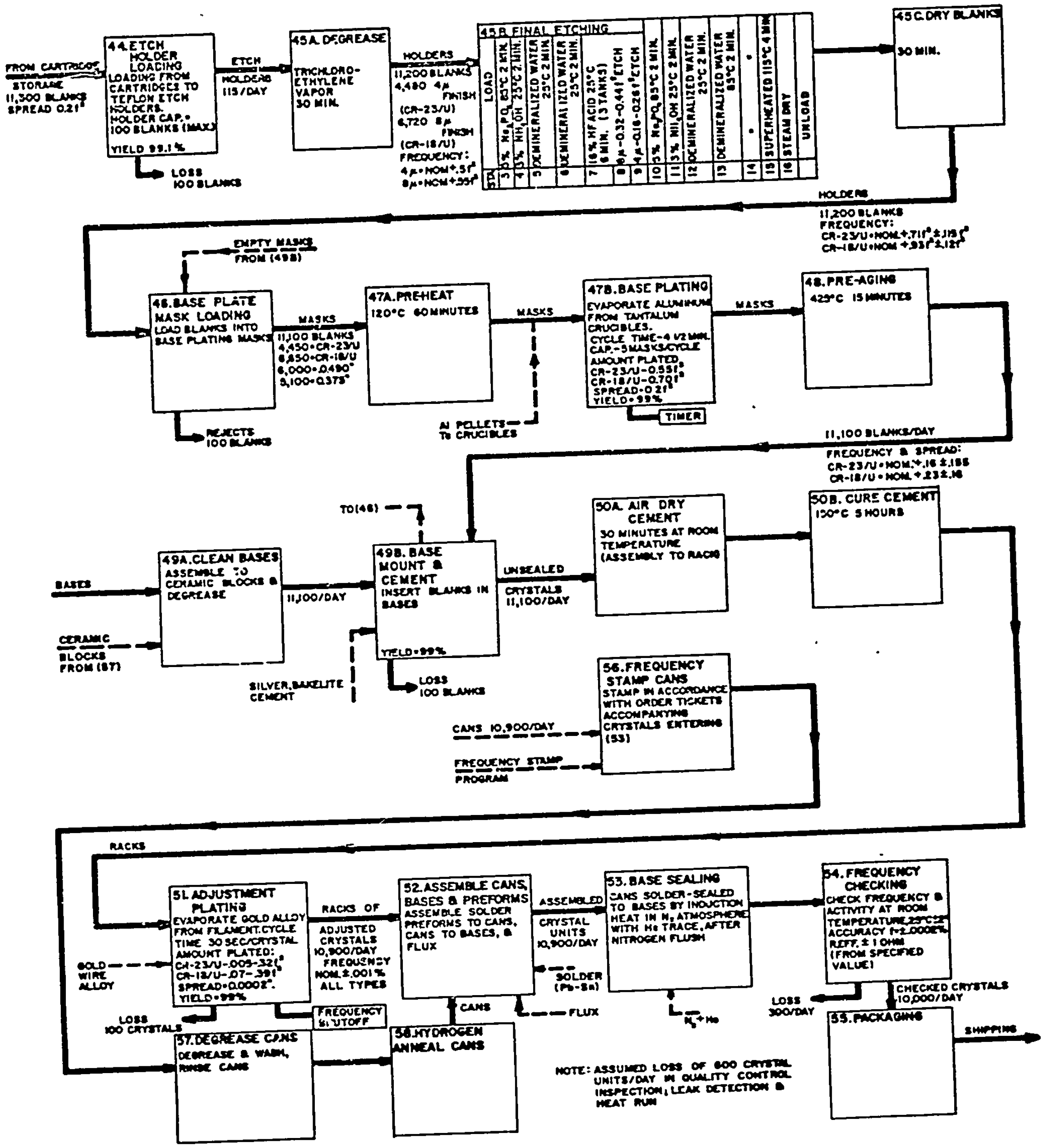


APPENDIX IIIb

INTERMEDIATE OPERATIONS



APPENDIX IIIc
FINISHING OPERATIONS



APPENDIX IV

Frequency Chart

The accompanying chart is a complete outline of the changes in frequency, thickness, and spread which occur during the processes chosen for the Mechanized Quartz Crystal Plant, from the sawing of wafers to the final adjustment plating of crystal units. The spreads of frequency or thickness shown are expressed in terms of standard deviations (σ) where spread is taken as equal to 6σ. Other terms used in this chart are explained in the Notes.

The examples (nominal frequencies) for which calculations are given were chosen on the basis of their relative demand as indicated by the Maximum Order Board (Appendix I), and indicated percentage-wise in the fourth column of this chart. Where the demand shown is zero, the examples were taken because they are terminal frequencies (i.e., the highest or lowest frequency of each crystal type considered in this contract), or significant because of a change in blank diameter.

The chart is useful in estimating the changes in thickness or frequency or tolerance which occur various stages in lapping and finishing. For example, the amount of quartz removal for each stage in lapping is shown, from which the average lapping times may be estimated. Also, the range and accuracy required of various measuring and sorting instruments can be deduced from the chart. What is more important, the chart serves as a preliminary schedule of operations and of quality control points throughout the plant, from and subsequent to the wafering process.

In this chart, ranges are added by combining them statistically, that is, the spread resulting from two processes, each of a given range, is the square root of the summation of the squares of the individual ranges.

	Freq. Range (mc.)	Nominal Freq. (mc.)	Blank Diam. (in.)	% Demand (12)	Fundamental Nom. Freq. $f_{1,nom}$ (mc.)	$f_1{}^2{}_{,nom}$ (kc.)	ZZ' Angle	Unsorted Blanks and Wafers. Thickness (Nom.) (inches)	Unsorted Blanks and Wafers. Thickness Range (inches)	Sorted Blanks Thickness Average of Lots used (1) (inches)	Sorted Blanks Range (inches)	First L Amt. Removed Average (in.)	First L Thickness (6) t_{nom} (in.)
CR-18/U (First Harmonic)	4.3-6.0	4.3(4)	.490	6.0	4.3	18.49	35°15'	.033	.006	.033	.002	.013	.0200
	6.0-9.0	6.1	.490		6.1	37.21	17.5'	.029	.006	.031	.002	.016	.0154
				48.1(2)									
		8.9	.490		8.9	79.21	17.5'	.029	.006	.027	.002	.015	.0120
	9.0-11.5	9.5	.375		9.5	90.25	20'	.025	.006	.027	.002	.015	.0115
				3.2(2)									
		10.4	.375		10.4	108.16	20'	.025	.006	.023	.002	.012	.0109
	11.5-18.0	12.9	.375		12.9	166.41	22.5'	.025	.006	.027	.002	.017	.0096
				2.7(2)									
		15.0	.375		15.0	225.00	22.5'	.025	.006	.023	.002	.014	.0089
		18.0	.375	0	18.0	324.00	22.5'	.025	.006	.023	.002	.015	.0082
CR-23/U (Third Harmonic)	17.0-25.0	17.0	.490	0	5.667	32.11	25'	.029	.006	.029(3)	.002	.014	.0152
	25.0-54.0	25.0	.375	0	8.333	69.39	26.5'	.025	.006	.027	.002	.016	.0115
		31.5	.375		10.5	110.25	26.5'	.025	.006	.027	.002	.017	.0098
				15.0									
		46.5	.375										
		46.7(4)	.375	10.0	15.567	242.31	26.5'	.025	.006	.025	.002	.017	.00775
		46.8	.375										
				15.0									
		54.0	.375		18.0	324.00	26.5'	.025	.006	.023	.002	.016	.0072

SYMBOLS AND SUBSCRIPTS

f_1 = fundamental frequency at any stage
$f_{nom.}$ = nominal frequency (after final plating)
1L = first lap
2L = second lap, etc.
$f_1{}^2$ = ratio of fundamental frequency increment in kilocycles to the square of the nominal fundamental frequency expressed in megacycles, $(f_{1,\,nom.})^2$

NOTES

(1) Blanks sorted into 3 ranges each type,

(2) Flat order board distribution in this rang

(3) All blanks made for this frequency would

(4) Order board peaked at this frequency.

(5) Formula: thickness, $t = \dfrac{66.60}{f_1}$ used th

(6) Assumed 2:1 improvement possible in firs

APPENDIX IV FREQUENCY CHART

anks	First Lap					1st Freq. Sort (7)		Second Lap						2nd Freq. Sort		Third Lap				F.
Range	Amt. Removed Average (in.)	Thickness (5) t_{nom} (in.)	Thickness Range (6) (in.)	Frequency $f_{1, 1L}$ (mc.)	Range (kc.)	Thickness Range (in.)	Range (kc.)	Amount Removed (in.)	Thick. t_{2L} (in.)	Thick. Range (in.)	Freq. $f_{1, 2L}$ (avg.) (mc.)	Range (kc.)	Range (f_1^2)	Range (7) kc.	Range (7) (f_1^2)	Amount Removed (in.)	Thickness Average (in.)	Freq. $f_{1, 3L}$ (mc.)	F. above Nom. (8) (kc.)	No
.002	.013	.0200	.001	3.330	166.6	.0002	33.3	.003	.01695	.0001	3.9292	23.2	1.25	4.6	0.25	.0015	.01545	4.31017	10.17	
.002	.016	.0154	.001	4.325	281.1	.0002	56.1	.003	.0:238	.0001	5.3796	43.5	1.17	8.7	0.23	.0015	.01088	6.12047	20.47	
.002	.015	.0120	.001	5.550	463.3	.0002	92.5	.003	.00895	.0001	7.4413	83.2	1.05	16.7	0.21	.0015	.00745	8.94357	43.57	
.002	.015	.0115	.001	5.791	504.5	.0002	100.7	.003	.00847	.0001	7.8630	92.8	1.03	18.6	0.21	.0015	.006974	9.54964	49.64	
.002	.012	.0109	.001	6.110	561.7	.0002	112.2	.003	.00787	.0001	8.4625	107.6	1.00	20.6	0.20	.0015	.006367	10.4595	59.49	
.002	.017	.0096	.001	6.938	724.6	.0002	144.5	.003	.00663	.0001	10.0452	151.6	0.94	30.3	0.19	.0015	.005126	12.9915	91.53	
.002	.014	.0089	.001	7.483	843.5	.0002	176.0	.003	.00590	.0001	11.2881	191.4	0.85	38.3	0.17	.0015	.004404	15.1238	123.75	
.002	.015	.0082	.001	8.122	994.2	.0002	198.1	.003	.00516	.0001	12.9070	250.1	0.77	50.0	0.15	.0015	.003664	18.1782	178.2	
.002	.014	.0152	.001	4.382	282.6	.0002	57.7	.003	.01222	.0001	5.4491	44.6	1.39	8.9	0.28	.0005	.011720	5.6827	16.06	
.002	.016	.0115	.001	5.791	504.5	.0002	100.5	.003	.00846	.0001	7.8723	93.1	1.34	18.6	0.27	.0005	.007959	8.3680	34.70	
.002	.017	.0098	.001	6.796	695.3	.0002	138.7	.003	.00681	.0001	9.7797	143.7	1.31	28.7	0.26	.0005	.006310	10.5551	55.13	
.002	.017	.00775	.001	8.539	1099.2	.0002	219.0	.003	.00475	.0001	14.0211	295.3	1.22	59.4	0.24	.0005	.004245	15.6882	121.16	
.002	.016	.0072	.001	9.250	1290.3	.0002	257.0	.003	.00417	.0001	15.9712	383.2	1.18	76.5	0.24	.0005	.003667	18.1620	162.0	

NOTES

(1) Blanks sorted into 3 ranges each type, .002″ wide. Distribution is 68.1% center 2σ
15.8% 2σ each side of nominal.

(2) Flat order board distribution in this range.

(3) All blanks made for this frequency would be used only on that order.

(4) Order board peaked at this frequency.

(5) Formula: thickness, $t = \frac{66.60}{f_1}$ used throughout t = thickness in mil-inches
f_1 = fundamental frequency in megacycles/second

(6) Assumed 2:1 improvement possible in first and second lapping stages.

(7) Assumed 5:1 improvement in sorting stages.

(8) $(f_{1, 3L} - f_{1, nom})$ in kc.

(9) $(f_{1, 3L} - f_{nom})$ kc/f_1^2 (Units of f_1^2

(10) Range of (kc.)/f_1^2

(11) + Designates freq. increase

(12) From "Maximum Order Board". For frequencies ranges not shown in second column

(13) Deviation in terms of third harmonic for CR-23/U crystals units.

2nd Freq. Sort		Third Lap							3rd Freq. Sort		Final Etch				Base Plate					
ange (7) kc.	Range (7) (f_1^2)	Amount Removed (in.)	Thickness Average (in.)	Freq. $f_{1,3L}$ (mc.)	F. above Nom. (8) (kc.)	F. above Nom. (9) (f_1^2)	Frequency (kc.)	Range (10) (f_1^2)	Range (kc.)	Range (f_1^2)	Amt. Etch (11) ($+f_1^2$)	Range ($+f_1^2$)	Freq. Above Nom. after Etch ($+f_1^2$)	Range After Etch (f_1^2)	Amt. ($-f_1^2$)	Range of B. P. (f_1^2)	Freq. Above Nom. ($+f_1^2$)	Range after B. P. (f_1^2)	Min. ($-f_1^2$)	Ma ($-f$
4.6	0.25	.0015	.01545	4.31017	10.17	+0.55	3.7	0.2	3.7	0.2	0.38	0.12	0.93	0.24	0.70	0.20	0.23	0.32	0.07	0.3
8.7	0.23	.0015	.01088	6.12047	20.47	+0.55	7.4	0.2	7.4	0.2	0.38	0.12	0.93	0.24	0.70	0.20	0.23	0.32	0.07	0.3
16.7	0.21	.0015	.00745	8.94357	43.57	+0.55	15.8	0.2	15.8	0.2	0.38	0.12	0.93	0.24	0.70	0.20	0.23	0.32	0.07	0.3
18.6	0.21	.0015	.006974	9.54964	49.64	+0.55	18.0	0.2	18.0	0.2	0.38	0.12	0.93	0.24	0.70	0.20	0.23	0.32	0.07	0.3
20.6	0.20	.0015	.006367	10.4595	59.49	+0.55	21.6	0.2	21.6	0.2	0.38	0.12	0.93	0.24	0.70	0.20	0.23	0.32	0.07	0.3
30.3	0.19	.0015	.005126	12.9915	91.53	+0.55	32.2	0.2	32.2	0.2	0.38	0.12	0.93	0.24	0.70	0.20	0.23	0.32	0.07	0.3
38.3	0.17	.0015	.004404	15.1238	123.75	+0.55	45.0	0.2	45.0	0.2	0.38	0.12	0.93	−0.24	0.70	0.20	0.23	0.32	0.07	0.3
50.0	0.15	.0015	.003664	18.1782	178.2	+0.55	64.8	0.2	64.8	0.2	0.38	0.12	0.93	0.24	0.70	0.20	0.23	0.32	0.07	0.3
8.9	0.28	.0005	.011720	5.6827	16.06	+0.50	6.4	0.2	6.4	0.2	0.21	0.10	0.71	0.23	0.55	0.20	0.16	0.31	0.005	0.3
18.6	0.27	.0005	.007959	8.3680	34.70	+0.50	15.8	0.2	13.8	0.2	0.21	0.10	0.71	0.23	0.55	0.20	0.16	0.31	0.005	0.3
28.7	0.26	.0005	.006310	10.5551	55.13	+0.50	22.0	0.2	22.0	0.2	0.21	0.10	0.71	0.23	0.55	0.20	0.16	0.31	0.005	0.3
59.4	0.24	.0005	.004245	15.6882	121.16	+0.50	48.4	0.2	48.4	0.2	0.21	0.10	0.71	0.23	0.55	0.20	0.16	0.31	0.005	0.
76.5	0.24	.0005	.003667	18.1620	162.0	+0.50	64.8	0.2	64.8	0.2	0.21	0.10	0.71	0.23	0.55	0.20	0.16	0.31	0.005	0.

Assumed 5:1 improvement in sorting stages.

$(f_{1,3L} - f_{1,nom})$ in kc.

$(f_{1,3L} - f_{nom})$ kc/f_1^2 (Units of f_1^2

Range of (kc.)/f_1^2

+ Designates freq. increase

From "Maximum Order Board". For frequencies ranges not shown in second column there is no demand.

Deviation in terms of third harmonic for CR-23/U crystals units.

Third Lap					3rd Freq. Sort		Final Etch				Base Plate				Final Plate					
Freq. f_1, 8L (mc.)	F. above Nom. (8) (kc.)	F. above Nom. (9) (f_1^2)	Frequency (kc.)	Range (10) (f_1^2)	Range (kc.)	Range (f_1^2)	Amt. Etch (11) ($+f_1^2$)	Range ($+f_1^2$)	Freq. Above Nom. after Etch ($+f_1^2$)	Range After Etch (f_1^2)	Amt. ($-f_1^2$)	Range of B. P. (f_1^2)	Freq. Above Nom. ($+f_1^2$)	Range after B. P. (f_1^2)	Min. ($-f_1^2$)	Max. ($-f_1^2$)	Range (%f_1)	Range Kc. (12)	Range (f_1^2)
4.31017	10.17	+0.55	3.7	0.2	3.7	0.2	0.38	0.12	0.93	0.24	0.70	0.20	0.23	0.32	0.07	0.39	±0.001	±0.043	±.0023
6.12047	20.47	+0.55	7.4	0.2	7.4	0.2	0.38	0.12	0.93	0.24	0.70	0.20	0.23	0.32	0.07	0.39	±0.001	±0.061	±.0016
8.94357	43.57	+0.55	15.8	0.2	15.8	0.2	0.38	0.12	0 93	0.24	0.70	0.20	0.23	0.32	0.07	0.39	±0.001	±0.089	±.0011
9.54964	49.64	+0.55	18.0	0.2	18.0	0.2	0.38	0.12	0.93	0.24	0.70	0.20	0.23	0.32	0.07	0.39	±0.001	±0.095	±.0011
10.4595	59.49	+0.55	21.6	0.2	21.6	0.2	0.38	0.12	0.93	0.24	0.70	0.20	0.23	0.32	0.07	0.39	±0.001	±0.104	±.0011
12.9915	91.53	+0.55	32.2	0.2	32.2	0.2	0.38	0.12	0.93	0.24	0.70	0.20	0.23	0.32	0.07	0.39	±0.001	±0.129	±.0008
15.1238	123.75	+0.55	45.0	0.2	45.0	0.2	0.38	0.12	0.93	0.24	0.70	0.20	0.23	0.32	0.07	0.39	±0.001	±0.150	±.0007
18.1782	178.2	+0.55	64.8	0.2	64.8	0.2	0.38	0.12	0.93	0.24	0.70	0.20	0.23	0.32	0.07	0.39	±0.001	±0.180	±.0006
5.6827	16.06	+0.50	6.4	0.2	6.4	0.2	0.21	0.10	0.71	0.23	0.55	0.20	0.16	0.31	0.005	0.315	±0.001	±0.170	±.0018
8.3680	34.70	+0.50	13.8	0.2	13.8	0.2	0.21	0.10	0.71	0.23	0.55	0.20	0.16	0.31	0.005	0.315	±0.001	±0.250	±.0012
10.5551	55.13	+0.50	22.0	0.2	22.0	0.2	0.21	0.10	0.71	0.23	0.55	0.20	0.16	0.31	0.005	0.315	±0.001	±0.315	±.0010
15.6882	121.16	+0.50	48.4	0.2	48.4	0.2	0.21	0.10	0.71	0.23	0.55	0.20	0.16	0.31	0.005	0.315	±0.001	±0.465	±.0006
18.1620	162.0	+0.50	64.8	0.2	64.8	0.2	0.21	0.10	0.71	0.23	0.55	0.20	0.16	0.31	0.005	0.315	±0.001	±0.540	±.0006

ges not shown in second column there is no demand.

stals units.

