MACHINE LAPPING OF QUARTZ OSCILLATOR-PLATES

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Contents

Abstract

A description is given of several types of machine lapping methods and equipment used in the manufacture of quartz oscillator-plates from the rough cut stage up to the final etching-to-frequency operations. The blanks are lapped from *ca.* 0.045″ thick to 0.012″ to 0.018″ depending upon the desired frequency and at the completion of the final stage the major surfaces must be parallel to within a few fringes of light, have a fine finish (usually with #303 optical flour), oscillate, and be close to final frequency (0.00004″ above final thickness).

A three-stage high-speed lapping-to-frequency procedure using planetary-type motion laps is described in detail. 30 to 55 crystals (depending upon their size) are carried in five revolving work-holders between two stationary lap plates so that both sides are lapped at the same time and rate. The weight of the top plate, speed, and abrasive size are progressively reduced in the three stages. A group of crystals is transferred from one stage to the next without intermediate grouping and one random transposition is made at *ca.* 0.0006″ from the final thickness to equalize thickness differences and contour on both sides. Total thickness variation is ±0.00002″. A calibrated sensitive radio receiver coupled directly to machine laps can be used to follow the progress of the crystals and to achieve precision control of the stopping point.

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Various other types of lapping equipment and procedures are described. The converted drill press lap is the most widely used in the crystal industry. The work-holder carrying the crystals is driven between a pair of stationary lap plates; the calibrating machine lap works on the same principle but is smaller. Optical-type laps have disadvantages for crystal work and are not commonly used. A special lap for single crystals and the milling technique in which as many as 1000 crystals at a time are tumbled, are described.

INTRODUCTION

This paper describes the machine lapping methods and equipment used in the manufacture of quartz oscillator-plates. The rough surface from the sawing operations must be removed and the blank properly lapped so that it will oscillate. The rough cut blanks are *ca.* 0.045″ thick and are lapped to 0.012″ to 0.018″ depending upon the desired final frequency.

Some of the several problems which must be simultaneously solved in the ideal lapping procedure are:

a. The lapped crystals must have the proper finish (usually with #303 optical flour) and contour (approximately 0.0001″ to 0.00005″ thicker in center than at four corners for 6 to 8 MC BT-cuts). The two major surfaces should be parallel to within a few fringes of light.

b. The crystal surfaces, edges and corners must be free from scratches and chips, and have the highest quality to prevent later difficulties in final finishing and use.

c. All crystals in each lap load must be closely alike in frequency at the completion of the final lapping stage. The approximate frequency spread should not exceed 10 to 15 KC for 6 MC BT-cuts which corresponds to 0.00004″. This eliminates the necessity of accumulating huge stocks of various frequencies, channel sorting, etc.

d. Recent experimental work has shown that 15 to 30 KC must be etched off 6 to 9 MC BT-cut crystals respectively, to prevent ageing.[1] Therefore each lap load of crystals must be brought to within 0.00004″ of final thickness without overshooting in order to reduce hand finishing to a minimum and obtain uniform crystals.

e. The entire lapping operation should be only a small fraction of the entire manufacturing cost. This means a large volume of high quality crystals, with a low rejection rate and hence the methods and equipment must be simple so that comparatively unskilled help can use them in a routine manner.

This study deals with the machine lapping of $\frac{3}{8}''$, $\frac{1}{2}''$ and $\frac{3}{4}''$ square BT-cut crystals in the 5 to 9 MC fundamental frequency range and $\frac{3}{4}''$ square AT-cut crystals, 2 to 5 MC. In these types of crystals the frequency is

[1] All lapped crystals age but the ageing is effectively stopped by etching off the disoriented surface layers after lapping. Frondel, Clifford, Final frequency adjustment of quartz oscillator-plates: *Am. Mineral.*, this issue.

dependent upon the thickness

$$\text{Frequency (KC)} = \frac{K}{\text{Thickness (inches)}};\ \frac{dF}{dT} = -\frac{K}{T^2}$$

and their relationship is shown graphically in Fig. 1. The frequency-

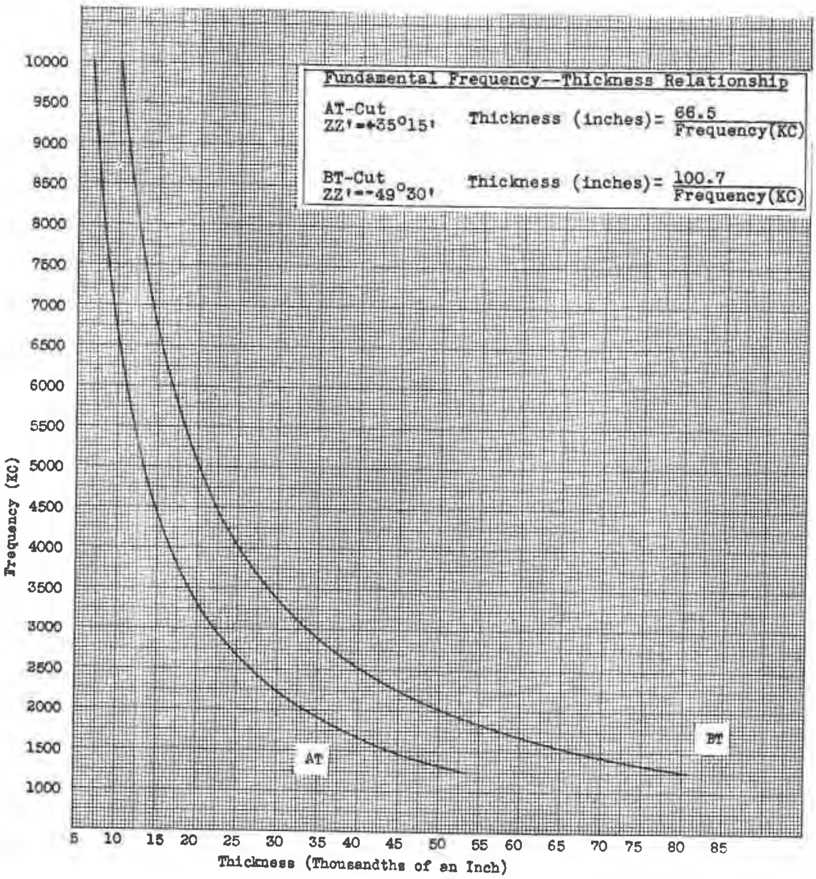


FIG. 1. Fundamental frequency-thickness relationship for AT- and BT-cuts.

thickness constant varies with the angle of cut, and for the angles used in this work the approximate values are: $K=100.7$ for BT-cuts, $ZZ'=49°30'$, $XX'=0°$; $K=66.5$ for AT-cuts, $ZZ'=+35°15'$, $XX'=0°$. In the higher frequencies, a minute decrease in thickness causes a large frequency increase so that the general practice is to make measurements directly in terms of approximate frequency (± 2 to 4 KC) using a rapid direct reading device such as the channel sorter described later, rather than attempt precision thickness measurements.

It will be recognized that machine lapping of quartz crystals is a high precision job requiring a skillful procedure and good equipment. The sudden unprecedented demand for crystals after Pearl Harbor produced a variety of procedures and equipment hurriedly designed, with little opportunity to study even the barest principles involved, in order to get production started in the shortest possible time. Many of the fundamental problems have been solved and a few of the best practices will be briefly summarized. Some of the methods are applicable to the preparation of polished and thin-sections for mineralogical work, especially when used with the sawing procedures described in another paper in this Journal.[2]

Acknowledgments. The work on high speed planetary lapping to frequency was carried out under a development contract with the Signal Corps of the U. S. Army through the Signal Corps Ground Signal Agency. The work would not have been possible without their encouragement and support.

The writer is indebted to several engineers at N.A.P. for aid in this work: Mrs. S. Tinto[3] was in charge of the experimental work; the description of the radio receiver technique is based upon the development work of Mr. John D. Davies; Mr. T.W.M. Schaffers and Mr. E. F. Sheeder were responsible for the mechanical engineering; Mr. J. T. Derbyshire took the photographs; Mr. Charles E. Goldmann and several technical assistants carried out the detailed work. Mr. J. N. Bagwell, Jr. of Commercial Crystal Co., Lancaster, Pa. and Mr. P. R. Hoffman of Carlisle, Pa. were consulted on several problems. Bliley Electric Co., Erie, Pa. supplied Fig. 10 and information on the optical type lap. Atlas Sales Co., Chicago, Ill., supplied Fig. 12. Dr. Hal F. Fruth of Galvin Mfg. Corp. Chicago, Ill. reviewed the section on milling methods and contributed the data for Fig. 16.

Lapping Procedures

Only a few plants use a one-stage lapping process. A lapping stage refers to the grinding of crystals to a specific thickness with one size of abrasive. The three-stage process has proven the most successful although the four-stage and even the two-stage processes are in use.

The disadvantage of the single stage of lapping is that it requires a longer time than in the case of several stages. As the crystals acquire the

[2] Parrish, William, Methods and equipment for sawing quartz crystals: *Am. Mineral.*, this issue.

[3] Now at Research Division, Reeves Sound Laboratories, Brooklyn, N. Y.

finish of the abrasive in which they are being lapped, the lapping time increases enormously, particularly with the optical flours. It is practically impossible to lap rough cut blanks (0.045″) thinner than 0.020″ using only optical flour for the operation. In a two-stage process, the crystals are lapped with a coarse abrasive to a point where that surface can be removed with the final abrasive. A practical working process is the three-stage procedure with planetary laps tabulated in Table 1 using #320 and #600 silicon carbide in the first two stages and finishing with #303 optical flour (aluminum oxide).

TABLE 1. PLANETARY LAP INFORMATION

Lap Stage	1	2	3
Abrasive	#320 SiC	#600 SiC	#303 Al_2O_3
Outer ring speed (r.p.m.)	120–150	65–85	35–60[a]
Wt. top plate incl. collar (lbs.)	25– 28	20–22	15–18
Amount lapped off in one minute	0.0085″	0.0017″	0.0004″
Time for all operations, including loading, lapping, etc.	4 min.	6 min.	12 min.[b]
Stopping point	Final thick. +.011″	Final thick. +.003″	−10 to −30 KC from final freq.[c]
Stopping point control	Stopwatch, counter or radio	Counter or radio	Radio

[a] Variable speed control desirable in final stage.
[b] Includes time for transpositions.
[c] Transpose at frequency corresponding to 0.0006″ from final frequency; for BT-cuts, 6 to 8 MC.

The large frequency spread after the final stage and the use of laps carrying different quantities of crystals led to the grouping of blanks by thickness and/or frequency between each lapping stage. At the end of the procedure, those crystals which did not fall into immediately usable channels were either placed in stock or regrouped and relapped to a higher frequency. When the frequency spread occured again the process was repeated and in this way many crystals never reached the finishing department after having been relapped so many times that their frequency was too high for existing channels.[4] Grouping crystals did not permit a flexibility in scheduling, required much additional help and equipment, built up huge stocks and did not reduce the frequency spread.