APPENDIX V

Estimated Yields and Shrinkage in Mechanized Crystal Unit Manufacture

Process		*Input to Process*		*Shrinkage in Process*				*Process Yield*		*Cumulative Yield*		
No.	*Process Group*	*Pieces*	*Weight*	*Pieces*	*Weight*	*%Pieces*	*%Weight*	*%Blanks* *(see note*)*	*%Weight*	*%Blanks*	*%Weight*	*Remarks*
1-4	Stone Inspection to Stone Initial Etch	*(stones)* 175	96.5 lb.		1.5 lb.	0.0	1.5		98.5		98.3	250 gram stones, none rejected
5-9	Section Stones	175	95.0		34.8	0.0	36.5		63.5		62.4	2.6 sect./stone avg. wt. 60g.
10-11	Inspect Sections	(sections) 450	60.2	(sect.) 30	3.6	(sect.) 6.7	6.0		93.7		58.7	
13-18	Wafer Sections	420	56.6		40.7	—	73.0		27.0		16.5	20 wafers avg./sect., avg. wt. 0.85g.
19-20	Inspect Wafers	(wafers) 8400	15.9	(wafers) 1000	2.0	(wafers) 11.9	12.6		87.4		14.4	Undersized rejected; mark other defects, dice all ≥ 2 blanks
21-23	Dice Wafers	7400	13.9									Avg. yield 2.5 blanks per wafer (before insp.)
24	Inspect Blanks	(blanks) 18,500		(blanks) 3600		(blanks) 19.5						On uninspected blanks (raw diced)
25-27	X-Ray & Thickness Sort	14,900		300		2.0		98.0		98.0		*Inspected blanks (14,900) assumed 100% for blanks yield figures.
28-31	Primary Lap	14,600		600		4.1		95.9		94.0		
32	Frequency Sort	14,000		600		4.3		95.7		89.9		
33-36	Secondary Lap	13,400		600		4.5		95.5		85.9		
37	Frequency Sort	12,800		500		3.9		96.1		82.5		
38-42	Final Lap	12,300		500		4.1		95.9		79.2		
43	Frequency Sort	11,800		500		4.2		95.8		75.8		
44-45	Final Etch	11,300		100		0.9		99.1		75.2		
46-47	Base Plate/Preheat	11,200		100		0.9		99.1		74.5		Includes aging preheat
48-50	Mounting and Cementing	11,100		100		0.9		99.1		73.8		
51	Adjustment Plate	11,000		100		0.9		99.1		73.2		
53	Base Sealing & Leak Det'n	10,900		200		1.8		98.2		71.8		Quality Control Test
54	Activity & Freq. Check	10,700		300		2.8		97.2		69.8		
—	Final Heat Run	10,400		400		3.9		96.1		67.1		Quality Control Test
55	Packaging	10,000										

APPENDIX 6-1

Effective Resistance vs. Frequency for Crystal Units.

The choice of blank diameters for crystal units of the frequency range to be produced in the Mechanized Plant is in part based on the Military Specification for effective resistance. Measurements have been made over the range of frequencies for the two diameters selected, and the results have been compared with the specification allowance. The results of these tests are summarized in Table 6-1-1 (below). Following the table we have listed the important crystal design factors for the test conditions.

The table and accompanying notes show why it is necessary to use the larger blank size below 9 megacycles for first harmonic units and below 25 megacycles for third harmonic units.

Table 6-1-1

EFFECTIVE RESISTANCE vs. FREQUENCY FOR CRYSTAL UNITS

CR—18/U

Nominal Frequency	*Allowable Effective Resistance MIL-C-3098B*	*Effective Resistance Measured* *0.490″ Diam*	*0.375″ Diam*
4.3 mc.	120 ohms	60 ohms	150 ohms
6.6	50	25	120
7.0	50	24	80
7.8	35	12	20
8.7	35	11	15
10.0	25	8	11
12.0	25	—	9
15.0	25	—	7
	CR—23/U		(on third harmonic)
17. mc.	40 ohms	18.3 ohms	24.5 (1)
25	40	15	21 (1)
30	40		18.6
44.5	40		17
50	40		17

Note (1): Although effective resistance for 0.375″ diam. is well below Mil-C-3098B specification, heat runs in this frequency range (17-24 mc) indicate that the larger diameter (0.490″) is required.

	CR—18/U
Diameter of blanks:	.490″ ± .002″ and .375″ ± .002″
Diameter across flat:	.473″ ± .002″ and .361″ ± .002″
Surface finish last lap:	8 micron (Scientific Abrasives)
Final Etch (with HF):	$0.31f^3$
Baseplated (Aluminum):	$0.9f^3$

Crystals mounted in standard HC-6/U holders, .006″ wires and cemented with Bakelite Silver Cement. No cans.

	CR—23/U
Diameter of blanks:	.490″ ± .002″ and .375″ ± .002″
Diameter across flat:	.473″ ± .002″ and .361″ ± .002″
Surface finish last lap:	4 micron (Scientific Abrasives)
Final Etch (with HF):	$0.21f^3$
Baseplated (Aluminum):	$0.7f^3$

Crystals mounted in standard HC-6/U holders, .006″ wires, and cemented with Bakelite Silver Cement. No cans.

APPENDIX 15-1

Choice of ZZ′ Angles for AT-cut Wafers in the Frequency Range 4.3—18mc. (CR-18/U) and 17-54 mc. (CR-23/U)

The optimum ZZ′ angle for AT-cut quartz crystals of a given frequency has been the subject of many investigations, published and unpublished. There is not entire agreement among the various authorities as to the angle resulting in the lowest temperature coefficient of frequency variation. Some discrepancy is due, perhaps, to different methods and precision of measurements, of slight variations in the interpretation of the basic crystallographic data, and in experimental differences in such parameters as the diameter/thickness ratio, (d/t).

In view of these varying interpretations, the target AT angles chosen for the Mechanized Quartz Crystal Plant have been based on the results of the operations of the Quartz Crystal Division of the Bulova Watch Company, in which the types of crystal and measurement means are similar to those selected for the mechanized plant. The curves of Fig. 15-1-1 show the angles which have produced satisfactory crystals for d/t ratios equal to or greater than 35. This ratio will be substantially exceeded in our crystal design.

A deviation of approximately ± 3′ of arc from the optimum ZZ′ angle for any frequency can be tolerated without sacrificing crystal quality. Using this criterion, the optimum curve can be approximated by five steps. However, certain break points exist for which changes of blank diameter and thickness have already been established through other criteria. (See Appendix 16-1 for example.) To maintain a minimum number of blank types, the break points for ZZ′ angle have been made at those frequencies wherever possible.

The resulting approximation is shown in Figure 15-1-1, and requires only one additional angle break, for a total of six ZZ′ angles, three blank thicknesses and two diameters. The target angles are placed between the breaks, allowances being made for the relative number of crystal orders expected at each frequency.

It will be noted that the Hoffman wafering saw is by no means capable of holding angle tolerances as small as ± 1′ or less (which would be implied from the graph), and as a matter of fact, the combined saw and prepositioning tolerances may be no better than ± 3′ of arc. This means that the blanks must be sorted by ZZ′ angle to within approximately 3′ increments, in order to reduce the spread. In order to keep the angle within 3′ of optimum, each angle type must be sorted into at least two increments, and there will be some loss of blanks by virtue of being out of tolerance at either end of the angle spread.

If, in order to improve yield or crystal quality, it should prove desirable to shift the target angles somewhat, the design of the prepositioning fixtures will be such as to permit this to be done easily.

Table 15-1-1
WAFERING ANGLES

Type	*Frequency Range*	*ZZ′ Angle*
CR-18/U	4.3— 6.0 mc.	35° 15′ ± 3′
	6.0— 9.0 mc.	35° 17.5′ ± 3′
	9.0—11.5 mc.	35° 20′ ± 3′
	11.5—18.0 mc.	35° 22.5′ ± 3′
CR-23/U	17.0—25.0 mc.	35° 25′ ± 3′
	25.0—54.0 mc.	35° 26.5′ ± 3′

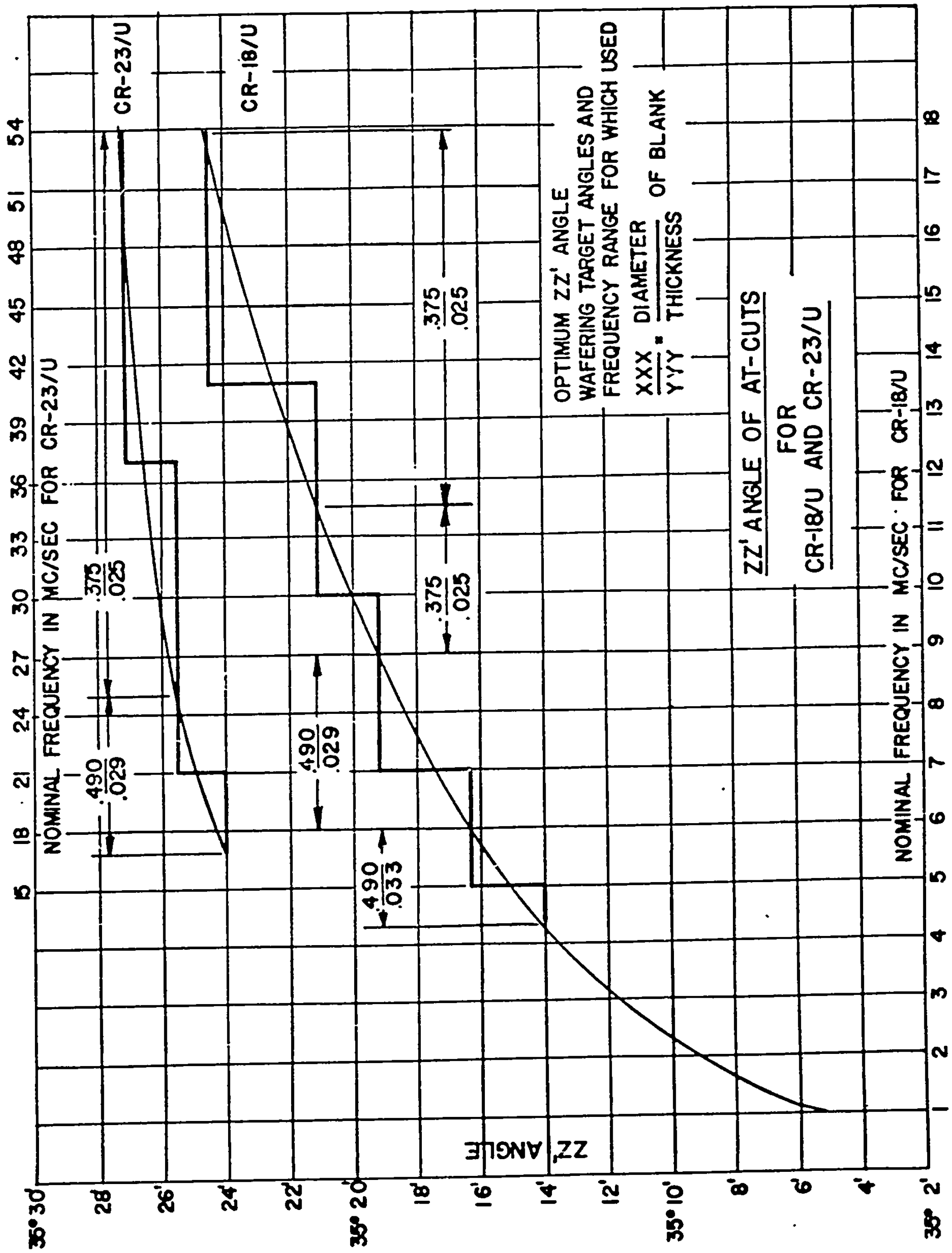

ZZ' ANGLE OF AT-CUTS
FOR
CR-18/U AND CR-23/U
OPTIMUM ZZ' ANGLE
WAFERING TARGET ANGLES AND
FREQUENCY RANGE FOR WHICH USED
XXX/YYY = DIAMETER/THICKNESS OF BLANK
CR-23/U
CR-18/U
NOMINAL FREQUENCY IN MC/SEC FOR CR-23/U
15
18
21
24
27
30
33
36
39
42
45
48
51
54
NOMINAL FREQUENCY IN MC/SEC FOR CR-18/U
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
ZZ' ANGLE
35°30'
28'
26'
24'
22'
35° 20'
18'
16'
14'
12'
35°10'
8'
6'
4'
35° 2'
.490/.029
.375/.025
.490/.029
.375/.025
.375/.025
.490/.033

Figure 15-1-1.

APPENDIX 16-1

Thickness of Wafers

This appendix discusses the means of arriving at a choice of target thicknesses for wafers produced in the mechanized plant.

The decision as to the thickness to saw wafers from X-sections is based on a number of factors, among them being:

The range and distribution of the crystal frequency orders (Order Board).

The surface finish produced by the wafering saw and blade.

The minimum thickness possible with a given wafering saw.

The spread of thickness variations produced by the saw.

The thickness sorting procedure used on the unlapped blanks.

The lapping procedure—number of stages and the grit sizes.

The lapping rate and desire to keep lapping time at a minimum.

The crystal design, with respect to optimum angles and diameters required.

The desire to maintain a minimum number of wafer types. (Cost of saw set-up and minimum inventory.)

The overall yield of wafers, including breakage after sawing.

The state of the crystal art and the amount of information available makes it necessary to treat many of the factors qualitatively; hence a certain amount of judgment and experience is needed in the final choice.

The factors related to saw-blade finish, lapping, and crystal quality can be summarized in a single parameter, minimum removal. The total minimum removal must be sufficient to remove all saw marks; in the case of the Hoffman saw this has been experimentally determined to be .0105". The minimum removal in each lapping stage must be sufficient to remove all traces of grit used in the previous stage. The removal in Primary Lap must be sufficient to make the total removal .0105". This has been discussed in more detail in Progress Report No. 21 of this contract (dated 26 June 1956), and is summarized in the accompanying graph (Figure 16-1-1) and the table below, reproduced from that report.

Table 16-1-1

MINIMUM QUARTZ REMOVAL and LAPPING STAGES

Lapping Stage	*Abrasive*	*Minimum Removal for*	
		CR-18/U	*CR-23/U*
1	25μSiC	.006"	.007"
2	12μSiC (Crystolon)	.003"	.003"
3	$8\mu Al_2O_3$ (So. African Corundum)	.0015"	—
3'	$4\mu Al_2O_3$ (So. African Corundum)	—	.0005"
	Total Removal	.0105"	.0105"

* Permanently suspended in synthetic oil, as manufactured by Scientific Abrasives Co.

Allowing some safety factor for variations in saw quality, grit size and other lapping control factors, a minimum removal of .012" has been established.

The Hoffman Multiple blade wafering saw, as used in our experiments, is capable of maintaining a total thickness spread of ± .003". Hence to reduce loss by virtue of undersized wafers, the target thickness of wafers cut should be .015" above the final thickness of the blank. The final thickness is determined by the nominal fundamental frequency of the crystal, and is shown as the lower curve in Figures 16-1-2 and 16-1-3, as computed by the standard formula. (In actuality, the blank is lapped slightly below theoretical to achieve a frequency approximately $0.5f^2$ above nominal, to allow for plating back. The amount is negligible, corresponding to a few ten-thousandths of an inch.)

The upper curve in these graphs would represent the optimum target thickness of wafers sawn for the corresponding frequencies. This is a continuous curve, however, and must be broken into straight-line increments for any practical production system.

The smooth curves can be reasonably approximated by a choice of three target thicknesses, as shown in the two graphs. All three are required for CR-18/U pro-

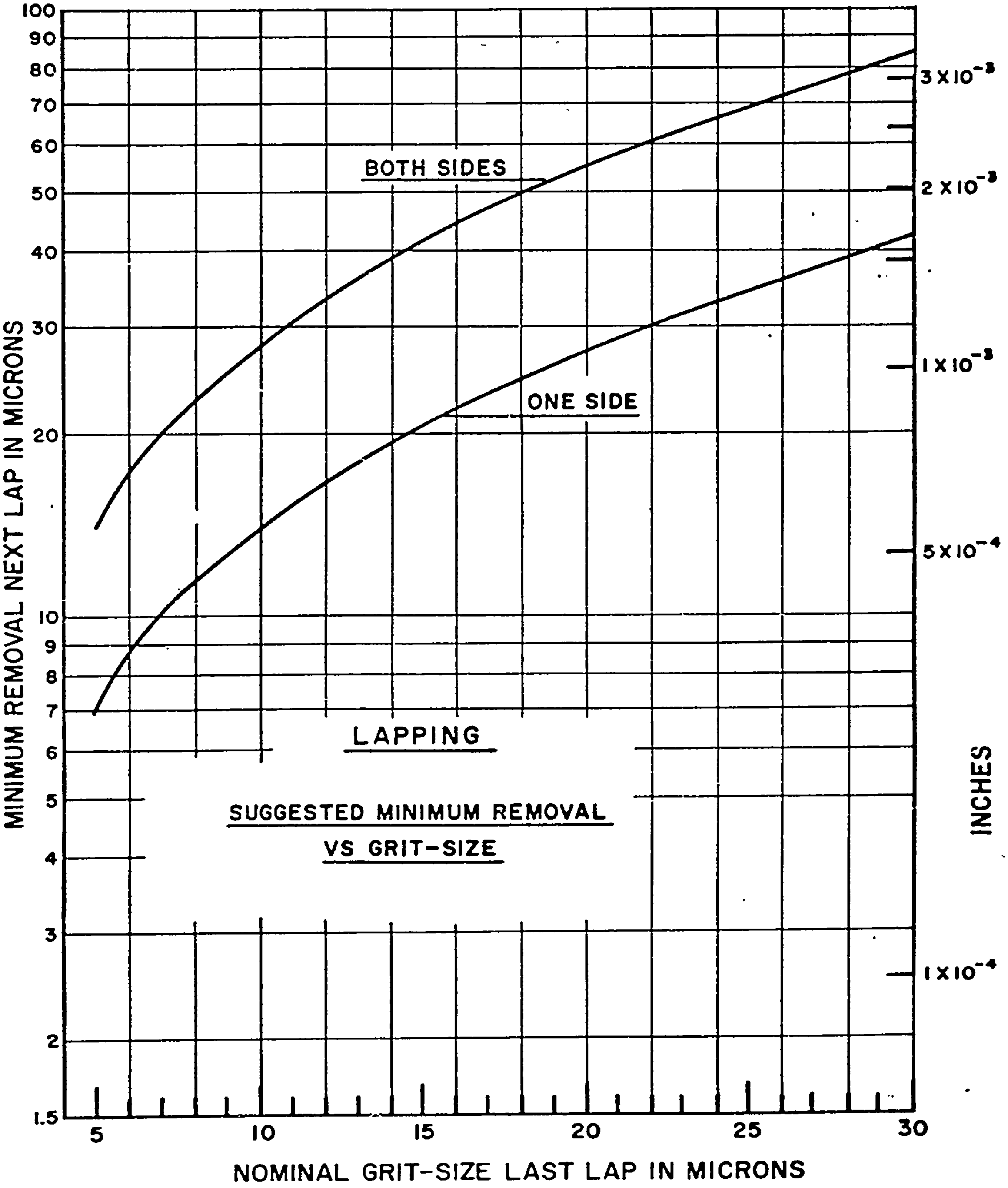

100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1.5
MINIMUM REMOVAL NEXT LAP IN MICRONS
BOTH SIDES
ONE SIDE
LAPPING
SUGGESTED MINIMUM REMOVAL
VS GRIT-SIZE
3 X 10⁻³
2 X 10⁻³
1 X 10⁻³
5 X 10⁻⁴
1 X 10⁻⁴
INCHES
5
10
15
20
25
30
NOMINAL GRIT-SIZE LAST LAP IN MICRONS

Figure 16-1-1.

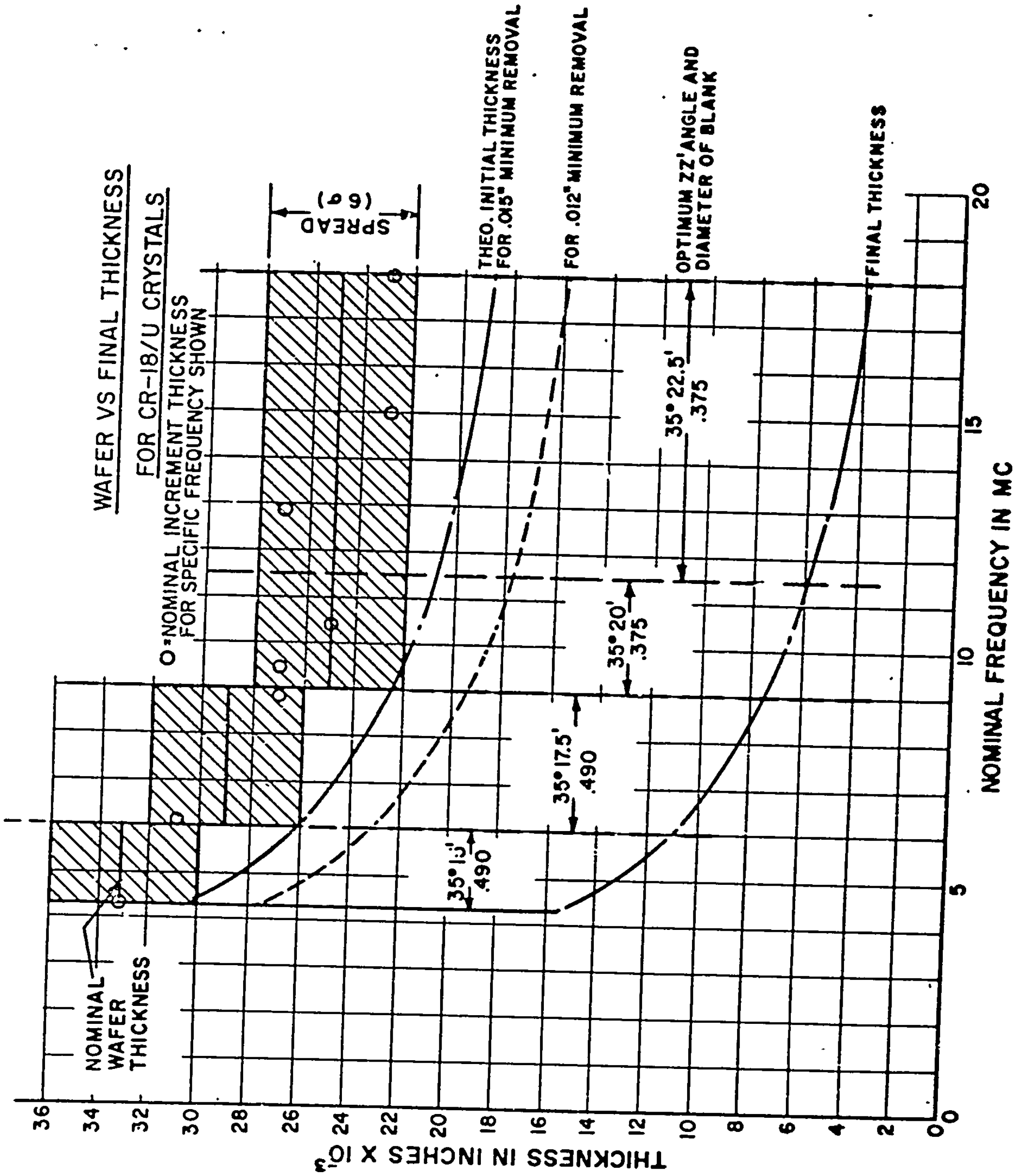

WAFER VS FINAL THICKNESS
FOR CR-18/U CRYSTALS
O=NOMINAL INCREMENT THICKNESS FOR SPECIFIC FREQUENCY SHOWN
SPREAD (6 q)
THEO. INITIAL THICKNESS FOR .015" MINIMUM REMOVAL
FOR .012" MINIMUM REMOVAL
OPTIMUM ZZ' ANGLE AND DIAMETER OF BLANK
FINAL THICKNESS
NOMINAL WAFER THICKNESS
35° 15' .490
35° 17.5' .490
35° 20' .375
35° 22.5' .375
THICKNESS IN INCHES X 10⁻³
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
NOMINAL FREQUENCY IN MC
0
5
10
15
20

Figure 16-1-2.

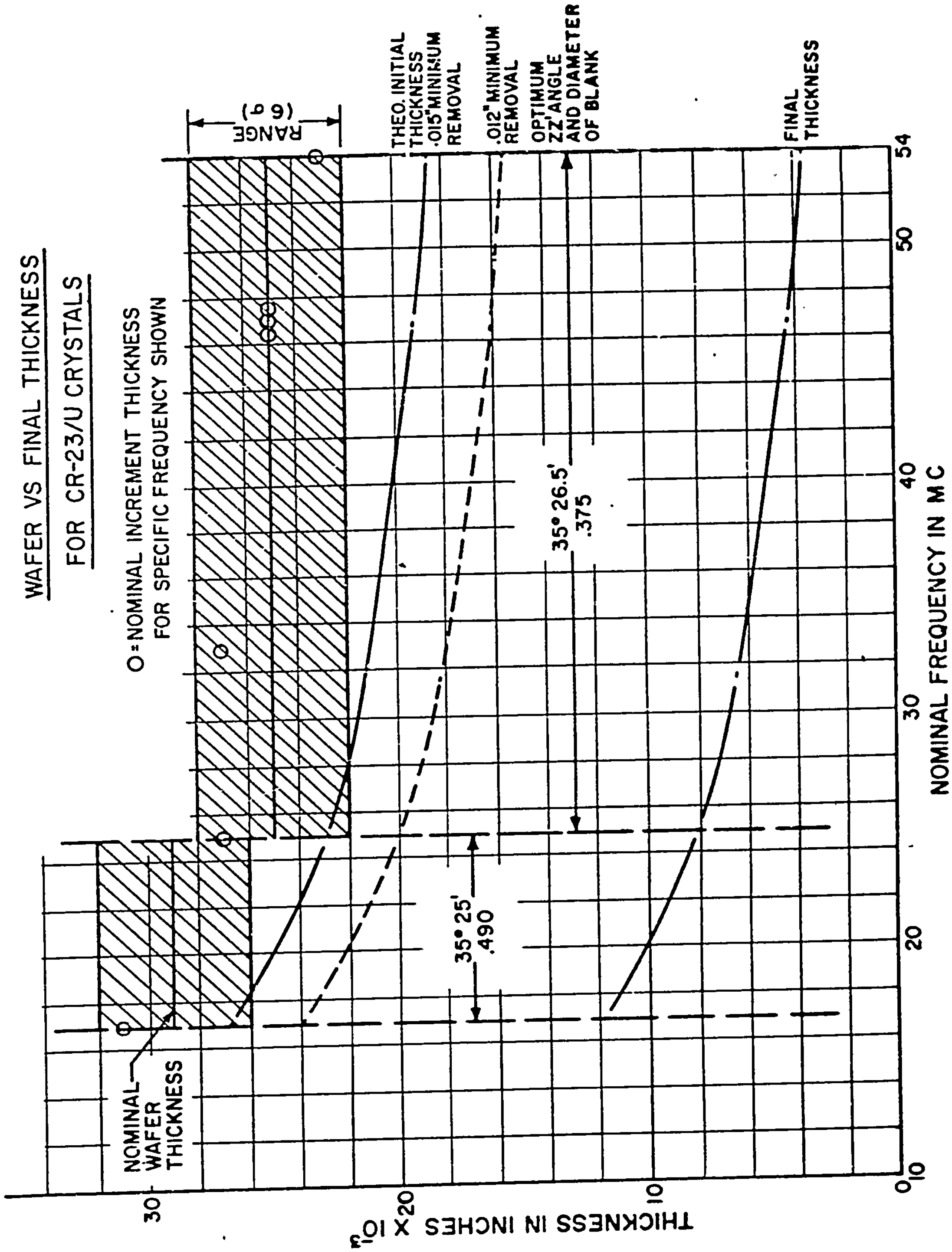

WAFER VS FINAL THICKNESS
FOR CR-23/U CRYSTALS
O = NOMINAL INCREMENT THICKNESS FOR SPECIFIC FREQUENCY SHOWN
RANGE (6 q)
THEO. INITIAL THICKNESS .015" MINIMUM REMOVAL
.012" MINIMUM REMOVAL
OPTIMUM ZZ' ANGLE AND DIAMETER OF BLANK
FINAL THICKNESS
35° 26.5'
.375
35° 25'
.490
NOMINAL WAFER THICKNESS
THICKNESS IN INCHES X 10⁻³
30
20
10
0
NOMINAL FREQUENCY IN MC
10
20
30
40
50
54

Figure 16-1-3.

duction and two of the same three chosen for CR-23/U. Thus, the number of saw set-ups is reduced to three. The thicknesses finally chosen lie two or three thousandths above that required by the .015″ target curve. The additional allowance has been made from considerations of saw capabilities and yield, as well as fragility of the final wafer and handling difficulties. It appears now that the Hoffman saw is capable of achieving a good yield of wafers with target thicknesses as low as .020″. However the question of wafer handling is somewhat in doubt, so that thicknesses chosen may be regarded as conservative, subject to revision downward without change in the overall system picture.

It should be noted that the possibility of thickness sorting and the variations in demand of each crystal frequency alter the final picture somewhat. If the blanks are sorted into increments, there is a most desirable increment (usually the lowest) within the nominal thickness and spread and within the optimum ZZ′ angle and diameter requirements, to produce a given crystal. If the demand for that frequency is high, however, it is probable that all blanks within the sawing range must be used to produce it, since the lowest increment (assuming normal distribution) will have less than 16% of the total number of blanks produced. If the demand is low, it is probable that a sufficient number of blanks requiring the least lapping will be in stock.

The circled points on the plots of Figures 16-2 and 16-3 represent the center of the sorted increment that would actually be used to produce a specified frequency, assuming that the increment width was .002″, the original saw cut distribution was normal, and the crystal demand that specified in the Maximum Order Board.

The nominal wafer thickness for the frequency ranges indicated are thus summarized in the table below.

Table 16-1-2

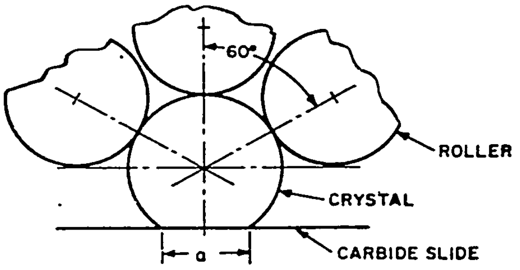
Crystal Type	*Frequency Range mc.*	*Nom. Angle*	*Blank Diameter*	*Wafer Thickness*
CR-18/U	4.3— 6.0	35° 15′	.490	.033 ± .003
	6.0— 9.0	35° 17.5′	.490	.029 ± .003
	9.0—11.5	35° 20′	.375	.025 ± .003
	11.5—18.0	35° 22.5′	.375	.025 ± .003
CR-23/U	17.0—25.0	35° 25′	.490	.029 ± .003
	25.0—54.0	35° 26.5′	.375	.025 ± .003

APPENDIX 22-1

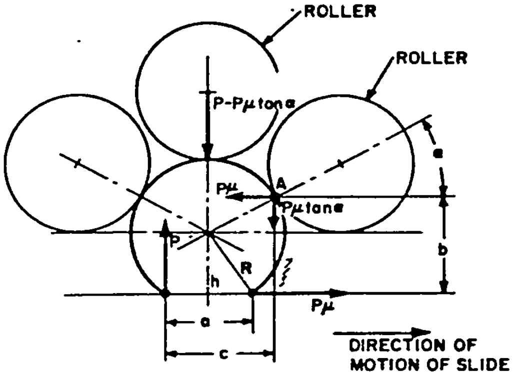
Rough Orientation of Crystals in the X-Ray Sorter

This appendix discusses limitations on the dimension of the flat on the round blanks, used to orient them in the X-ray sorter of the Mechanized Quartz Crystal Plant.

The smallest allowable flat on the crystal blank depends only on the coefficient of friction whereas the largest allowable flat depends on mechanical conditions. The crystal has to rotate until the flat reaches the carbide slide. During this rotation the flat has to pass the three rollers which press the crystal to the carbide slide and this is only possible if at least two rollers are always in contact with the circular portion of the circumference of the crystal.



Therefore the largest allowable flat is given by the positioning of the rollers over the crystal. Theoretically, it is possible to have a 90° angle between the common centerlines of the crystal and each roller, but practically, this angle should not be larger than 60°. This results in the largest permissible flat equal to the radius of the crystal.



The crystal is pressed down by three spring loaded rollers, which together produce the total force P. The movement of the surface, on the which the crystal is sliding, creates a force $P\mu$, where μ is the coefficient of friction between the crystal and the slide.

When the slide moves, the crystal pushes against one roller at point A. The force P is then split into two forces:

I. $P - P\mu \tan\alpha$
and II. $P\mu \tan\alpha$

Shortly before the crystal tries to turn over, the reaction force P is acting on one end of the flat and produces a moment, which acts to prevent the rolling of the crystal. Two moments are developed by all the forces on the crystal. Moment M_1 acts to turn the crystal. Moment M_2 acts to stop the crystal from turning.

The crystal will be oriented properly if $M_1 < M_2$ and therefore the crystal will not turn after it is on the flat.

Limit conditions are $M_1 = M_2$, and under this condition the smallest allowable flat is determined. ($a = a_{min}$)

The two moments are:

$$M_1 = P\mu b$$

where $b = h + R \sin\alpha$

$$h = \sqrt{R^2 - \frac{a^2}{4}}$$

therefore

$$M_1 = P\mu \sqrt{R^2 - \frac{a^2}{4}} + R \sin\alpha$$

and $M_2 = \left(P - P\mu \tan\alpha\right) \frac{a}{2} + P\mu \tan\alpha \ C$

where $C = \frac{a}{2} + R \cos\alpha$

therefore

$$M_2 = P\left(\frac{a}{2} + \mu R \tan\alpha \cos\alpha\right)$$

when $M_1 = M_2$:

$$P\mu \sqrt{R^2 - \frac{a}{2}} + R \sin\alpha = P\left(\frac{a}{2} + \mu R \sin\alpha\right)$$

resulting in: $a_{min} = \frac{\mu D}{\sqrt{1 + \mu^2}}$

where D = Diameter of the crystal,

for a_{min} expressed in fractions of D is ε

and $\varepsilon = \frac{a_{min}}{D} = \frac{\sqrt{1 + \mu^2}}{\mu}$

The analysis shows that the length of the smallest flat in relation to the diameter of the crystal depends only on the coefficient of friction between the crystal and the slide.

It shows also that the diameter or location of the rollers over the crystal has no influence on the security of orientation of the crystal.

It was observed that proper orientation of crystal with a diameter of .375″ was possible only if the length of the flat was equal to or larger than .125″. This indicates that the apparent coefficient of friction is approximately $\mu = 0.35$ for clean fresh crystals sliding on a surface of polished tungsten carbide.

From this experimentally found value of μ the smallest allowable flat on the 0.490 inch diameter crystal can be calculated. This calculation shows that the smallest flat for proper orientation is 0.163 inch.

SUMMARY

The dimensions of the flats of the crystals used in the X-Ray Sorter are:

Diameter	a_{min}	a_{max}
0.375	0.125	0.187
0.490	0.163	0.245

(All dimensions in inches)

APPENDIX 22-2

Cost Estimates on Dicing of Quartz Blanks

Presented below is a comparative cost study of two methods of dicing which was prepared in order to establish the process design goals. It is not based on the exact quantities of blanks specified in the body of this report, but as a comparison, the results are believed valid.

These cost estimates have been prepared to compare Process 'A', the contemplated ultrasonic method and Process 'B', a composite of the best current methods used by the quartz crystal industry.

The processes have been analyzed on the basis of the following precepts:

a) Cost of quartz material, conveyor equipment and general plant maintenance has not been included.

b) Capital equipment has been amortized over five years, straight line depreciation with no allowance for scrap value.

c) The following constants are assumed:

One working day = 7 hours
One working year = 250 days
Plant output 20,000 diced blanks from 10,000 wafers per day
Direct labor charge of $12/day (8 hrs. at $1.50).

d) Development costs are charged only to Process 'A'.

e) Round blanks without flat on Process 'B'.

f) Round blanks with oriented flat on Process 'A'.

g) Process plant area of 1,000 sq. ft.

h) Degrease and etch time are not included.

Advantages and disadvantages of each process are summarized in the estimates. The analysis shows that the costs per blank are as follows:

Process 'A'—$0.031 per diced blank
Process 'B'—$0.034 per diced blank

Thus, on the basis of the above estimates it can be concluded that the ultrasonic process 'A' is competitive.