Intermediate grouping is unnecessary if laps carrying the same number of crystals are used for all stages in the process. The only grouping required is to separate the rough cut blanks in 0.005″ groups so that they have approximately the same starting thickness. An ordinary hand

[4] This was referred to as the "lapping merry-go-round" in the trade.

micrometer is sufficiently accurate for the purpose. After the first stage of rough lapping, the crystals are kept as a group and transferred to the second stage, and then to the final stage. If some crystals are broken during the process, they are removed but none are added. At the end of the second stage the crystals are then automatically more closely grouped for thickness than is possible by any convenient production scheme now in use.

Transpositions. One of the most difficult problems is to reduce the frequency spread to a point where the large majority of the crystals can be handled as one group in the finishing operations. The tolerable frequency spread will depend upon the frequency and finishing methods; 10 to 30 KC below final frequency has been the usual acceptable limit for 6 to 8 MC BT-cuts. This means that the crystals in a lap load must have the same nominal thickness to *ca.* $\pm 0.00002''$.

A detailed study of the problem was made with the planetary type of lap described below. This work involved lapping more than 10,000 crystals, 50,000 frequency measurements and numerous production data, so that it would be impossible to describe the numerous techniques tried. Using either three, four or five work-holders and either two or three stages of lapping, the frequency spread considerably exceeds the accepted limits. Spreads up to 200 KC were obtained on 8 MC BT-cuts but this was about the extreme, the average being 60 to 125 KC.

In order to determine the nature of the frequency spread the frequency of all crystals was measured after the second stage and the crystals from each work-holder were kept separate and measured at various times during the final stage. Numerous analyses of this type showed that the frequency spread in each work-holder was usually small, 10 to 20 KC, and the large spread was between the crystals in the different work-holders. This is illustrated in Fig. 2 where the smallest vertical line represents one crystal; the upper line in each stage gives the frequencies of all the crystals in the load and the smaller lines underneath show the frequencies of the crystals in the individual work-holders. Various patterns of frequency spreads were observed. Generally two work-holders had approximately the same frequency and the crystals in remaining work-holders were either higher or lower in frequency. No correlation between the pattern of frequency spread and lapping conditions could be made and it changed with time as the lap was in operation.

Since the spread in each work-holder is small, the spread for the run may be determined within close limits by measuring the frequency of one crystal from each work-holder. This can be done conveniently at the lap with a channel sorter of the type described below. If only a few work-

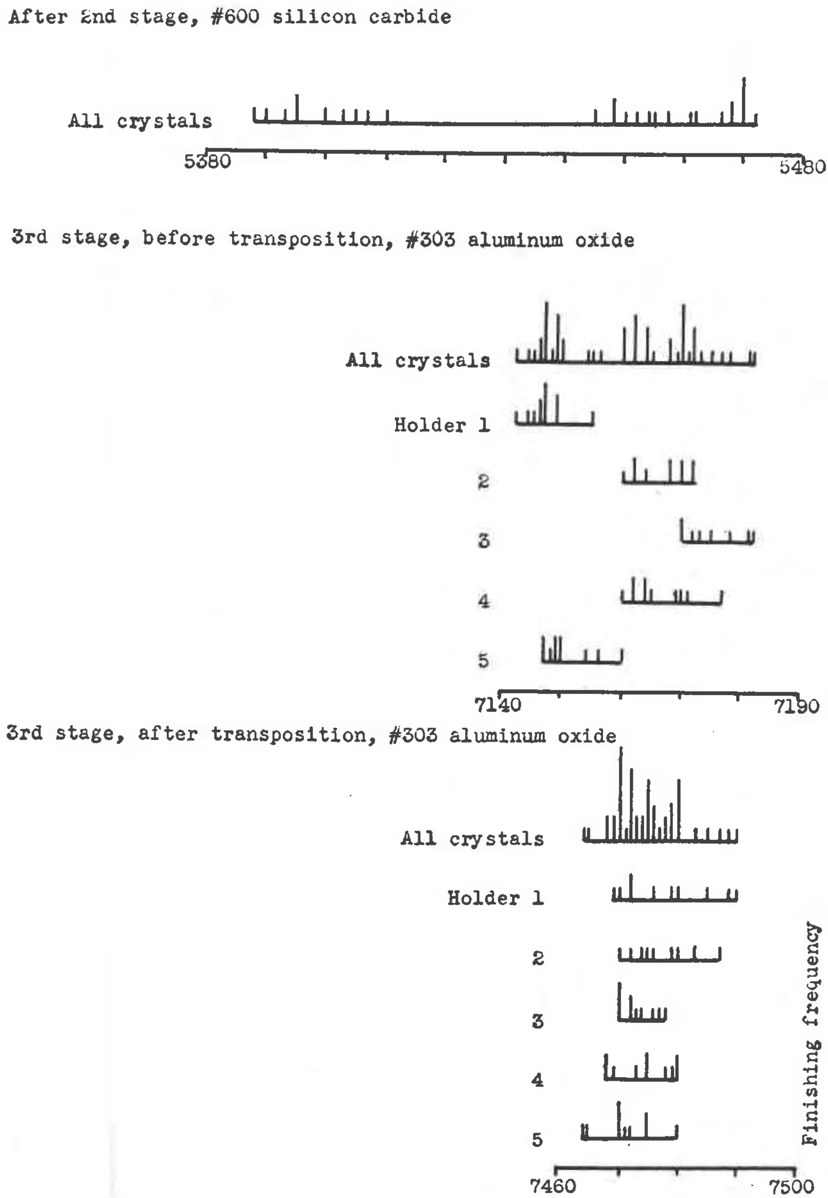


FIG. 2. Frequency spread within each work-holder is small but spread occurs between work-holders and is reduced by transposition of crystals. Smallest vertical line represents one crystal. $\frac{3}{8}''$ square BT-cut crystals.

holders are found to be at the desired end frequency, these crystals are removed from the lap and the remaining crystals of slightly lower frequency redistributed in the work-holders and the lap given a few additional turns to eliminate the spread. In this way frequency spreads were reduced from 53 to 18 KC, 70 to 30 KC, etc., at 8 MC.