PROCESS A

Ultrasonic Dicing

Preliminary Cost Estimate

A. OPERATION	*No. of pcs. Daily*	*No. of Operators*	*No. of Machines*
1. Inspect and layout wafers	10,000	2	2
2. Mount wafers to glass plates	10,000	3	3
3. Trim locating edge	10,000	2	—
4. Dice blanks from wafer	20,000	4	4
5. Degrease and sort blanks	20,000	1	—
		12	

B. CAPITAL EQUIPMENT	
1. Machinery—	
a) Dicing machine 4 at $15,000 ea.	$60,000
b) Ovens and controls 3 at $500 ea.	1,500
c) Degreaser (automatic) 1/2 at $5,000 ea.	2,500
d) Trays, racks, benches, etc.	5,000
e) Installation (pwr., air, water, etc.)	15,000
	$84,000
2. Tools & Fixtures—	
a) Brazing, fixture for tool bits	$1,200
b) Induction heating generator	2,500
c) Cementing Fixtures 3 at $1,500 ea.	4,500
d) Inspection Fixtures 2 at $500 ea.	1,000
e) Misc. (replacements, gages, etc.)	6,800
	$16,000
3. Development—	65,000
TOTAL	$165,000

Appendix 22-2

PROCESS A (Cont)

C. MATERIAL	cost/day
1. Tool Bits 40 at $1.00 ea.	$40
2. Tool holder 4 at $150/62.5 days	10
3. Wax 5 lbs. at 5.00	25
4. Glass mounting plates 2500 at $0.026 ea.	65
5. Abrasive SiC 80 lbs. at $0.60	50
6. Brushes 4 at $5.00	20
7. Trichlorethylene 1 drum (55 gals.) at $0.13/lb.	20
8. Miscellaneous	30
TOTAL	$260
Total 5 yrs. (1250 days)	$325,000

D. LABOR	cost/day
1. Direct 12 at $12/day	$144
Supv. 1 at $20/day	20
	$164
2. Indirect (G & A) 15% of item D-1	25
TOTAL	$189
Total (5 yrs.)	$236,000

E. BURDEN (1,000 sq. ft.)	cost/day
1. Rent (including heat) $0.75/sq. ft./yr.	$3.00
2. Utilities $0.15/sq. ft./yr.	1.00
3. Insurance & Misc.-$0.10/sq. ft./yr.	.50
4. Maintenance 1/2 man x $60/day	30.00
5. Miscellaneous	15.50
TOTAL	$50.00
Total (5 yrs.)	$62,500.00

F. SUMMARY	
1. Capital Equipment (Sec. B)	$165,000.00
2. Material (Sec. C) for 5 years	325,000.00
3. Labor (Sec. D) for 5 years	236,000.00
4. Burden (Sec. E) for 5 years	62,500.00
TOTAL	$788,500.00
5. Daily operating cost, item F/1250 days	$630.00
6. Cost per diced blank item F-5/20,000	0.031

G. REMARKS

1. Advantages—
   - a) Reduces amount of operator skill required, training time per operator and number of operators.
   - b) Oriented blank is cut directly from wafer.
   - c) The process allows for simpler material handling and mechanization.
   - d) Increase in quartz yield of approximately 5%.
2. Disadvantages—
   - a) High capital expenditure required for machinery and equipment.
   - b) Maintenance required is more complex and requires higher degree of technical competence.

Appendix 22-2

PROCESS B
Dicing (Round Blank)

Preliminary Cost Estimate

A. OPERATION	*No. of pcs. daily*	*No. of Operators*	*No. of Machines*
1. Mark X-Face of section	500	1	2
2. Inspect and layout wafer	10,000	2	2
3. Mount and Dice blanks	10,000	12	3
4. Degrease and sort blanks	20,000	1	—
5. Round blanks	20,000	14	9
6. Sort blanks	20,000	1	—
		31	

B. CAPITAL EQUIPMENT	
1. Machinery—	
a) Felker Saw 80-BQ 2 at $1000	$2,000
b) Dicing Saw 3 at $3000	9,000
c) Coolant pump & tanks	2,000
d) Kwik-Way Rounder 9 at $700	6,300
	$19,300
2. Tools & Fixtures—	
a) Dicing plates 40 at $150 ea.	$6,000
b) Saw fixture CL-4A 2 at $150 ea.	300
c) Loading fixtures 40 at $100	4,000
d) Light Box 2 at $500	1,000
	$11,300
TOTAL	$30,600

C. MATERIAL	*cost/day*
1. Wax 5 lbs at 5.00	$25
2. Trichlorethylene 1 Drum	20
3. Coolant	5
4. Paper (blank spacing)	5
5. Diamond Wheels 6"—30 at $40 ea/2 yr. life	2
6. Diamond Wheels 4"—60 at 25 ea/2 yr. life	2
7. Diamond Wheels 7/8—10 at $100 ea/1/2 yr. life	8
8. Misc.	30
TOTAL	$97

D. LABOR	
1. Direct 31 op. at $12/day	$372
3 supv. at 20/day	60
	$432
2. Indirect (G & A) 15% of item D-1	65
TOTAL	$497

PROCESS B (Cont)

	cost/day
E. BURDEN	
1. Similar to Sec. E of Process A	$50
F. SUMMARY	
1. Capital Equipment Sec. B	$30,600
2. Material Sec. C. 5 yrs.	121,000
3. Labor Sec. D 5 yrs.	621,250
4. Burden Sec. E 5 yrs.	62,500
TOTAL	$835,350
5. Daily Operating Cost item F/1250	$670.
6. Cost per diced blank item F-5/20,000	0.034

G. REMARKS

1. Advantages—
   - a) Low capital investment
   - b) High order of maintenance skill not required
2. Disadvantages—
   - a) Greater number of operators required
   - b) Does not lend itself readily to mechanization.

APPENDIX 26-1

Sorter Accuracy

INTRODUCTION

Three of the equipments under development on this program are sorters. It has been necessary to devise a means of evaluating these units as to sorting ability. The derivation contained in the following pages makes it possible to calculate the sorting accuracy of a sorter with respect to the three factors which describe the process:

1. *Input Distribution*—Because the probability of sorting correctly will depend on the value of the input item relative to the increment edges, it is necessary to know how the input item is distributed.

2. *Increment Width*—The larger the increment relative to the precision of measurement and the parameters of the input distribution, the better will be the sorting accuracy.

3. *Precision of Measurement*—This is a measured quantity dependent only on the equipment measurement ability.

DEFINITIONS

The accuracy of a sorting device shall be defined as the percentage of input items sorted correctly with reference to one quality of the input item. Correct sorting occurs when an input item is sorted into an output sorting increment which contains the true value of the reference quality.

LIST OF SYMBOLS

w = Sorter output increment width
σ_p = Standard deviation of precision of measurement
y_i = True value of reference quality of ith input item
x = Measured value of reference quality
P_i = Probability that ith input item is sorted in increment containing y_i
P = Probability that an input item is correctly sorted (sorter accuracy)
σ_{in} = Standard deviation of the distribution of input items
dp_{in} = Probability that dy contains y_i
dp = Probability that the ith input item is sorted correctly and that dy contains y_i

Let the measurement precision be defined by the distribution function of Figure 1:

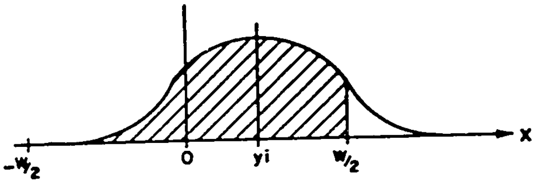


Figure 1. Measurement Precision Distribution Function

From Figure 1:

P_i = shaded area under curve

$$= \frac{1}{\sigma_p\sqrt{2\pi}}\int_{-w/2}^{w/2} e^{-\frac{1}{2}\left[\frac{x-y_i}{\sigma_p}\right]^2} dx \qquad (1)$$

If the input is normal, Figure 2 represents the input distribution function:

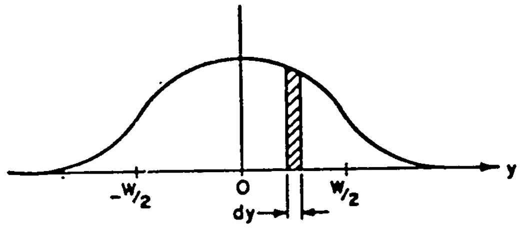


Figure 2. Input Distribution Function

From Figure 2:

$$dp_{in} = \frac{1}{\sigma_{in}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{y}{\sigma_{in}}\right)^2} dy \qquad (2)$$

By definition:

$$dp = dp_{in} P_i$$

Therefore:

$$P=\frac{1}{\sigma_{in}\sqrt{2\pi}}\left\{\int_0^{\infty} e^{-\frac{1}{2}\frac{y}{\sigma_{in}}^2}\left[\int_{-w/2}^{w/2}\frac{1}{\sigma_p\sqrt{2\pi}} e^{-\frac{1}{2}\frac{x-y}{\sigma_p}^2} dx\right] dy\right\} \qquad (3)$$

An approximate solution of the above equation can be obtained by assuming P_i to be constant over small ranges of y_i and solving the following equation (see Figure 3):

$$P = 2\left[P_a\int_0^{y_a} dp_{in} + P_b\int_{y_a}^{y_b} dp_{in} + P_c\int_{y_b}^{y_c} dp_{in} + P_d\int_{y_c}^{y_d} dp_{in} + P_e\int_{y_d}^{w/2} dp_{in} + P_e\int_{w/2}^{y_f} dp_{in} + P_d\int_{y_f}^{y_g} dp_{in} + \cdots\right] \qquad (4)$$

The value of P_a is defined as the average probability of range 0 to y_a; P_b, the average probability of range y_a to y_b and similarly for the other ranges.

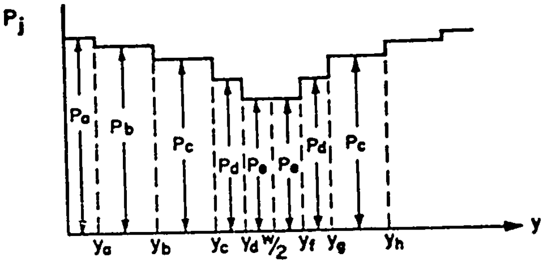


Figure 3. Approximation of P_t

If it is assumed that $w \gg 6\sigma_p$, the following table can be constructed:

j	$\frac{w}{2} - y_j$	P_j
a	$3\,\sigma_p$	1.00
b	$2\,\sigma_p$	.99
c	σ_p	.91
d	$\frac{1}{2}\,\sigma_p$	.76
e	0	.60

Therefore, given any values for w, σ_p, and σ_{in}, P can be computed.

If the input is uniformly distributed, the calculation of P becomes the calculation of the average ordinate of Figure 3. The value of this based on the input distribution over an integral multiple of w/2 is:

$$P = \frac{P_a y_a + P_b (y_b - y_a) + P_c (y_c - y_b) + P_d (y_d - y_c) + P_e (\frac{w}{2} - y_d)}{w/2} \quad (4)$$

For the values tabulated above, the sorter accuracy P, is:

$$P = \frac{1\,(\frac{w}{2} - 3\sigma_p) + 0.99\sigma_p + 0.91\sigma_p + 0.76\,(0.5\sigma_p) + 0.6\,(0.5\sigma_p)}{w/2} \quad (5)$$

CONCLUSION

Based on equations (4) and (5), it is possible to calculate sorter accuracy as defined above. This analysis indicates the dependence of the sorter accuracy on both prior and following processes, as prior processes determine the input distribution, and the following processes determine the choice of increment width. By making assumptions as to those two factors and as to the sorting accuracy desired, the required precision of measurement of the sorter can be determined.

To demonstrate the use of this technique on the X-Ray Sorter, an example can be presented. Assume that the following parameters are given:

$W = 2$ minutes
$\sigma_p = 10$ seconds
$\sigma_{in} = 40$ seconds

Figure 4 indicates how the increments are divided for integration purposes:

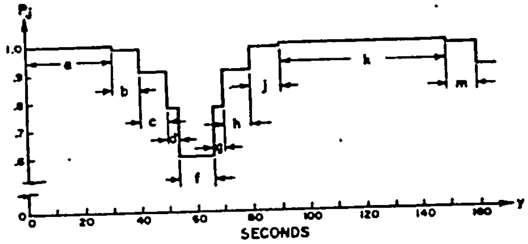


Figure 4. Calculation Intervals

Let P'_j = percentage of crystals whose true value lies in interval j. The following table therefore shows the values of P'_j for each interval.

j	y_j (seconds)	y_j/σ_{in}	P'_j
a	30	0.75	.273
b	40	1.00	.068
c	50	1.25	.053
d	55	1.375	.021
f	65	1.625	.033
g	70	1.75	.012
h	80	2.00	.017
i	90	2.25	.011
k	150	3.75	.012
m	160	4.00	0

Substituting the value of P'_j and P_j into equation 4 results in a value for the sorting accuracy (P) of 94.4%. Figure 5 is a graph of the sorting accuracy for four different input conditions.

The above analysis assumes that the center of the input distribution is located at the center of an increment. If this is not true, the sorting accuracies will be lower than those given in Figure 5. However, it is possible to eliminate the incorrect sorting of crystals. This can be accomplished by recognizing the fact that practically all the crystals sorted in one increment will be less than $3\sigma_p$ outside the increment limits. Therefore, the spread of crystals in each increment can be considered to cover the range $W + 6\sigma_p$. As applied to the above example, the spread of crystals in the two minute increments will be three minutes.

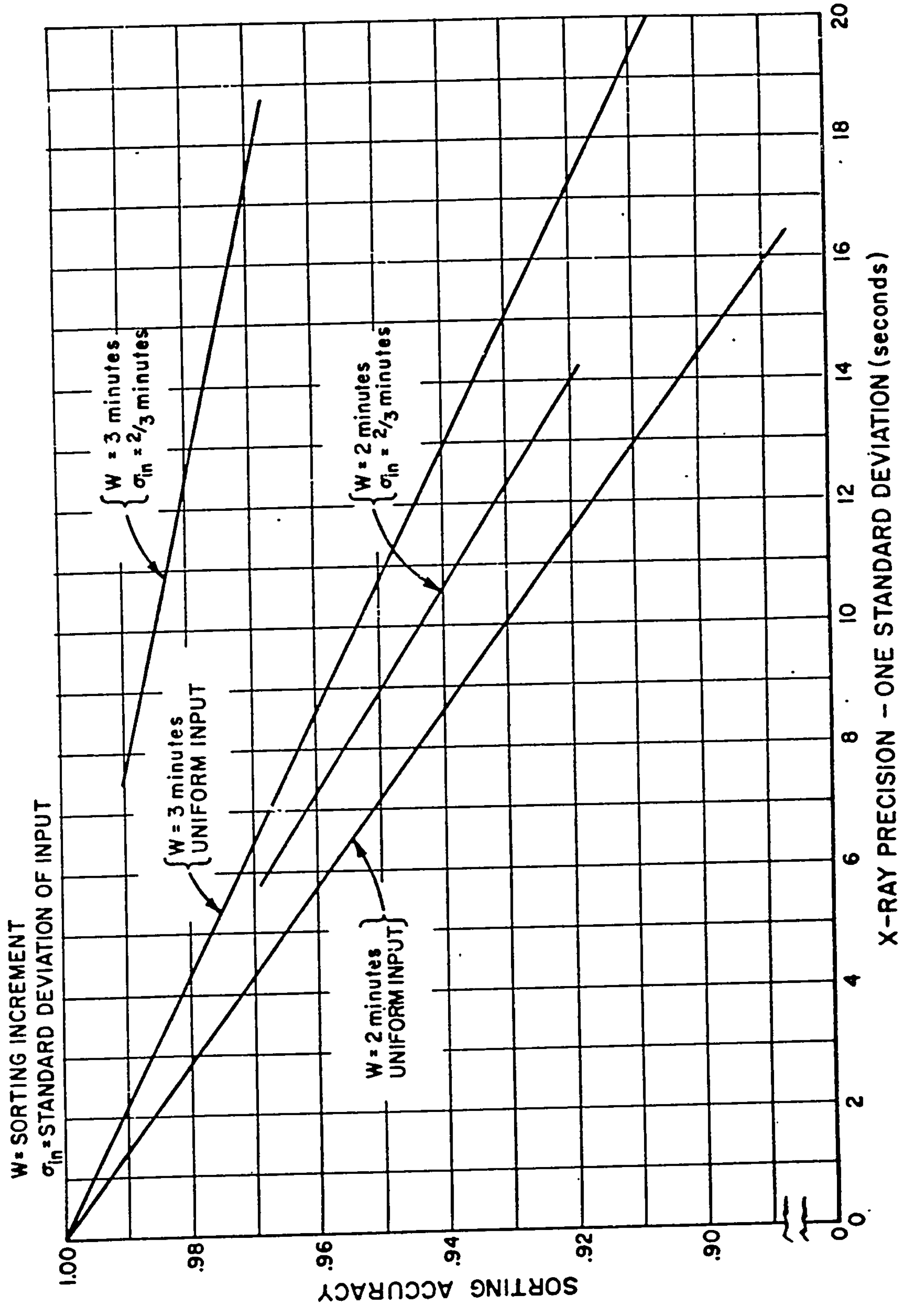

W = SORTING INCREMENT
σ_{in} = STANDARD DEVIATION OF INPUT
W = 3 minutes
σ_{in} = 2/3 minutes
W = 2 minutes
σ_{in} = 2/3 minutes
W = 3 minutes
UNIFORM INPUT
W = 2 minutes
UNIFORM INPUT
SORTING ACCURACY
1.00
.98
.96
.94
.92
.90
X-RAY PRECISION – ONE STANDARD DEVIATION (seconds)
0
2
4
6
8
10
12
14
16
18
20

Figure 5.

APPENDIX 26-2

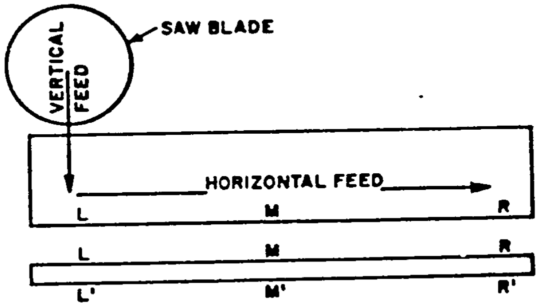
Analysis of the Effect of X-Ray Sorting on the Distribution of ZZ' Angle

SUMMARY:

In a series of experiments with the Hoffman Wafering Saw (at SCEL), statistical information was obtained on the spread of ZZ' angle and wedginess of wafers. An investigation was then made of the distribution of orientation angles of blanks diced from these wafers after lap, based on assumptions as to the effect of lapping on wedginess, and correlation coefficients of angles on opposite sides of the blanks. Finally the effect or sorting or non-sorting was examined relative to the criterion that the orientation angle be within ± 1.5 minutes of the average angle. It is concluded that approximately 75% of blanks will lie within a 3 minute tolerance without sorting, but that 94% will be within 3 minutes with sorting. On the basis of a 10% increase in yield, a sorter will be economically justified within six months.

PART I—ORIENTATION ANGLE ANALYSIS OF WAFERS

1) Using the Hoffman Wafering Saw, we have measured the orientation angle at six points on each wafer. They are designated by L, L', M, M', R, R'.



2) In order to determine the parallelism of individual blanks, we have calculated $\overline{r}$ and σ_r where

$\overline{r}$ = average difference between readings L, L' (or M, M' or R, R')

σ_r = standard deviation of the difference between the readings L, L' (or M, M' or R, R')

Values of $\overline{r}$ and σ_r

	.030 Thickness		*.023 Thickness*	
	Minutes $\overline{r}$	*Minutes* σ_r	*Minutes* $\overline{r}$	*Minutes* σ_r
L, L'	1.63	1.286	1.48	.527
M, M'	1.27	.948	2.375	2.337
R, R'	3.1	2.153	3.75	2.269

We note that the R, R' average difference is larger than the L, L' and M, M' average differences.

3) We have also checked the consistency of the average orientation angle as we move along the wafer from left to right. This is called the $\overline{L}$, $\overline{M}$, $\overline{R}$ variation which was found to be stable, with average ranges of 2.15 and 1.68 minutes for the .030" and .023" thicknesses respectively. ($\overline{L}$ is the average between L and L'; similar definitions apply to $\overline{M}$ and $\overline{R}$)

4) We have observed no relationship between the variation in parallelity of a blank (as measured by L, L' or R, R' variation) and cutting feed for the range of feeds used (approximately 6 to 19 inch/min. horizontal feed and .35 to 1.3 inch/min. vertical feed)

PART II—DISTRIBUTION OF ORIENTATION ANGLE AFTER LAP

Case 1—Assume Orientation Angles on Opposite Sides of Blanks are Uncorrelated ($\rho = 0$)

A. Assume blanks are sorted into ±1' increments

1. The orientation angle after lap is assumed to be within

$$\bar{\alpha} \pm K(|\alpha_1 - \alpha|)$$

where α_1' = orientation angle on measured side of blank

α_2 = orientation angle on unmeasured side of blank

$$\overline{\alpha} = \frac{\alpha_1 + \alpha_2}{2}$$

K = 0.25 to 0.50 (See Note 1. for definition of K)

$K(|\alpha_1 - \bar{\alpha}|)$ is taken as three standard deviations.

2. The orientation angle before lap is distributed with a standard deviation of 1.8 minutes. This is based on Part I, i. e. experience with Hoffman saw cutting 0.030 and 0.023 wafers.

For α_1 independent of α_2 ($\rho = 0$) the cumulative distribution of orientation angles after lap is shown in the solid curve. (Fig. 26-2-1). The results for K = 0.25 and 0.50 are the same. This shows that 94% of the orientation angles after lap will be within ± 1.5 minutes of the average angle, taken as zero in the Figure.

For K = 1, the percentage approaches 92%.

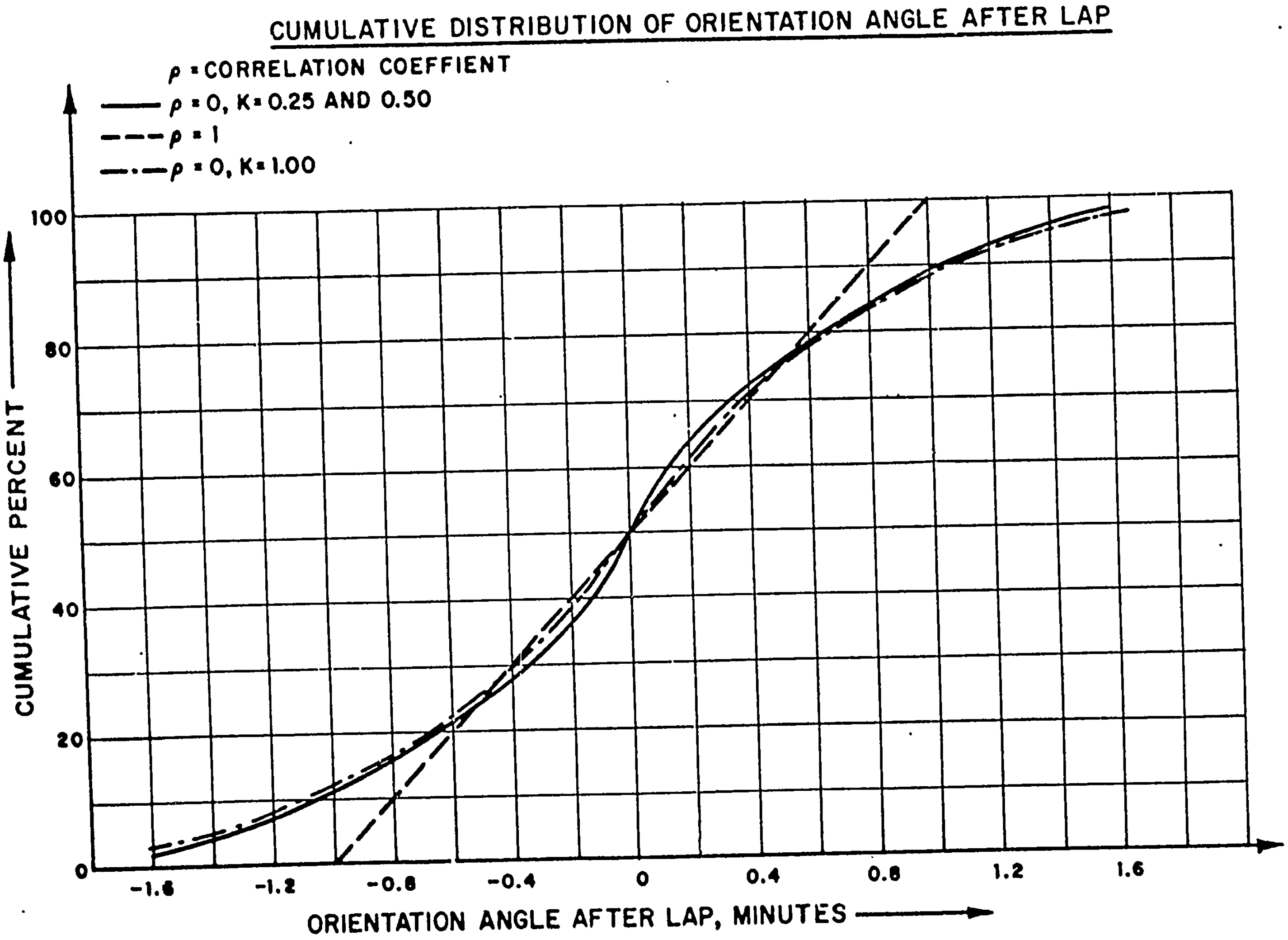

CUMULATIVE DISTRIBUTION OF ORIENTATION ANGLE AFTER LAP

Figure 26-2-1.

B. Assume blanks are not sorted

If the blanks are not X-ray sorted, then theoretically the orientation angle after lap is normally distributed with mean zero and standard deviation $C\sigma$ where $\sigma = 1.8$ and C is given below:

K	C	% angles within ±1.5′
0.25	.717	75
0.50	.745	73
1.00	.85	67

Case 2—Orientation Angles on Opposite Sides Correlated

Experience with the Hoffman saw (See Part I) yields the following values of linear correlation Coefficient ρ :

	Wafer Thickness	
	0.030″	0.023″
LL′ (left)	0.695	0.087
MM′ (middle)	0.328	0.418
RR′ (right)	0.128	0.086

Owing to the relatively high correlation between L and L′, the average cumulative distribution for orientation angle after lap has been plotted for the limiting case of $\rho = 1$ (See Figure 26-2-1, straight dashed line). This represents the average taken over five intervals into which the X-ray sorter sorts the imput blanks. Standard deviation of normal angle input distribution minutes wide. For this case $\alpha_1 = \alpha_2 = \bar{\alpha}$

SUMMARY: The results of this study (for $\rho = 0$) are given in the following table:

Percent Blanks Within ± 1.5′

K	*Sorted*	*Unsorted*
0.25	94	75
0.50	94	73
1.00	92	67

The limiting case for $\rho = 1$ is shown in the graph.

NOTE 1. The factor "K" is the fraction of the initial blank wedginess, taken about the bisector of the wedge angle, into which the orientation angle of the lapped blanks will fall. For example, if the two surfaces of the blank are oriented at 35°15′ and 35°17′ (that is, a 2′ wedginess) and K is assumed to be 0.5, then the orientation of the parallel lapped blanks will be between 35°15.5′ and 35°16.5′.

APPENDIX 26-3

Errors in X-Ray Sorting With a Double Crystal Goniometer

INTRODUCTION

A double crystal X-ray goniometer can be used to improve the accuracy of measurement of the orientation angle of quartz crystal blanks. A goniometer of this type has been incorporated in a machine which automatically sorts AT-cut crystals based on the ZZ' orientation angle. This Crystal Blank X-Ray Sorter has been developed by Bulova R & D Labs., Inc. as one automatic machine of the mechanized plant for quartz crystal production.

Consideration of the problems implicit in the design of the X-Ray Sorter indicated the necessity of an analysis to correlate mechanical positioning errors with machine errors in orientation measurement. The results developed here are applied to the X-Ray Sorter to indicate the theoretical requirements for preparation and mechanical orientation of the crystal blanks for accurate measurement.

ORIENTATION ERRORS

Two possible deviations of the crystal blank position from its ideal position shall be considered. The ideal position is shown in Figure 1. The face of the crystal is perpendicular to the Y-Z plane and the edge upon which the crystal rests is in the Y-Z plane. A true reading of the ZZ' angle will be obtained if the plane of the X-ray beam is parallel to the Z-Y plane. One of the errors to be considered is rotation of the plane of the X-ray beam about the intersection of the crystal face and the Z-Y plane. These rotations of the plane of the X-Ray beam are due to errors in positioning of the crystal in the goniometer or errors in cutting of the crystal blank.

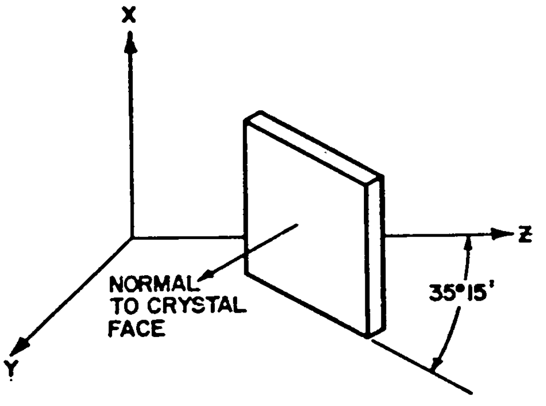


Figure 1. Location of AT-cut Crystal Blank Relative to Crystal axes (X,Y,Z Coordinate System)

In Figure 2, a new set of axes is shown which is determined by the plane of the X-ray beam (y-z) and the crystal face (x-z). The errors stated above are here equivalent to a rotation of the blank about the y axis and z axis. The angle μ is the angle the atomic plane makes with the crystal face and is a measure of the orientation of the blank. The unit vector normal to the atomic plane is also shown.

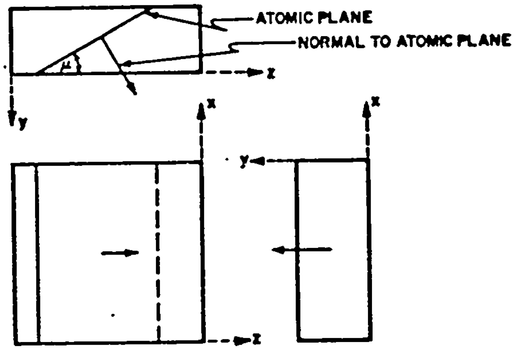


Figure 2. Location of Crystal Blank in the x, y, z, Coordinate System

First, the effect of rotation about the y axis shall be examined. The crystal is shown rotated about the y axis by an angle ϕ in Figure 3.

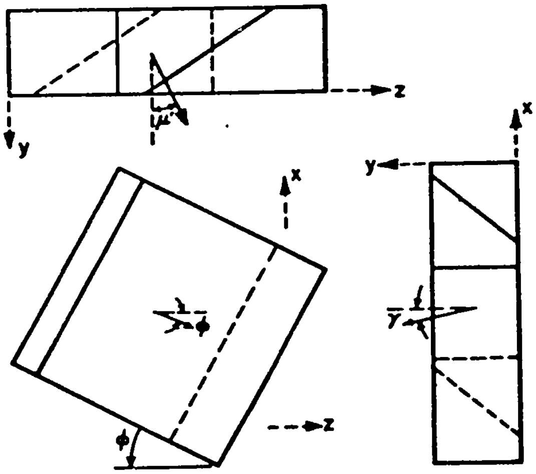


Figure 3. Effect of Rotation About the y Axis

It is clear from Figure 3 that the rotation about y produces two effects:

1. The normal to the atomic plane now makes an angle δ_1 (not shown), with the plane. of the X-ray beam.
2. The angle μ that the projection of the normal makes on the plane of the X-Ray beam changes from μ to μ'. This is a direct error in measurement of the orientation.

It can be shown (Note A) that:

$$\tan \mu' = \tan \mu \cos \phi$$

$$\tan \delta_1 = \frac{\tan \mu \sin \phi}{1 + \tan^2 \mu \cos^2 \phi}$$

The errors $(\mu\text{-}\mu')$ and δ_1 can be expressed for values of ϕ less than five degrees as:

$$\mu\text{-}\mu' = \frac{\phi^2}{4} \sin 2\mu$$

(μ, μ' and ϕ are in radians)

$$\delta_1 = \phi \sin \mu$$

The effect of rotation about the z axis will now be considered. In Figure 4 the crystal of Figure 2 is shown rotated about the z axis by an angle β.

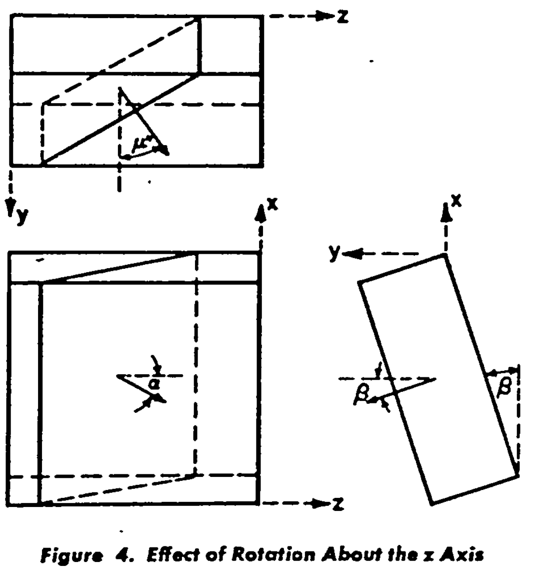


Figure 4. Effect of Rotation About the z Axis

This rotation also produces two effects:

1. The normal to the atomic plane makes an angle δ_2 (not shown) with the plane of the X-ray beam.
2. The projection of the normal on the plane of the X-ray beam changes from μ to μ''.

It can be shown (Note B) that:

$$\tan \mu'' = \frac{\tan \mu}{\cos \beta}$$

$$\tan \delta_2 = \frac{\sin \beta}{(\cos^2 \beta + \tan^2 \mu)^{1/2}}$$

for $\beta <= 5°$

$$\mu\text{-}\mu'' = \frac{\beta^2}{4} \sin 2\mu$$

(μ, μ'' and β in radians)

$$\delta_2 = \beta \cos \mu$$

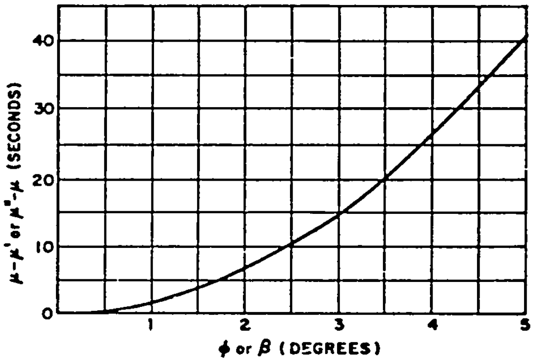


Figure 5. Maximum Direct Error due to ϕ or β Misorientation (μ=3°)

Although the errors due to simultaneous rotation about the y and z axes are dependent, it can be assumed that the total error will be less than the sum of the magnitudes of the two separate errors. This sum for the direct error can be determined from the sum of the magnitudes of $(\mu\text{-}\mu')$ and $(\mu\text{-}\mu'')$. The variation of these direct errors is shown in Figure 5 for μ equal to three degrees. The X-Ray Sorter was designed to measure AT-cut crystals which have a value for μ of approximately three degrees, thus Figure 5 applies. For this small value of μ, δ_1 can be negelected and δ_2 is approximately equal to β. As will be discussed later, the effect of the δ component is to reduce the resolution of the two crystal system.

The above analysis of direct errors can be correlated to the operations of sectioning, wafering and dicing and can be used to determine the effect of these errors on the ZZ' angle measurement. The maximum error in dicing is a ϕ error and has been given as 15 minutes. The maximum error in wafering is a β error and can be assumed to be 15 minutes. The error in sectioning can contribute both a β and ϕ error. The maximum value of this error is probably such that the sum of β and ϕ

is less than 15 minutes. Combining these errors to give the highest possible orientation error results in a ZZ' error of less than one second. Therefore, this error is negligible even in the few cases where the cutting errors are maximum and additive. This indicates that the tolerances on cutting can be widened without introducing an appreciable ZZ' angle error. Doubling the errors in each process results in a maximum ZZ' angle error of less than two seconds. Therefore, the cutting error tolorances, if within this range, are determined by considerations other than direct ZZ' error; e. g. by the direct influence of X-axis errors on the crystal temperature-frequency coefficient.

RESOLUTION CONSIDERATIONS

The application of the two crystal system to X-ray goniometry has been described by W. L. Bond[*]. A schematic diagram of the system is shown in Figure 6. The first or reference crystal is oriented so that the X-rays impinging on it are reflected. The property of the quartz is such as to reflect a beam of X-rays at one angle of incidence (the Bragg angle). Therefore the reflected beam consists of essentially parallel rays. The beam of reflected X-rays impinges on the second or work crystal. This crystal is rocked, and the angle at which reflection occurs is the measure of the orientation of the blank with respect to the crystal axis. If the crystal can be considered perfect (in the sense that reflection of X-rays occurs only at the Bragg angle) and if the crystal is assumed to be perfectly cut and oriented, the reflection can only occur if the 01.1 atomic planes of the two crystals are parallel. However, due to imperfections in the lattice structure of the quartz and errors in cutting or alignment, the reflected beam assumes an angular width with a peak occurring at the Bragg angle. In order to understand the effect of the tilt, δ, on the measurements, some aspects of the double crystal system must be examined.

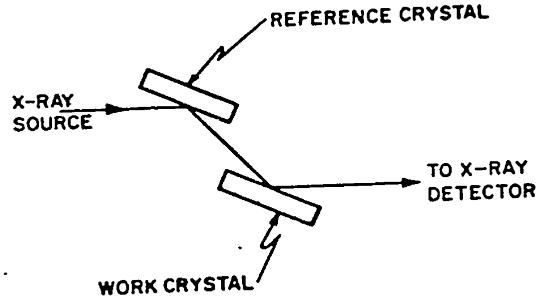


Figure 6. Double Crystal X-ray Goniometer

Consider a point source of monochromatic X-rays free to radiate in all directions. If a perfect crystal of infinite extent is placed anywhere in the space surrounding the point source, it is possible to describe, on the atomic plane of the crystal, a circle which is the locus of all points for which the Bragg equation is satisfied. The locus of lines connecting points on this circle with the point source forms a right cone. This cone has the property that only rays lying in its surface will be reflected from the crystal. This cone along with the unique cone of reflection is illustrated in Figure 7.

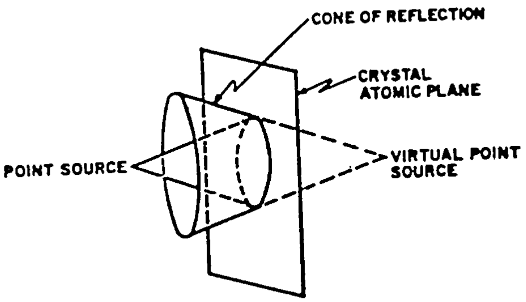


Figure 7. Cone of X-ray Reflection

To an observer shielded from the direct radiation of the source, the reflected rays appear to be coming from a virtual point source behind the atomic plane of the crystal. This is also illustrated in Figure 7.

Thus the observer at the left sees what can be called a "cone of transmission" (i.e., the X-rays are present only in the surface of a unique cone and emanate from a point which is the apex of the cone).