It was determined empirically that if one random transposition was made in the final stage at a frequency corresponding to 0.0006″ from the final frequency that the spread was reduced to the required limits. The probable accuracy of this value is ±0.0002″ and should be redetermined for a new set of conditions. If the transposition is made too far from the final stopping point, the spread will again develop, and if made too close to the final frequency, the spread will not be sufficiently closed. It was found that several transpositions made during the procedure did not further reduce the spread but in transferring the crystals from one stage to the next a random transposition is automatically made. Figure 2 and Table 2 vividly show the effectiveness of the transposition technique in reducing the frequency spread.

Several types of transpositions were tried but a simple and useful one is to take all crystals from one work-holder keeping the upper surface face up, and stack them in the palm of the hand. This is repeated until all work-holders have been emptied and can be started from any work-holder and followed clockwise or counterclockwise. The entire group of crystals are then turned upside down so that the upper surface from the previous lapping will now be down. Starting with any work-holder, the top crystal from the stack is placed in the first work-holder, the second crystal in the second work-holder and so forth until the lap is filled. If some crystals are broken, the vacancies should be balanced on each side of the lap.

Transpositions are also useful in reducing the spread in the drill-press type of lap.

Abrasives. The most frequently used abrasives for machine lapping are #320 silicon carbide for the first stage, #600 silicon carbide for the second and #303 optical flour (aluminum oxide) or #800 silicon carbide for the final stage. #240 silicon carbide in water, laps almost two and a half times faster than #600.[5] Table 3 gives a summary of frequently used abrasive sizes. One-quart jars containing approximately 6 oz. of abrasive and filled with a lubricant such as Keystone Penetrating Oil #2[6] was used in the high speed planetary lapping method. The used abrasive is collected in

[5] Bond, W. L., Processing quartz: *Bell Lab. Record*, **22**, 359–361 (1944).

[6] Keystone Lubricating Co., Philadelphia, Pa. have supplied the following information regarding this oil: gravity Baumé 35.2; flash point 225°F., fire point 280°F., Seybolt viscosity 56 sec. at 100°F., 33 sec. at 210°F.

TABLE 2. RESULTS WITH HIGH SPEED PLANETARY LAPPING PROCESS
ONE TRANSPOSITION, RADIO RECEIVER CONTROL

Blank Size	Cut	1st Stage #320 Silicon Carbide		2nd Stage #600 Silicon Carbide			3rd Stage—#303 Aluminum Oxide						Acceptable Range
							Before Transposition			After Transposition			
		Starting Thickness	Lapped To	Lapped Off	Spread	Lapped To	Lapped Off	Spread	Frequency	Lapped Off	Spread	Frequency	
3/8" sq.	BT	.044–.045"	.025"	.0053"	42 KC	5095–5137 KC	.0028"	10 KC	5974–5984[a] KC	.0005"	13 KC	6179–6192[b] KC	6170–6190 KC
"	"	.045–.047	.0263	.0070	d	5222[c]	.0024	27	5958–5985[a]	.0005	17	6179–6190	6170–6190
"	"	.040–.045	.0255	.0073	50	5515–5565	.0023	27	6348–6375	.0006	10	6580–6590	6580–6600
"	"	.042–.045	.024	.0064	d	5730[c]	.0026	21	6700–6721[a]	.0006	24	6978–6992	6980–7000
"	"	.039–.045	.0221	.0051	56	5878–5934	.0025	65	6905–6970	.0007	27	7238–7265	7240–7270
"	"	.040–.046	.0235	.0070	28	6102–6130	.0024	66	7100–7166	.0004	10	7330–7340	7330–7360
"	"	.046–.051	.0225	.0063	46	6214–6260	.0023	37	7225–7262	.0006	15	7595–7610	7580–7610
"	"	.045–.050	.0215	.0059	36	6464–6500	.0025	56	7654–7710	.0005	31	7959–7990	7958–7998
1/2" sq.	"	.045	.025	.0075	d	.0175"	.0024	d	d	.0005	23	6882–6905	6885–6905
"	"	.046	.026	.0085	d	.0175	.0027	d	d	.0006	16	7059–7075	7050–7080
"	"	.047	.024	.0066	d	.0174	.0026	d	d	.0006	20	7060–7080	7050–7080
.5×.6"	AT	d	d	d	22	3335–3357 KC	.0033	39	4030–4069	.0006	16	4189–4205[b]	4185–4205
"	"	d	d	d	29	4058–4087	.0025	8	4808–4812	.0006	28	5090–5118[b]	5080–5120
.7" sq.	"	d	d	d	7	2892–2899	.0037	15	3438–3453	.0005	7	3539–3546[b]	3540–3550

[a] Measurements on one crystal from each work-holder.
[b] #303½ aluminum oxide.
[c] Only one crystal measured.
[d] No data recorded.

cans under the lap, filtered and the oil reused for rough lapping. The crystals must be cleaned with a solvent such as carbon tetrachloride to remove the oil. Three parts by volume of a water-soluble oil[7] to one part of Reprol[8] is reported to be successful and allows washing the crystals with warm soapy water. Good practice is to mix the abrasives by tumbling (see section on milling technique) and dispense it from an ordinary oil can. The crystals should be thoroughly washed between each lap stage to prevent contamination from the previous abrasive.

TABLE 3. ABRASIVE GRAIN SIZES[a]

Grit Size Designation	Average Grain Size in Microns		
	American Optical Co.	Carborundum Co.	Norton Co.
240			63
280		38	54
320		31.5	40
400		22.5	30
M302	22		
500		20	18
M302½	18		
600		17.5	12
M303	15		
700		14.5	
800		12.5	
M303½	11		
900		9.5	
M304	8		
M305	5		
F			44
2F			33
3F			23

[a] Data supplied by Companies noted. For smaller sizes see National Bureau of Standards "Simplified Practice Recommendation R118–40, Abrasive Grain Sizes," Aug. 15, 1940. See also *Optical Shop Eng. Bull.* No. 5, March 12, 1945, Off. of Chief of Ordnance, Fire Control Sub-Office, Frankford Arsenal, Philadelphia, Pa.

Thickness to be Lapped Off. In the final stage of lapping with #303 optical four, 0.003″ is lapped off the crystals to remove the #600 silicon carbide surface. In the intermediate stage 0.008″ is lapped off to remove the #320 surface. In the first stage the crystals are lapped from the original

[7] Sun Oil Co., *Sun Emulsifying;* Houghton Oil Co., *Permasol Oil.*

[8] Atlantic Refining Co., *Reprol.*

thickness to the final thickness plus 0.011″. Thus a load of crystals which is to be lapped to 6700 KC (approx. 0.015″) would be lapped to 0.026″ in #320, to 0.018″ in #600 and to final lap frequency in #303.

The amount to be lapped off the crystals in each stage was determined from the maximum grain size of the various abrasives. It was assumed that the maximum size of grain will produce a scratch of the same depth in the crystal. Since both sides are lapped, this value is multiplied by two and a safety factor of 100% added to each side so that the thicknesses were calculated on the basis of at least four times the maximum grain size of abrasive used. This procedure has been successful and assures that all lapped crystals have the same degree of optical flour finish regardless of frequency. Hence the crystals are properly prepared for the final etching-to-frequency operation. This is important for the lap finish markedly effects the etching time and where the finish is not controlled the etching rate is not predictable within the close limits usually required.

Quality of Lapped Crystals. Using the process described above, the crystals have good activity after the final lap stage so that hand edging at the finishing positions may be eliminated and the etching-to-frequency process is simplified. It is not uncommon to lap crystals to an activity of 0.4 to 0.7 where 0.3 ma. is passing in final test. Transpositions increase the quality of the crystals by producing crystals with a similar contour on both sides and decreasing wedging. Edge and corner chips and scratches (usually caused by contaminated abrasives) are the principal causes for rejection in the lapping process. The contour of the lapped crystals may be observed with a pair of high precision optical flats at least a few inches in diameter and a monochromatic light source such as a G. E. Sodium Lab-Arc. Quartz flats[9] are often used to prevent scratching the flats. The crystal is placed between the flats and the interference pattern observed at almost grazing incidence.

Controlling Stopping Point of Lap[10]

In all the lapping stages, it is important to be able to stop the lap at any desired crystal frequency or thickness. The need for precision control, particularly in the final stage, will be evident from the following discussion. If it is desired to lap a load of BT-cut crystals to 8000 KC, overlapping them by 0.0010″ will produce crystals approximately 700 KC higher than the desired frequency. In the final stage the stopping point tolerance is exceedingly small. 6 to 8 MC BT-cut crystals must be ma-

[9] Acme Industrial Co., Chicago, Illinois.

[10] This section was prepared in collaboration with Mr. John D. Davies, N.A.P., Research Laboratory, who also did much of the development work.

chine lapped to within 10 to 30 KC below the final finishing frequency which corresponds to a few one-hundred thousandths of an inch in thickness.

The rate of lapping under a particular set of conditions may be determined by the use of a stop watch or an electric counter attached to the

FIG. 3. Top view of planetary lap with upper lap plate removed showing crystals and work-holders.

lap. Many carefully run tests have shown that these methods do not have the required precision in the final stage and that even experienced operators generally have to stop the lap at least a few times to check the thickness or frequency of a few crystals from the load in order to follow the progress of the operation. The lapping speed is dependent upon the grit size, composition and rate of feeding abrasive, crystal size and finish, weight of the top plate and speed of the machine.

A far more precise and simple method employing a sensitive calibrated radio receiver has been developed for determining the stopping point in all stages of lapping. With this technique the increase in frequency and the frequency spread of the crystals in the lap may be followed while the lap is in operation. The method is capable of high precision and eliminates guess work and difficulties in manual routine. It has been used for several years in a number of crystal plants but the writer is unaware of its origin.[11] The method as described here has been so refined and simplified that it may be placed in the hands of comparatively unskilled people with no background in radio who may be trained to use it successfully within a few hours.