If then, we replace the observer with a second perfect crystal of infinite extent, the cone of transmission will intersect the second crystal atomic plane in one of the four conic sections: a circle, an ellipse, a parabola, or a hyperbola. The latter two are of no interest in this analysis, so attention will be confined to orientations of the second crystal which intersect the cone of transmission in either a circle or an ellipse. This plane curve can be called the "locus of transmission". A typical locus of transmission is illustrated in Figure 8.

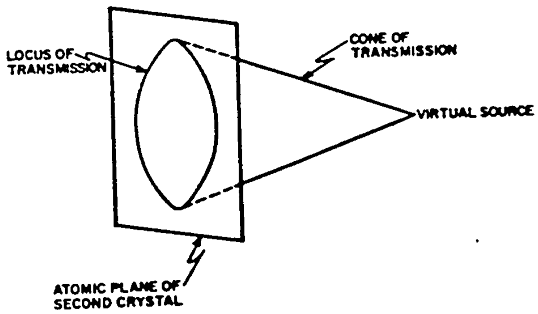


Figure 8. Typical Locus of Transmission

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[*] W. L. Bond, A Double Crystal X-Ray Goniometer for Accurate Orientation Determination, Proc. I. R. E. Vol. 38 pp 886-889

It is possible, as in the case of the first crystal, to determine a circle on the atomic plane of the second crystal which is the locus of all points that satisfy the Bragg equation (assuming that the previously described virtual source is the origin of the X-rays). This locus shall be called the "circle of acceptance". The right cone formed by the virtual source and the circle of acceptance will be called the "cone of acceptance". It is clear, according to Bragg's equation, that if the interatomic spacing of the second crystal is the same as that of the first, the cone of transmission and the cone of acceptance will subtend identical solid angles. These newly defined elements are illustrated in Figures 9 and 10.

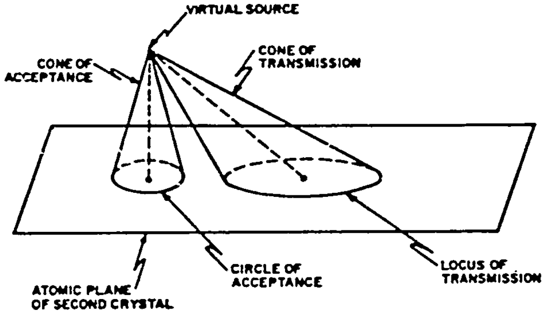


Figure 9. Circle of Acceptance and Locus of Transmission

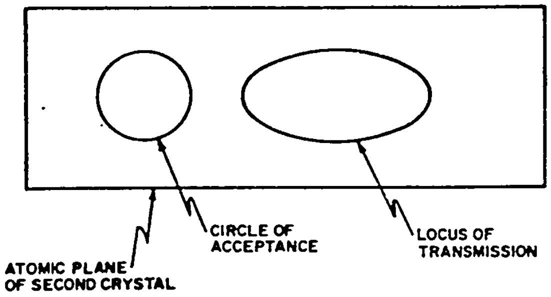
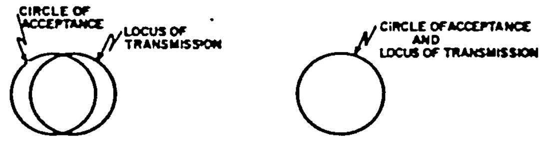


Figure 10. Plan View of Circle of Acceptance and Locus of Transmission

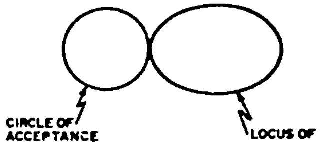
Study of Figures 9 and 10 indicates that as the angle between the atomic planes of the first and second crystals decreases two things occur. The locus of transmission and the circle of acceptance approach each other and the eccentricity of the elliptical locus of transmission decreases. When the two atomic planes are parallel the locus of transmission and the circle of acceptance are superimposed.

It is proper at this point to state explicitly something which has been implied in the foregoing analysis: there is a reflection of X-rays from the second crystal only where there is coincidence between the circle of acceptance and the locus of transmission. Figure 11 illustrates the three modes of intersection.



a. TWO POINT

b. LINE SEGMENT



c. ONE POINT

Figure 11. Types of Intersection of Locus of Transmission and Circle of Acceptance

The preceding discussion has presumed crystals of infinite extent. However, the X-Ray Sorter utilizes crystals of finite dimensions (round disks either 3/8 or 1/2 inch in diameter) and ideally the measurements of the orientation angle is made when the crystals are parallel. Therefore the condition illustrated in Figure 11c will not be discussed further.

Figure 12 illustrates how the preceding general discussion can be applied to the problems of the X-Ray Sorter. The figure is illustrative only of the perfectly parallel case. The section of the conical X-ray sheet actually transmitted is shown, along with those sections of the "infinite" crystals which are actually present in the mechanism.

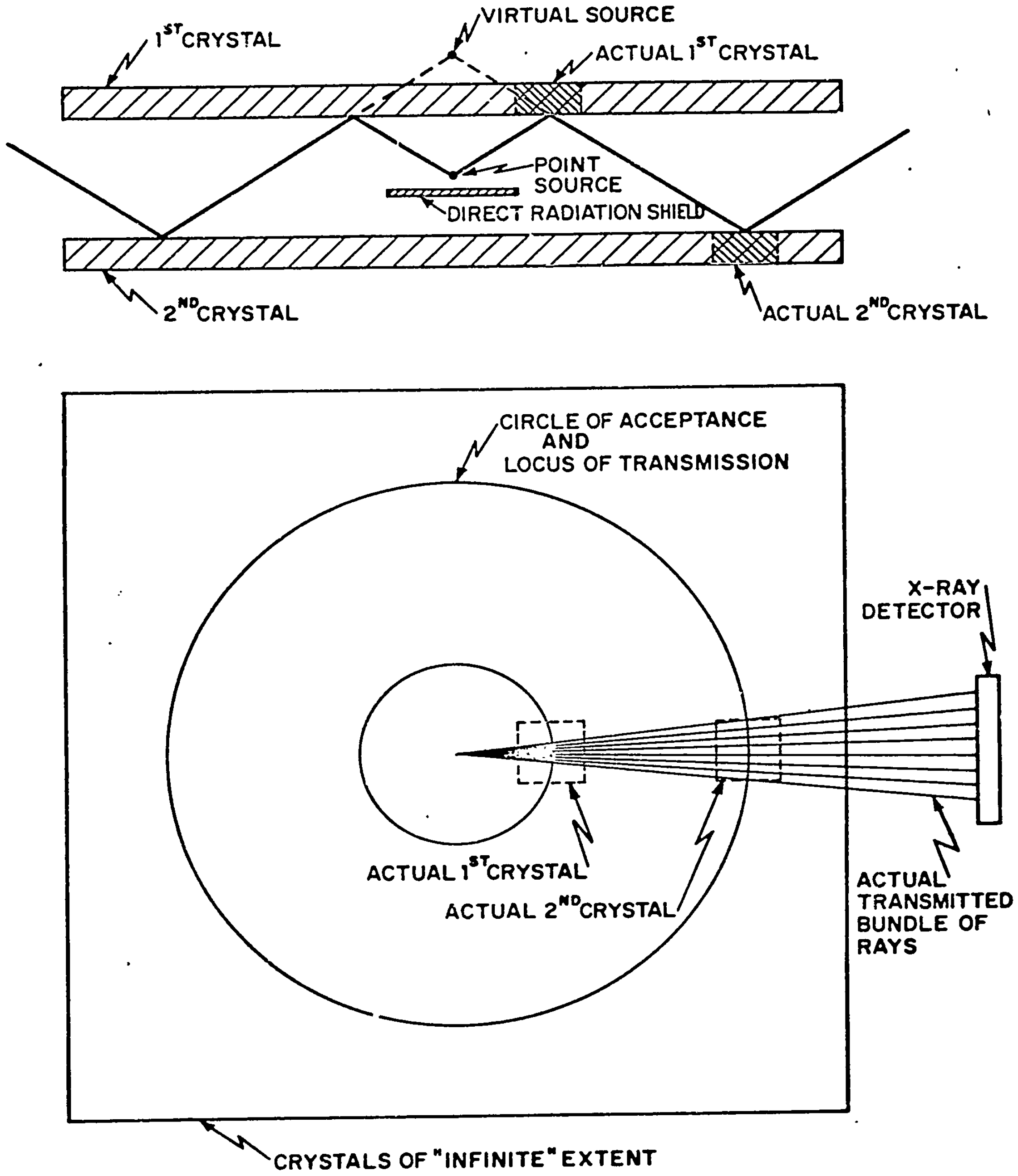


Figure 12. Parallelism of First and Second Crystal

Figures 13 and 14 illustrate the effect of the rotation of the second crystal about the x axis. Figure 13 represents the situation where there is no tilt to the second crystal. In Figure 14, the second crystal is tilted.

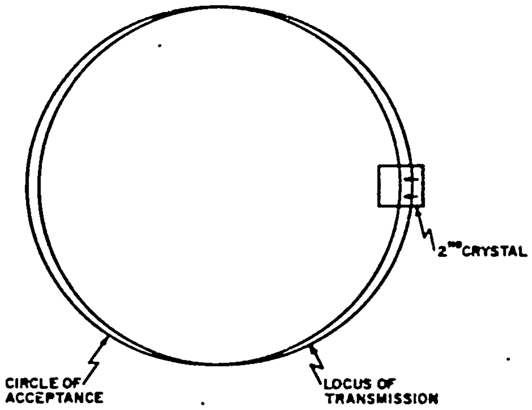


Figure 13. Rotation of the Second Crystal About the x Axis When it is Not Tilted

Rotation of the second crystal about the x axis serves to rotate the locus of transmission into the circle of acceptance in the direction shown by the arrows. When there is tilt of the second crystal Figure 14, shows that total coincidence does not occur.

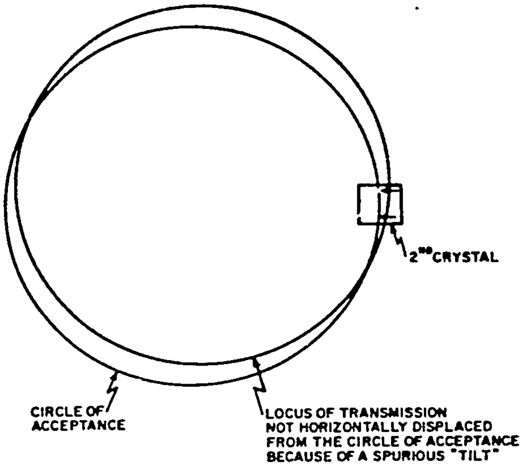


Figure 14. Rotation of the Second Crystal About the X-Axis

It is clear that in Figure 13 there will be only one angular position at which there will be coincidence of the two loci segments (and therefore reflection). In Figure 14, however, there will be a range of angular positions over which there will be coincidence of points on the two loci. In Figures 15a and b reflection intensity versus angular position is plotted for the two cases of Figures 13 and 14. The intensity of reflection will obviously be different in the two cases.

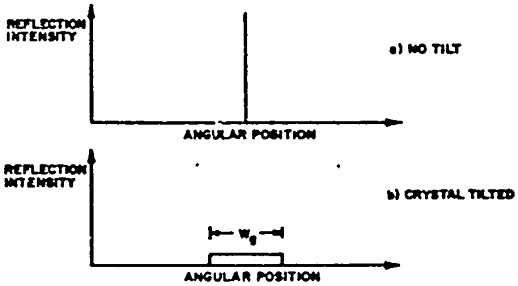


Figure 15. Theoretical X-ray Reflections

M. M. Schwarzshild,* whose mathematical article this physical description supplements, derives an approximate formula for the width, W_g, of Figure 15b. It is:

$$W_g \cong \frac{2\,\delta_a + \delta_b}{\cos\Theta}\tan\psi$$

where:

δ_a = angular derivation of the normal of the first crystal from the plane of the instrument.

δ_b = angular derivation of the normal of the second crystal from the plane of the instrument.

Θ = Bragg angle of the crystal

ψ = Maximum angular derivation of the detected X-ray beam from the plane of the instrument.

Note: $\delta_b = \delta$ (derived above)

W_g is called the geometric width because it arises from purely geometric causes and is not dependent on the quality of the crystal. As is apparent from the formula and from the physical picture presented above, W_g can be minimized by reducing δ and ψ.

Another factor affects the resolution of the two crystal system. Ideal crystals do not exist. Due to imperfections, stresses, surface distortions and other imperfections, the reflection intensity is distributed about the theoretical Bragg angle. This results in a finite width of the reflection peak. Thus, even when the crystals are perfectly cut and positioned the resolution has a definite upper limit. (See Figure 16.)

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*M. M. Schwarzshild, Theory of the Double X-Ray Spectrometer, Phys. Rev. Vol 32, pp 162-171

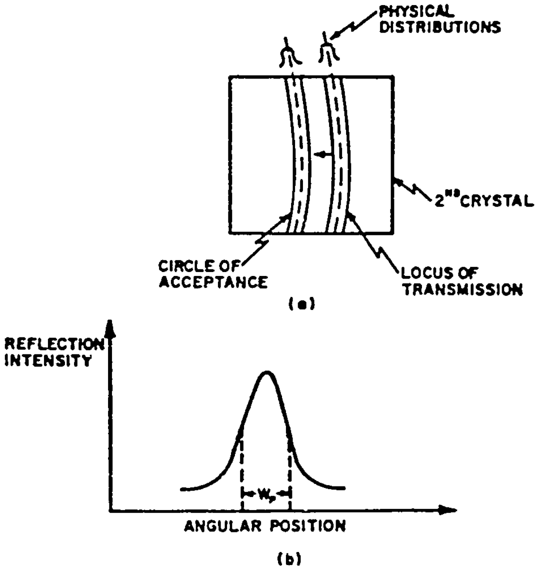


Figure 16. Reflection from Non-Ideal Crystals

W_p is called the physical width because it is independent of the geometry and is solely a function of the physical condition of the crystals.

When the concurrent effects of geometric error (i.e. $\delta =$ finite value) and physical (i.e. non-ideal crystals) are considered, a situation like that illustrated in Figure 17 is obtained.

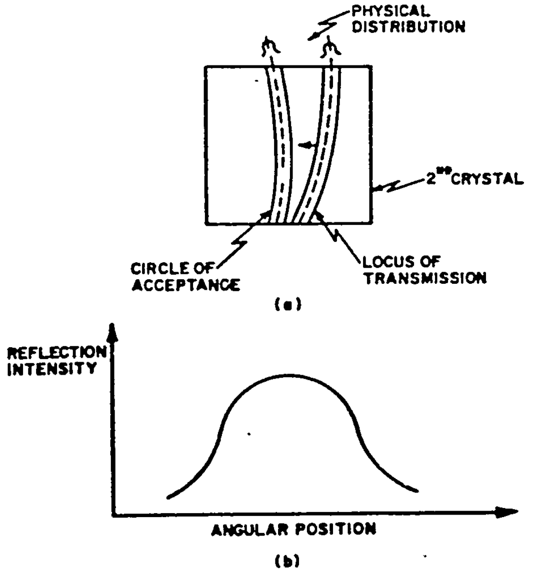


Figure 17. Concurrent Effects of Geometric Error and Non-Ideal Crystals

Here the shape of the peak is a composite of the rectangular form of Figure 15b, and the physical distribution of Figure 16.

APPLICATION TO X-RAY SORTER

In practice, the two widths, W_g and W_p, are of the same order of magnitude. The value of W_p can be reduced by etching to improve the surface quality of the second crystal. Of course, the first crystal should be of the highest quality so that the contribution to the physical width will be due in large measure to the second crystal.

The geometric width W_g is dependent on δ and ψ. The value of δ is dependent on the accuracy of the crystal blank positioning and also on the accuracy of the reference edge and face. The positioning error of the X-ray Sorter can be separated into two components, the set-up error and a random mechanical handling error. The random error can be minimized by proper equipment design. The set-up error can be minimized by using the following procedure. Since the crystals are not perfect, there is a minimum beam width (at $\delta = 0$) that can be obtained. This minimum beam width occurs when superposition of the locus of transmission and circle of acceptance is obtained. When this condition is reached, the X-ray reflection will have its highest peak value because the reflection is obtained from the largest possible area of the second crystal. Thus setting the second crystal for maximum peak reflection with respect to the z-axis should result in minimum beam width.

The accuracy of the reference face and edge is determined by the sawing operations, which precede the X-ray sorting process. It is posible therefore to set specifications for these operations based on the beam width requirement of the X-ray Sorter.

The maximum value of ψ is determined by the size of the second crystal and the length of the X-ray path to it. The minimum value of ψ is determined by the height of the slit through which the X-rays pass.

The maximum value of ψ can be calculated for the X-ray Sorter. The path distance from the X-ray source to the second crystal is 9.4 inches and the maximum height of the second crystal is approximately 0.5 inches. This results in a value of ψ of three degrees. It was previously shown that the value of δ is approximately equal to the inclination angle (β) of the face of the crystal. Substitution of these values in the expression for W_g results in:

$$W_g \overset{\sim}{=} 0.11\beta \text{ where } \beta \text{ and } W_g \text{ are expressed in the same units.}$$

Thus the beam width of the X-ray reflection can be minimized by prolonged etching, proper crystal alignment and use of the minimum height of X-ray beam consistent with the sensitivity of the detecting system.