In lapping with the planetary- or drill press-type of lap the crystals are carried by work-holders between the stationary upper and lower lap plates. Except for the thin abrasive and oil mixture, the lap plates rest directly on the crystals. During lapping the crystals are shock excited and emit a signal whose frequency is directly dependent upon the thickness-frequency constant of the type of cut (*AT* and *BT*, etc.) being lapped. This is an application of the familiar piezoelectric phenomenon of voltage produced by mechanical stress. The random voltages produced by the lapping action are sharply and strongly peaked at the thickness-frequency of the crystal (the crystal may be considered as a very high-Q tuned circuit.)[12]

A sensitive communications-type receiver is used to obtain the required delicacy of adjustments. In this work a Skyrider 32 (Fig. 4) was used.[13] The receiver-to-lap connections are shown in Fig. 5. The correct coupling is important because the average signal strength is of the order of a few microvolts and hence there is the problem of signal to noise ratio. Furthermore, since a sensitive receiver is used, the upper lap plate becomes an effective antenna and in the average industrial plant there is considerable electrical interference. One antenna post is connected to the upper lap plate and the other to the lower lap plate by means of the abrasive-guard shield which is more convenient than a direct connection. A common external ground is used for receiver and lap. Shielded cable is used for these connections to reduce the possibility of their acting as an antenna.

The upper and lower lap plates are separated by the crystals being lapped. Bakelite tubing is slipped over the two pins on the collar of the upper lap plate to prevent shorting to the lower lap plate. Bakelite workholders are used also for the purpose of preventing shorting. Zinc work-holders have been used when they are much thinner than the crystals for otherwise they short the two lap plates and the noise interferes with the signal coming from the crystals being lapped.

[11] About a year after the experimental work was completed, a patent was found which described essentially the same method: Bailey, Richard S., Piezoelectric apparatus and method: *U. S. Patent Office* No. 2,340,843, Feb. 1, 1944.

[12] Van Dyke, K. S., The piezoelectric resonator and its equivalent network: *Proc. Inst. Radio Eng.* **16,** 742–764 (1928).

[13] Manufactured by The Hallicrafters Co., Chicago, Ill.

The receiver is calibrated at the frequency at which the lap is to be stopped by means of a calibrated oscillator loosely coupled to the former. A crystal oscillator with a standard crystal may be used but has the disadvantage of requiring a crystal for each desired frequency and also lacks flexibility. A simple and convenient method is to use a direct-reading calibrated variable oscillator, often called a *channel sorter* in the crystal industry (see Figs. 4 and 8). These have been built for the 1 to 5 and 5 to 9 MC ranges which covers the ordinary lapping frequencies. The variable oscillator has a large tuning dial marked to 5 or 10 KC

FIG. 4. Planetary lap equipment. (A) Channel sorter, (B) button electrode and anvil, (C) radio receiver, (D) foot switch for lap, (E) variable speed control for lap, (F) abrasive containers, (G) abrasive dispensers.

and is calibrated with a standard crystal whose frequency is within a couple of hundred KC or less of the frequency at which the channel sorter is to be used. The standard crystal is plugged into the untuned Pierce oscillator circuit, the dial set to the frequency of the standard crystal and the variable oscillator calibration adjustment tuned to 0-beat. The standard crystal is removed, the dial set to the desired frequency and the signal is picked up by the receiver. The tuning dial of the receiver is set to the dial mark nearest the desired frequency (for a convenient reference point) and the receiver calibrated at this point by adjusting the bandspread dial to maximum deflection of the carrier level (S) meter. The receiver dial setting is then noted, as this is to be the final stopping point.

The electrical connections to the lap are put in place and the channel sorter dial turned far from the desired frequency so as not to interfere with the signal from the lap. With the R. F. gain turned up, the radio operator locates the starting frequency of the crystals when the lap operator turns the outer gear by hand at the beginning of the lapping operation. The radio operator starts the lap by means of a foot switch and follows the progress of the lap by turning the main tuning dial back and forth across the signal.

The best adjustments of receiver controls for lapping AT- and BT-crystals in the 4 to

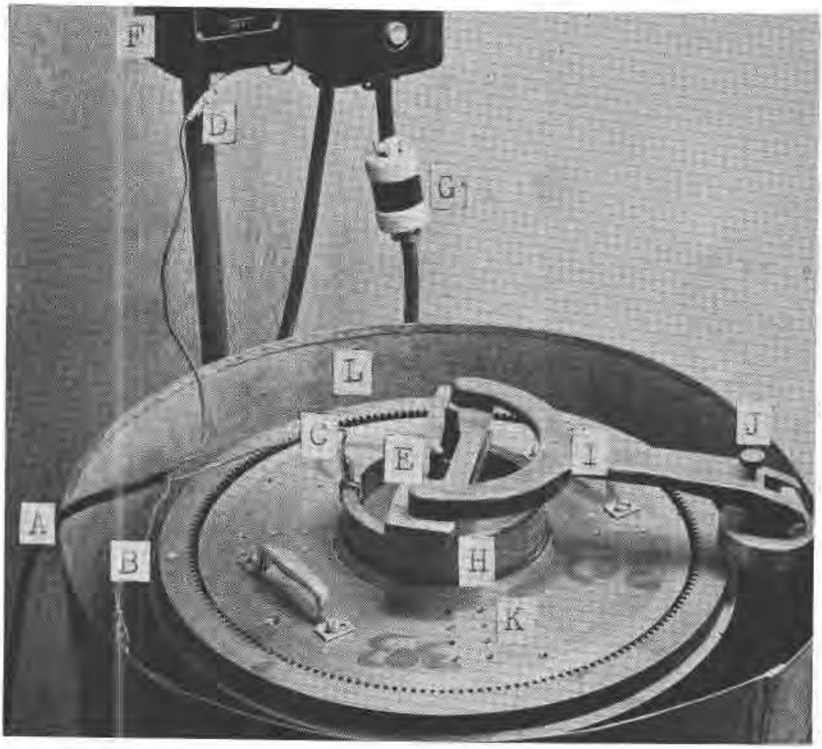


FIG. 5. Planetary lap. (A) Shielded cable, (B) antenna connection for lower lap plate, (C) antenna connection for upper lap plate, (D) ground connection, (E) bakelite bushing over collar pins, (F) main switch, (G) connection for foot switch, (H) special collar, (I) arm for holding upper lap plate in position, (J) screw stop for controlling vertical position of arm, (K) holes for feeding abrasive, (L) abrasive splash guard.