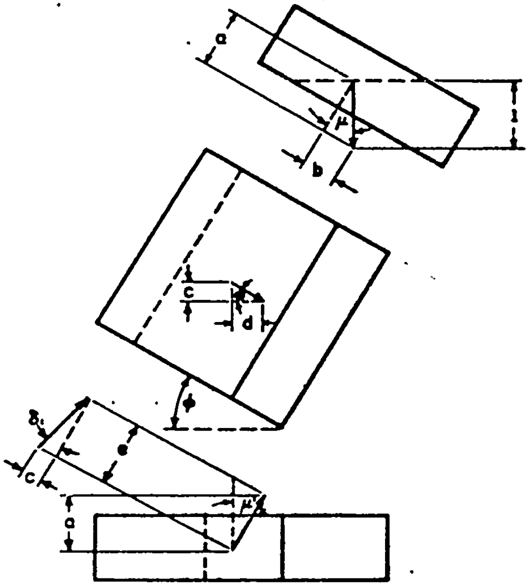
Appendix 26-3

NOTE A

Referring to the figure below:

$a = \cos\mu$

$b = \sin\mu$



Therefore:

$d = \sin\mu\cos\phi$

and,

$$\tan\mu' = \frac{d}{a} = \frac{\sin\mu\cos\phi}{\cos\mu}$$

$$= \tan\mu\cos\phi.$$

Also:

$c = \sin\mu\sin\phi$

$e = (a^2 + d^2)^{1/2}$

$= (\cos^2\mu + \sin^2\mu\cos^2\phi)^{1/2}$

Therefore:

$$\tan\delta_1 = \frac{c}{e}$$

$$= \frac{\sin\mu\cos\phi}{(\cos^2\mu + \sin^2\mu\cos^2\phi)^{1/2}}$$

and,

$$\tan\delta_1 = \frac{\tan\mu\sin\phi}{(1 + \tan^2\mu\cos^2\phi)^{1/2}}$$

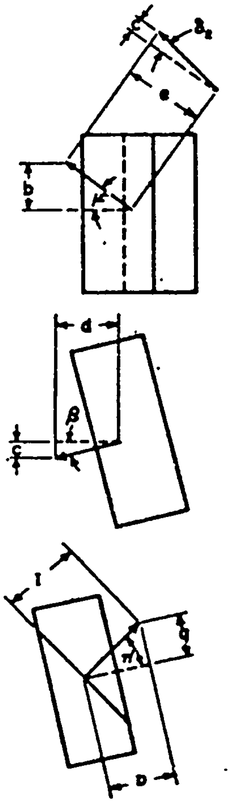
NOTE B

Referring to the figure below:

$a = \cos\mu$

$b = \sin\mu$

$d = \cos\mu\cos\beta$



Therefore:

$$\tan\mu'' = \frac{b}{d} = \frac{\sin\mu}{\cos\mu\cos\beta}$$

$$= \frac{\tan\mu}{\cos\beta}$$

Also:

$c = \cos\mu\sin\beta$

$e = (b^2 + d^2)^{1/2}$

$= (\sin^2\mu + \cos^2\mu\cos^2\beta)^{1/2}$

Therefore:

$$\tan\delta_2 = \frac{c}{e}$$

$$= \frac{\cos\mu\sin\beta}{(\sin^2\mu + \cos^2\mu\cos^2\beta)^{1/3}}$$

and,

$$\tan\delta_2 = \frac{\sin\beta}{(\tan^2\mu + \cos^2\beta)^{1/2}}.$$

APPENDIX 41-1

Contouring Survey

An industry survey was made in order to obtain more detailed information about procedures used by other quartz crystal manufacturers for the production of low frequency AT blanks (between 4.3 mc. and 9.0 mc.) In the course of this survey, the following companies were visited:

P. R. Hoffman, Co., Carlisle, Pa.
The Hunt Corp., Carlisle, Pa.
McCoy Electronics, Mt. Holly Springs, Pa.
Scientific Radio Co., Omaha, Nebraska
Union Thermoelectric Corp., Chicago, Ill.

In addition, the Army Signal Supply Agency transmitted to us information on the contouring procedures being used at present by the Bliley Electric Company of Erie, Pa.

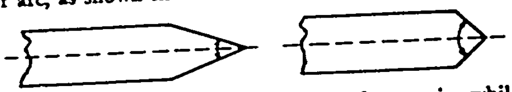
The survey has disclosed that square, rectangular and round blanks are produced by manufacturers as shown in Table 1 below:

No. Manufacturers	*Squares*	*Rectangulars*	*Rounds*
3	—	—	X
1	—	X	X
1	X	X	—
1	X	X	X

The following methods in Table 2 are in use for beveling, edge-contouring and full contouring:

No. Manufacturers	*Optical Cup Only*	*Optical Cup plus others*	*Others Only*
1	—	—	X
2	—	X	—
3	X	—	—

The amount of contour or bevel is controlled either by time or by change in frequency. The crystal designs for beveling and edge-contouring vary so that the two beveled surfaces include an angle between 20° and 90° of arc, as shown in the following sketch:



The smaller angles apply to low frequencies while the larger angles are used for higher frequencies only (above 7 mc. approx.).

The abrasives used for the contouring/beveling procedure are generally of a larger grit size than that used for the last lapping stage (approx. 20 microns). This results in a fairly rough surface. In order to obtain the right surface finish before base plating, some companies apply a heavy final etch to the blanks (approx. $1.5f^2$). Except for the very low frequencies, below 2.5 mc., all manufactures leave a large flat portion on both sides of the blanks. The diameter of this center in the case of round blanks, or the side-length in the case of square or rectangular blanks, is usually several mils larger than the comparable dimensions of the plated electrodes.

The depth of the contour or bevel varies from company to company; whereas one manufacturer deems it necessary to bevel down to the center plane of the blank (as shown in the above sketches), others feel that a sufficient amount of bevel or contour is obtained if a cylinder with a height of 1/3 of the original blank thickness remains in the blank.

A summary of the results of this survey will be found in the attached chart. Tumbling and barrel contouring procedures being investigated at present by Union Thermoelectric Corporation are not reviewed in this report for, to date, there are no final results.

SURVEY OF CONTOURING AND BEVELING PROCEDURES ON LOW AT'S

Company	A	B	C	D	E	F
Frequency Range	1 mc. to 10 mc.	3 mc. to 6 mc.	approx. 3 to 8 mc.	approx. 1/2 to 12 mc.	approx. 1 to 24 mc.	4.3 to 18 mc.
Blank size	sqs. .9" to .495" rectangulars in same limits round disks .500" dia.	round disks .548" dia.	squares .520" rectangulars .480" x .520"	rectangulars .490" x .515" .490" x .535" .470" x .520" round disks .435" dia. .486" dia.	round disks .500"	round disks .375" .490" .500" .550"
Full Contour	—	—	below 2.5 mc. only	below 2.1 mc. only	below approx. 3 mc.	—
Edge Contour	X	—	up to approx. 8 mc.	up to approx. 9 mc.	up to 9 mc.	up to approx. 9 mc.
Bevel	X	X	—	X	—	—
Flat Center Portion	on squares .5", approx. 3/8" on disks .5", 7/16" dia.	approx. .400 dia.	approx. .250" dia.	approx. 1/2 blank dia.	approx. 1/2 blank dia.	approx. .250" to .281"
Cylindrical Portion	none, knife-edge	approx. 1/3 thickness	none, knife-edge	approx. 1/3 thickness	approx. 1/4 thickness	not yet determined
Equipment Used	Optical cups #7 Diamond wheel with grit #320 water as coolant Brass arc 5" dia. with #500 SiC in suspension	horizontal steel disk with suspended abrasive	Optical cups, #2.75 & 4.75 with suspended abrasive	Diamond wheel with #320 grit & coolant Diamond wheel with #400 grit & coolant Optical cups #2 to #18 with suspended abrasive	Optical cups, #2, 3, 4 & 5 with suspended abrasive	Optical Cups up to #4 with suspended abrasive

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APPENDIX 45 B-1

Control of Final Etch Process

Although the spread and standard deviation of the frequency shift of quartz blanks etched in hydrofluoric acid is low for small batches etched in the laboratory, it is known that the conditions in the prototype etching machine must be carefully controlled in order to prevent over - and under-etching.

A predetermined amount of etching will be set into the machine via the timing mechanism. From experiment and from theoretical considerations, it is possible to estimate the deviation from this amount, presuming some level of precision achieved by the automatic controls. The factors which must be determined are:

1. The effect of deviations in etching time.
2. The effect of variation, in HF concentration.
3. The effect of variations in temperature.

It is assumed that the etch tank controls have the following precision (three times standard deviation).

Time: ±5 seconds per minute
(including variations in transfer time)

Concentration: ±0.5%

Temperature: ±0.5°C

The nominal concentration of HF to be chosen is one in which the minimum time in the etching bath is at least one minute (equivalent to $0.16f^2$ for blanks lapped to 4 microns finish) and the maximum time approximately 5 minutes ($0.40f^2$ for 8 micron finished blanks.) Figure 45B-1-1 in which the experimental determinations of total amount of etch versus etching time are plotted for two concentrations of HF, indicate that this result can be achieved with 16% H.F.

The effect of errors in preset etching time can be obtained directly from the 16% curve by measuring the slopes at 1 and 5 minutes.

16% HF:

For 1 minute etch, slope $= 0.102f^2/\text{min.}$

For 5 minute etch, slope $= 0.035f^2/\text{min.}$

To estimate the effects of variations from nominal concentration, the data of 45B-1-1 is cross-plotted in 45B-1-2, total etch versus concentration for the two times chosen. Taking the slope of the two curves at 16% concentration, we obtain

For 1 minute etch, slope $= 0.014f^2/\text{percent HF}$

For 5 minute etch, slope $= 0.030f^2/\text{percent HF}$

To obtain the effect of temperature variation, certain assumptions must be made concerning the nature of the HF - SiO_2 chemical reaction and the dependance of reaction rate on temperature. It is well-known that chemical reactions of this nature commonly double or treble their velocity for each 10°C temperature rise, in the neighborhood of room temperature (c.f. "Outlines of Physical Chemistry", F. Daniels, John Wiley 1948, p. 365). From the average slopes of the 16% HF curve of 45B-1-1, the average rate of reaction (proportional to rate of etch in f^2/min.) can be determined; that is, 0.134 and $0.080f^2$/min. for 1 and 5 minutes total etching time respectively. Assuming the reaction rate to increase by two and three times per 10°C rise, the following rates can be calculated.

Temp. °C	*Av. Rate, f^2/min.*			
	For 1 min. etch		*For 5 min. etch*	
(Assumed Reaction Rate Increase)	*2 x /10°C*	*3 x /10°C*	*2 x /10°C*	*3 x /10°C*
15°	0.067	0.045	0.040	0.027
25°	0.134	0.134	0.080	0.080
35°	0.268	0.402	0.160	0.240

These points are plotted in 45B-1-3. The slopes of the various curves in the vicinity of 25°C yield the desired temperature coefficients (increase in reaction rate per °C rise) from which the total effect of temperature rise can be readily calculated.

Finish Microns	*Total Etch Time, Min.*	*Temp. Effect., f^2/min. °C*		*Total Temp. Effect, f^2/°C*	
		(2 x /10°C)	*(3 x /10°C)*	*(2 x /10°C)*	*(3 x /10°C)*
4	1	0.010	0.015	0.010	0.015
8	5	0.006	0.004	0.030	0.045

FINAL ETCHING OF QUARTZ BLANKS WITH HYDROFLUORIC ACID

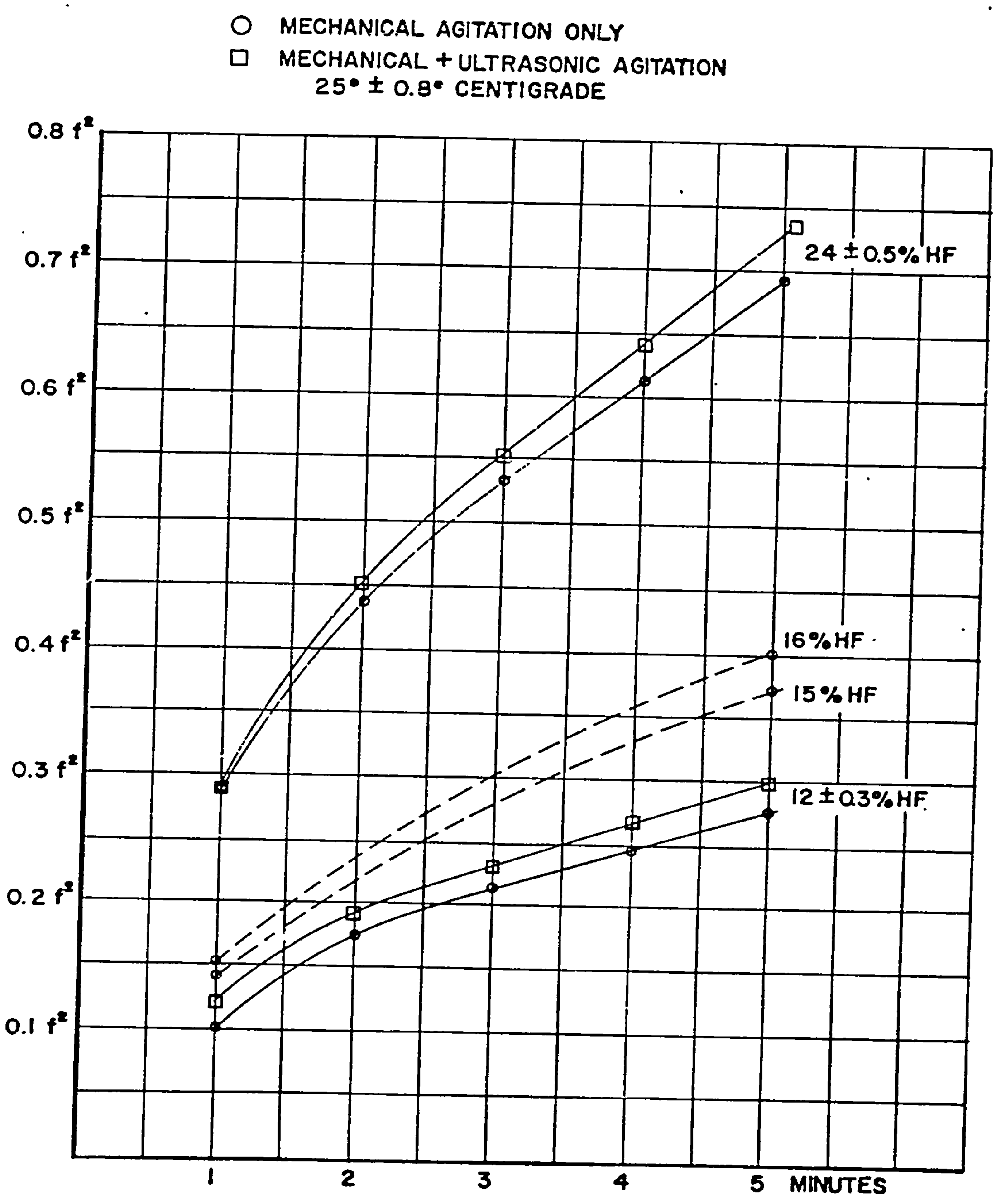

Figure 45 B-1-1.

TOTAL ETCH VS HF CONCENTRATION FOR 1 AND 5 MIN ETCH TIME
t = 25°C ±0.8

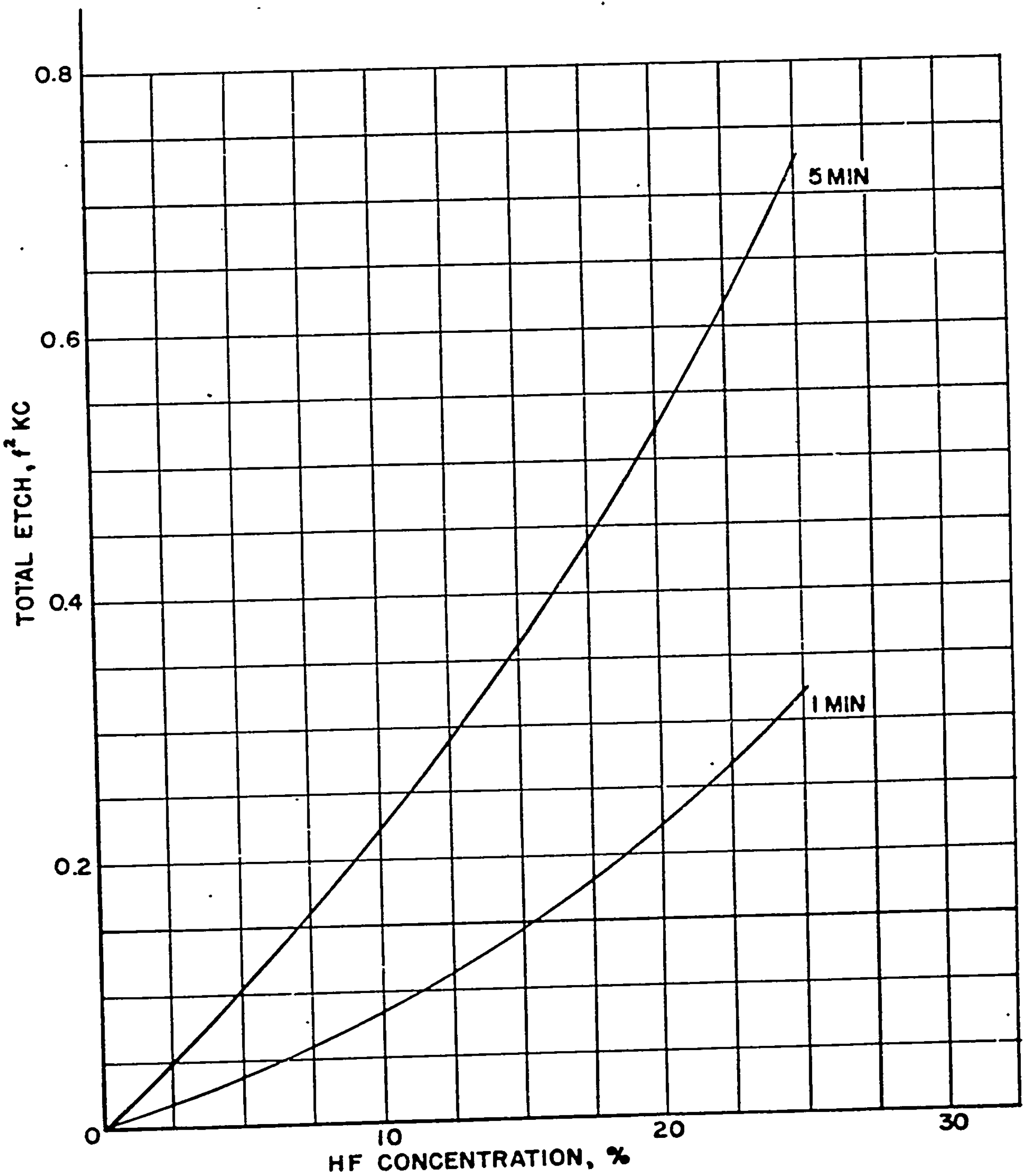

Figure 45 B-1-2.

CHANGE IN FINAL ETCHING RATE WITH TEMPERATURE (16% HF, 25°C)

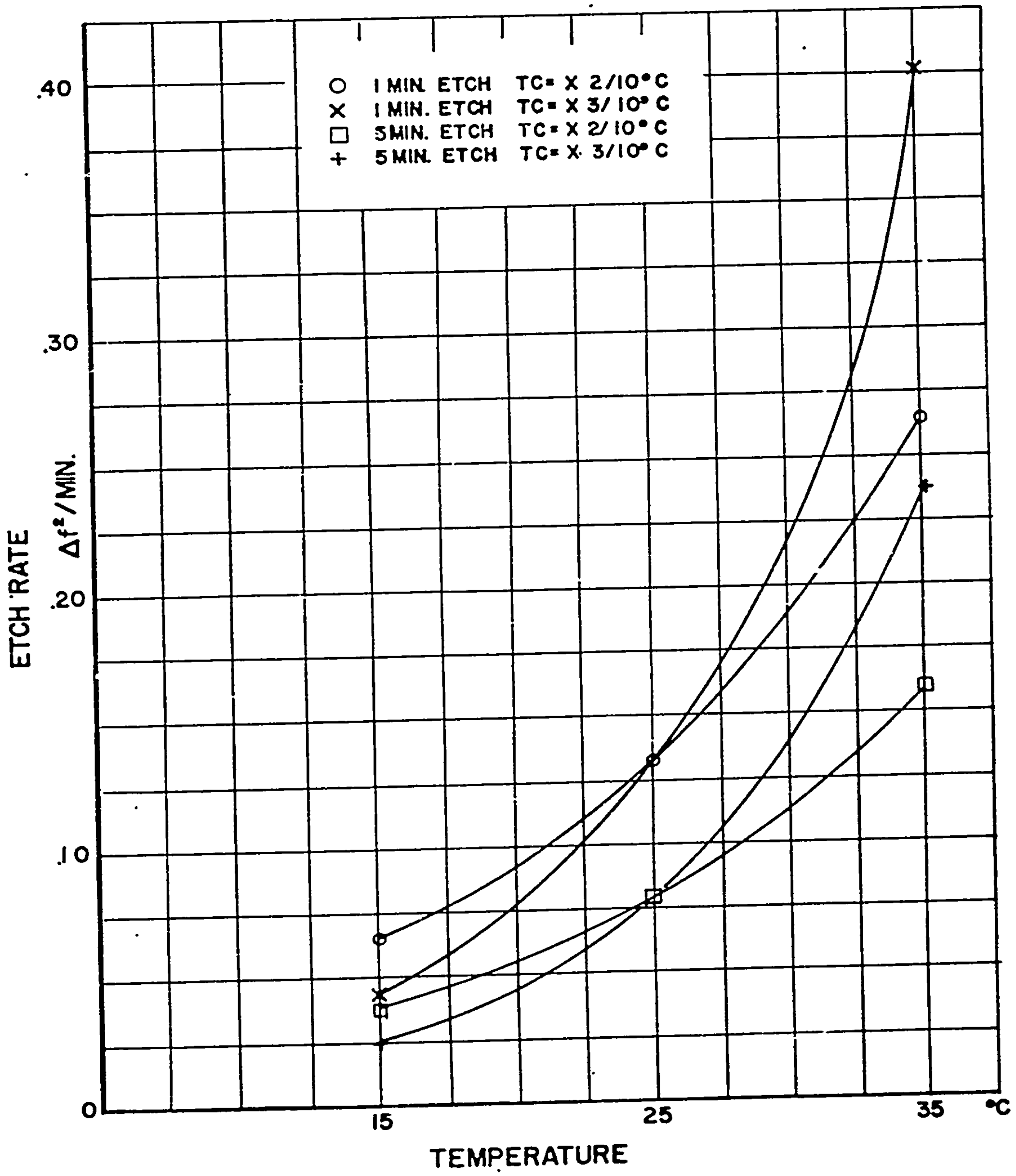

Figure 45 B-1-3.

Appendix 45 B-1

Since the exact temperature coefficients are unknown, a mean value is assumed.

The final effect considered is the variation between individual blanks within a given batch. The results of etching experiments indicate that the standard deviation within one batch etched for a given time should not exceed $0.015f^2$. This number probably accounts for variations in grain size of lapping compound and slight chemical or physical differences in the quartz, plus local differences in temperatures, concentration, and agitation rate. Hence, a variation (3 sigma) of $0.045f^2$ will be assumed within a given batch.

The variations due to time, temperature and concentration errors plus those due to batch spread as derived above can now be statistically combined. The total error is shown in the last column of Table 45B-1, below.

Table 45B-1

EFFECT OF CONTROL VARIATIONS ON TOTAL ETCH

Process Variable	*Control Precision (3σ)*	*Effect of Variable. Δf^2 per unit error*	*Variation $\Delta f^2 = (3\sigma)$*	*$(\Delta f^2)^2$ x10^4*	*Total Variation*
A. *4 Micron*					
Time	±5 sec.	$0.102f^2$/min.	.0085	0.72	
Concentration	±0.5%	$0.014f^2$/%	.0070	0.49	
Temperature	±0.5°C	$0.013f^2$/°C	.0065	0.42	
Batch Variation	——	——	.045	20.3 21.9	$\pm.047f^2$
B. *8 Micron*					
Time	±25 sec.	$0.035f^2$/min.	.015	2.25	
Concentration	±0.5%	$0.03f^2$/%	.015	2.25	
Temperature	±0.5°C	$0.038f^2$/°C	.019	3.60	
Batch Variation	——	——	.045	20.25 28.35	$\pm.053f^2$

In summary, the required precision of the final etching process can be met under the following conditions, using hydrofluoric acid solution:

Temperature: 25°C approximately

Concentration HF: 16% approximately

Control Precision (3σ):

Time: ± 8.5% (±5 sec. per minute)

Temp: ±0.5°C

Concentration: ±0.5%

These conditions will produce the following etch control results:

For 4 micron finish:	
Min. etch	$0.16f^2$
Max. etch	$0.26f^2$
Amount preset (average)	$0.21f^2$
Expected deviation (3σ)	$\pm0.05f^2$
For 8 micron finish:	
Min. etch	$0.32f^2$
Max. etch	$0.44f^2$
Amount preset (average)	$0.38f^2$
Expected deviation (3σ)	$\pm0.055f^2$

Hence, better than 99.7% of the blanks etched will be within these limits.

APPENDIX ILM-1

Effect of Dead Time on Quality of Lapping Machines

In Station ILM, equations were derived for the number of lapping machines required in each stage, and numerical values worked out for specific values of lapping rate, quartz removal, and dead time D, the latter being the sum of the load/unload time and the average lapping plate replacement time (per cycle).

Using the quantities given in Table ILM-2, the equations cited can be simplified as follows:

N_1 = number of machines in Primary Lap

$$= \frac{0.551}{e_1}(7.22 + D)$$

N_2 = number of machines in Secondary Lap

$$= \frac{0.505}{e_2}(5.54 + D)$$

N_3 = number of machines in Final Lap

$$= \frac{0.464}{e_3}(7.02 + D)$$

where e_1, e_2, e_3, is the efficiency of the lapping machine in that stage (i.e. the percent of total shift time the machine is in use).

The equations are plotted in Figure ILM-1-1 as number of machines required vs. percent utilization (efficiency), for three values of the parameter D in each stage. (Use of a special scale for the abscissa permits the curve to be plotted as a straight line.)

The intersection of a curve of constant D with an integral value of N denotes the minimum efficiency required before the next higher number of machines must be used. For a given efficiency and number of machines, the allowable dead time in that stage may be interpolated between curves.

For example: for a dead time of 2 minutes per cycle in Primary Lap, the machine efficiency must be greater than 84.5% for 6 machines to be sufficient. With a dead time of 1.5 minutes, 5 machines at greater than 96% efficiency may be used.

NUMBER OF LAPPING MACHINES VS. DEAD TIME

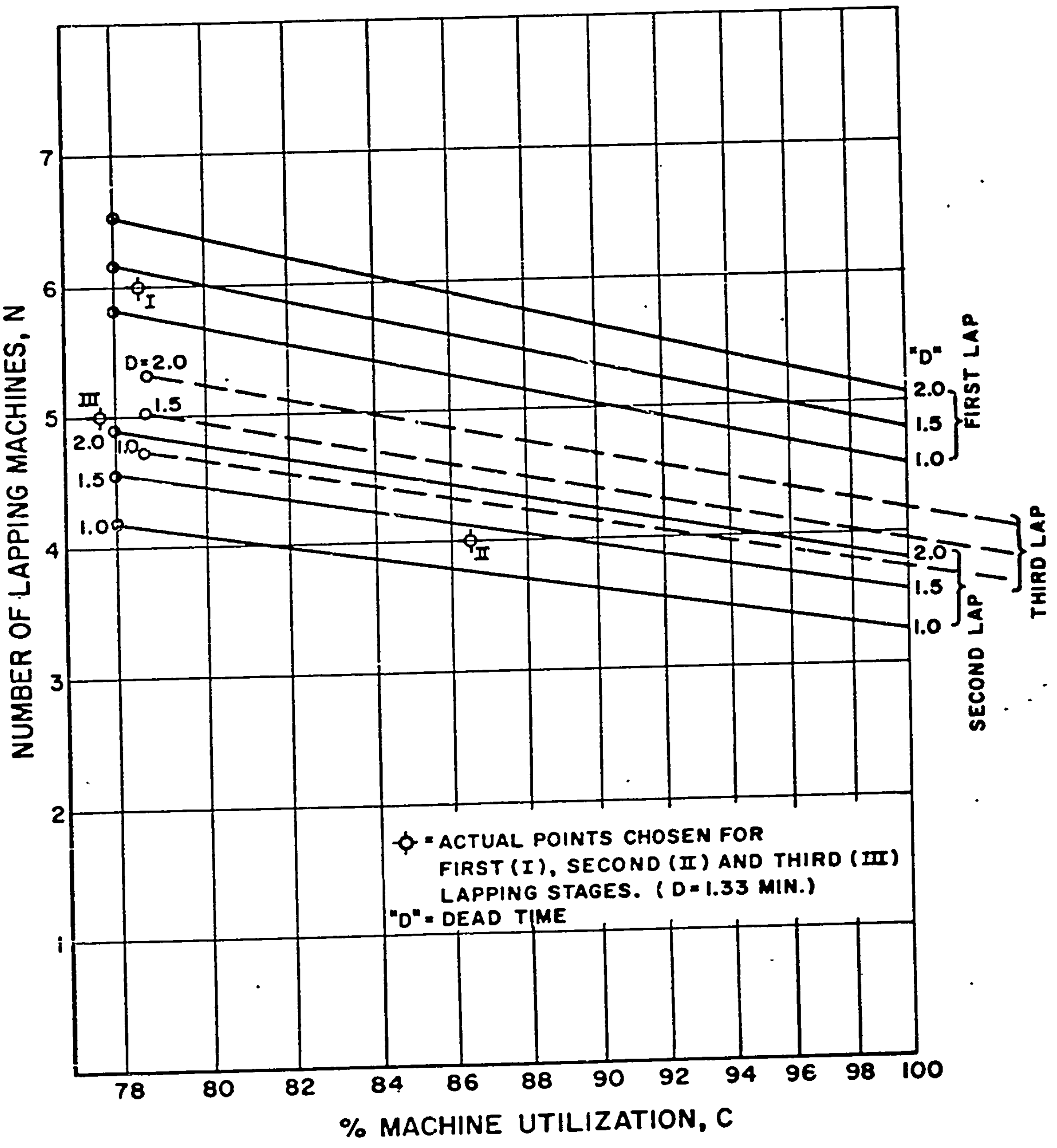

Figure ILM-1-1.

APPENDIX K-1

Estimate of the Number of Changes in Frequency Setting Necessary During Frequency Sorting Quartz Crystal Blanks in the Mechanized Plant System

In the Frequency Sorter designed for the subject plant, any of a given number of nominal frequencies and sorting increments may be preset in the electronic Control Panel unit and selected remotely from the Feed-Sort console by a push-button operation. However, in changing from one frequency to another which is substantially different, an air-gap in the measuring head of the Feed-Sort unit must also be adjusted. Since this operation may take as long as one minute during which time the Sorter is not operating, it is necessary to estimate the total number of frequency changes per day to compute the utilization efficiency of the machine.

The number of frequency changes required when going from one lapping stage to another or when completing the sorting of an order, is not simply capable of direct calculation. The number of variables and their interrelationship is so complex as to permit the sorting schedule to be considered as a random process. A rudimentary application of Game Theory, analogous to the Monte Carlo method applied in nuclear calculation, has been devised in order to evaluate the frequency changes required during sorting.

It is assumed that blanks are to be sorted without accumulating a substantial backlog. At the start of a day's run, one full cartridge from each lapping stage is available, containing the following number of blanks:

From Primary Lap	250 Blanks
From Secondary Lap	315 "
From Final Lap	360 "
Total	925

All blanks sorted during a day's run are of the same diameter, or the sorting head is changed during the noon hour so that the time to change diameters is not charged against the machine time.

The lapping stages produce blanks and full cartridges at the following rates:

	Blanks/min.	*Min./cartridge*
Primary	33.3	7.5
Secondary	30.5	10.6
Final	28.1	12.8

Assume initially that only one order is being processed in the plant. There are then three nominal frequencies to be selected by the sorter, one for each lapping stage. Hence every cartridge selected from a different stage from the last requires a change of sorter frequency.

The frequency change requires:

1. Selection of new frequency from the console.
2. Adjustment of sorter head air gap.
3. Removal and temporary storage (in order) of all output cartridges.
4. Selection and insertion of output cartridges (partially full) for the new frequency.

It is assumed that this task can be performed in one minute with the aid of suitable jigs or fixtures.

The sorting rates per cartridge are taken to be as follows:

	Time to Sort Cartridges:
From Primary Lap:	2.0 min.
From Secondary Lap:	2.5 min.
From Final Lap:	3.0 min.

(These time intervals are rounded off for simplicity in plotting.)

A graphical sorting game is prepared by plotting the backlog of blanks against time. The time at which full cartridges from the various stages of lapping become available and the number of blanks in each is indicated by circles on the plot. Transportation time between lapping stage and sorter is neglected. The negative sloping lines then indicate sorting of the cartridges at the rates indicated above, and a vertical rise indicates choice of a new cartridge from a lapping stage indicated by the ordinate. A horizontal line indicates a waiting period to change frequencies, or if on the zero blank axis, a waiting period because no cartridges are available.

Any cartridge waiting for sorting can be selected for sorting by rising to the appropriate ordinate value. If it is selected from the same ordinate (lapping stage) as the last, no time need be allowed for frequency change. If a different ordinate is selected, one minute of non-sorting time must be allowed.

It is permissible to wait for another cartridge from the same stage as last sorted if the waiting period does not exceed one minute, regardless of how many other cartridges are ready. If two or more cartridges are ready to be sorted, we select the one which does not require frequency change, or if both do, we select the one most likely to give a "double" (no change of frequency) on the next choice.

RESULTS

The results of one such game is shown in the attached plot, Fig. K-1-1.

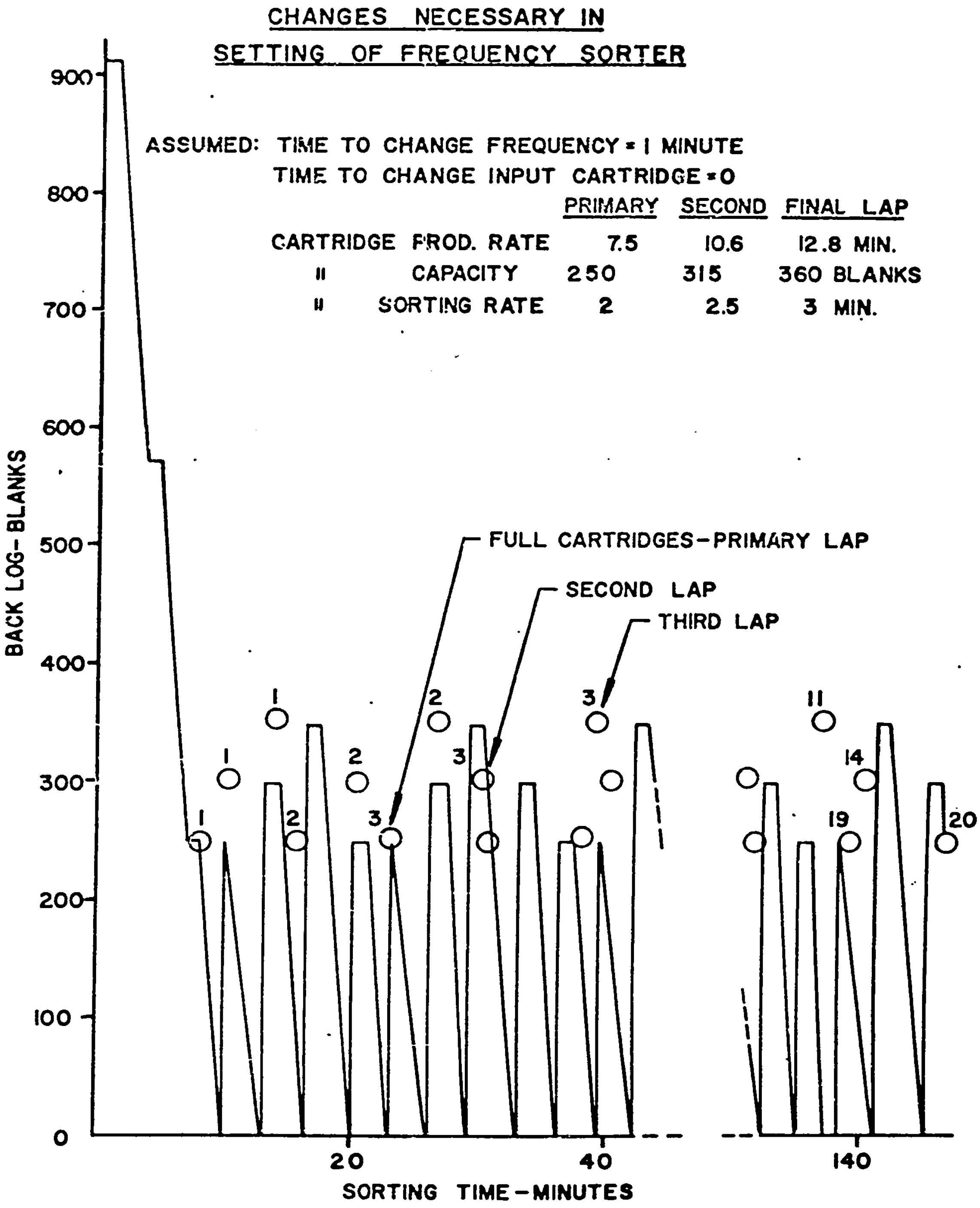
CHANGES NECESSARY IN
SETTING OF FREQUENCY SORTER
ASSUMED: TIME TO CHANGE FREQUENCY = 1 MINUTE
TIME TO CHANGE INPUT CARTRIDGE = 0
PRIMARY
SECOND
FINAL LAP
CARTRIDGE PROD. RATE 7.5 10.6 12.8 MIN.
" CAPACITY 250 315 360 BLANKS
" SORTING RATE 2 2.5 3 MIN.
FULL CARTRIDGES-PRIMARY LAP
SECOND LAP
THIRD LAP
1
1
1
2
2
2
3
2
3
3
3
11
14
19
20
900
800
700
600
500
400
300
200
100
0
BACK LOG-BLANKS
20
40
140
SORTING TIME-MINUTES

Figure K-1-1.

In 150 minutes of sorting (starting with a 925 blank backlog) the following number of blanks and cartridges were sorted.

	Cartridges	*Blanks*
From Primary Lap	20	5000
From Secondary Lap	14.2	4480
From Final Lap	12	4320
Total	46.2	13,800

The number of frequency changes required was 36.

The "raw" sorting rate (not adjusted for frequency changes, was

$$\frac{13{,}800}{150} = 92 \text{ blanks/min.}$$

The number of cartridges sorted per frequency change is

$$\frac{46.2}{36} = 1.29$$

and the number of frequency changes per day (= 140 cartridges)

$$\frac{140}{1.29} = 109$$

On the basis of blanks sorted:

$$\frac{\text{Blanks}}{\text{Freq. Change}} = \frac{13{,}800}{36} = 383$$

$$\frac{\text{Freq. Changes}}{\text{day}} = \frac{38{,}600}{383} = 104$$

Since blanks sorted is probably the better measure, 105 changes per day is taken as the correct result.

EFFECT OF ORDER CHANGES

In addition to those changes of frequency resulting from the production rates, there are 24 changes caused by completion of small orders during the day. Some of these are coincident with the changes that would be required in the first case.

Since there are 105 out of 140 cartridges which required resetting the nominal frequency, even without order change, the probability of these 24 cartridges coinciding with the former changes is

$$\frac{105}{140}$$

Hence,

$$\frac{105}{140} \text{x } 24 = 18 \text{ of the order changes can be}$$

neglected. This leaves 6 frequency changes due to completion of orders which must be added, for a total of 105 + 6 = 111 per day.