9 MC region were found to be as follows: *Selectivity:* sharp IF; *BFO:* off; *Tone:* open; do not eliminate any of the high or low frequencies for signal contains both; *ANL* (automatic noise limiter): off, suppresses peaks when used; *Antenna trimmer:* adjust to final frequency or adjust while following signals across dial; *Carrier Level (S) Meter:* used only in adjusting receiver to standard signal; *AF Gain:* keep at full intensity; *RF Gain:* high when first locating signal then reduce to lowest volume for hearing; this retains sharp signal and keeps interference at a minimum.

Head-phones, a loud speaker, or a recorder may be used to detect the signal but the first was found to be the most practical. In fact the stopping point may be automatically controlled.

The crystal signal from the lap may be recorded by connecting the 5000 ohm output terminals of the receiver through a rectifier (such as a 6H6 tube) to an Esterline-Angus 5 ma. DC graphic meter. A recording made in this manner is shown in the upper part of Fig. 9 for ½″ square BT-cut crystals in the final stage of planetary lapping with #303 optical flour. The receiver dial is set to the frequency at which the recording is to be made (B in Fig. 9). As the crystals are lapped thinner and their frequency approaches the dial frequency, the signal gradually increases in intensity, passes through a maximum and then falls off as the frequencies of the crystals pass the dial frequency. If the lap is stopped immediately and the crystals cleaned and channeled, their frequency distribution will be similar to the recorded curve as shown in the lower part of Fig. 9. The broadness of the left-side of the curve is caused by three crystals 25 to 30 KC lower in frequency than the other crystals, while the hump in the right-side of the curve is caused by all the crystals n one work-holder having a higher frequency than those in the remaining work-holders.

An additional advantage of the channel sorter used is that an anvil and button electrode in the Pierce oscillator provides a method of measuring frequencies directly to 3 or 4 KC, so that it may also be used for approximate frequency measurements after lapping. This further consolidates all operations into one position.

The radio receiver method may be applied to the lapping of other nonmetallic substances. For example, glass blocks could be lapped and their thickness followed by tuning in to a few quartz crystals of the same thickness placed in the same lap.

The Planetary Lap[14]

This is the most successful lap that has been developed specifically for quartz crystals. When properly used it is capable of high precision and enormous production. By making one transposition in the final stage the frequency spread is less than 15 KC for 6 MC BT-cut crystals. This corresponds to 0.00004″ difference in thickness between the thickest and thinnest crystal in the load. Daily production from five or six planetary laps (one for #320 abrasive, one or two for #600 and three for #303 final stage) operating 20 hours per day is well over 6000 lapped blanks passing all specifications with a rejection rate for all causes less than 10%.

The name planetary lap has been adopted because the crystals undergo a planetary type of motion during lapping in this type of machine. It is also called the Hunt-Hoffman lap, after G. C. Hunt and P. R. Hoffman of Carlisle, Pa., who developed it.[15]

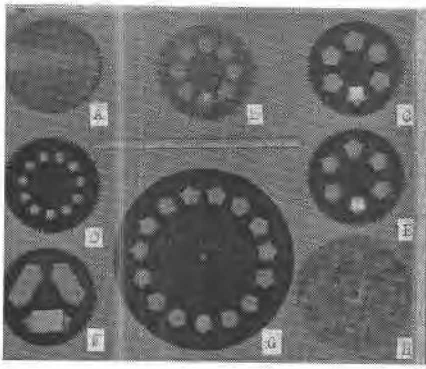
The crystals contained in either bakelite or zinc work-holders ride between the lap plates which are stationary. The periphery of the work-

[14] Manufactured by P. R. Hoffman Co., Carlisle, Pa., and New Jersey Wire Stitching Co., Camden, N. J.

[15] Hunt, Grover C., Grinding machine: *U. S. Patent Office* No. 2,314,787, March 23, 1943. Hoffman, P. R., Grinding machine: *U. S. Patent Office* No. 2,308,512, June 19, 1943.

holders is toothed so that they mesh with the outer and inner ring gears between the lap plates. The ring gears, driven by a $\frac{3}{4}$ h.p. 3-phase motor in the under part of the housing, drive the work-holders and cause them to rotate and produce a broad sweeping lap motion. In addition, each crystal is free to rotate within the pentagonal hole of the work-holder and this produces the spinning motion.

Work-Holders. The selection of proper work-holders is important in planetary lapping. Large frequency spreads, poor contour, low activity, chipping, etc., may result from the use of poor work-holders. Two types of material are widely used: linen-base bakelite and zinc. Although the latter has greater strength, it is a conductor and can be used with the



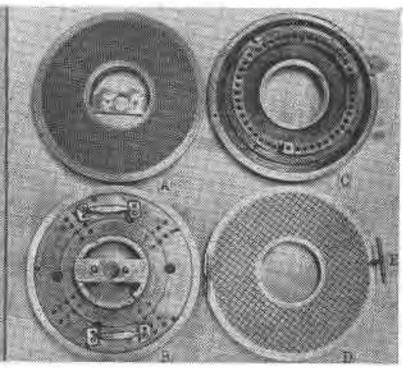


FIG. 6. Work-holders for lapping crystals. (A) Planetary lap, blank, (B) planetary lap, $\frac{1}{2}''$ crystal, straight side, (C) planetary lap, $\frac{3}{4}''$ crystal, straight side, (D) planetary lap, $\frac{3}{8}''$ crystal, straight side, (E) planetary lap, $\frac{3}{4}''$ crystal, curved side, (F) planetary lap, for lapping ultrasonic plates, (G) drill press lap, $\frac{3}{4}''$ crystal, curved side, (H) calibrating lap $\frac{1}{2}''$ crystal, slightly curved side.

FIG. 7. Planetary lap plates. (A) Lap surface of upper plate, (B) top view of upper plate, (C) bottom view of lower plate, (D) lap surface of lower plate, (E) removable handles for changing gear position of lower plate.

radio method only when the crystals are considerably thicker than the work-holders for otherwise the two plates will be shorted. Bakelite is preferred also because it produces less chipping, less wear on the gears and less damage in a crack-up. Several types of work-holders are shown in Fig. 6.

One of the principal difficulties in using bakelite work-holders is that they tend to become warped. Paper-base, double-and higher-ply, and single-ply linen base bakelite are used and they are listed in increasing order of their tendency to warp. Paper-base bakelite is so weak it can only be used with very light weight top plates such as in the small Bagwell planetary lap[16] or the Calibrating Machine Lap. Warped holders can sometimes be used by

[16] A small planetary lap employing small work-holders and a light weight top plate developed by J. N. Bagwell Jr., Commercial Crystal Co., Lancaster, Pa.

wetting them thoroughly with the abrasive mixture and placing the crystals in the middle of the hole rather than against the sides when loading the lap. When the top plate is put in place it will flatten the work-holder so that the crystals may not slip under the hole and cause a crack-up.

All five work-holders for the planetary lap should be grouped for thickness within 0.001″. Zinc work-holders should be lapped-in without crystals until most of the high spots disappear. Bakelite work-holders should not be lapped-in because it weakens their teeth. The work-holders should be at least 0.002″ thinner than the final lapped thickness of the crystal.

Pentagonal holes with sides slightly larger than the longest edge of the crystal allow the crystal to rotate during lapping and produce crystals with a proper contour for high activity. The corners may be cut back to reduce chipping the corners of the crystals. Curved-side pentagonal holes are also often used but the relative merits have not been rigorously determined.[17] Square holes in which the crystal fits snugly are undesirable because the crystals become wedge-shaped. The holes in which the crystals are contained must be so positioned that the crystals slightly over-ride the inner and outer periphery of the lap plate. This prevents excessive lapping of the edges and permits control of surface contour by varying the amount of over-ride.

Thurston has described a novel work-holder which may eliminate edge chipping.[18] The crystals fit snugly in a square hole cut in a small circular disc. The discs fit into a work-holder of the same thickness which has six circular holes just large enough to accommodate the discs and allow them to rotate during lapping. This paper should also be consulted for a description of a newly developed lapping machine for quartz crystals.

Lap Plates. Both upper and lower lap plates (Fig. 7) are normalized meehanite, 15 5/8″ in diameter with a $5\frac{1}{2}$″ diameter center hole. The plates are used as a pair and should lie one on top of the other at all times to prevent warping and contamination. A pair of plates is used for each abrasive. Four series of extra radial holes countersunk at the top, are drilled in the upper lap plate to allow a more even feeding of the abrasive. Both plates have square serrations on the lapping surfaces which are $\frac{1}{4}$″ apart on the upper plate and $\frac{1}{2}$″ apart on the lower plate. No published study of the effect of various types of serrations on lapping quartz has been made. Cast iron lap plates with serrations lap crystals almost twice as fast as smooth plates and as fast as smooth hard tool steel plates.[19] Glass lap plates are faster than smooth cast iron plates but the crystals and work-holders tend to stick to the lower surface of the upper plate when removing it from the machine. In addition to increasing the lapping speed, the serrations allow a more even distribution of abrasive so that the entire surface of the crystals receives an even lapping action and the edges are not lapped thinner than the center.

[17] Hunt, Grover C., Work-holder for grinding machines: *U. S. Patent Office* No. 2,309,080, Jan. 19, 1943.

[18] Thurston, G. M., Flatness and parallelism in quartz plates: *Bell Lab. Record,* **22,** 435–439 (1944).

[19] Bond, W. L., *op. cit.*

Both plates have inner ($\frac{15}{32}''$) and outer rings ($\frac{11}{16}''$ wide) which should be at least 0.005″ and not more than approximately 0.010″ below the lapping surface of the plate. The rings permit the crystals to slightly overlap the inner and outer edges of the lapping plate surface so that the latter will remain flat out to the edges. As the plate wears, the rings must be pounded back into position with a soft hammer.

An upper lap plate weighing approximately 25 to 28 lbs. is used for coarse lapping with #320 abrasive. Progressively lighter weight plates should be used for the intermediate and final stages of lapping to permit the use of thinner bakelite work-holders and reduce excessive breakage of crystals and damage to the plates in crack-ups. Upper lap plates weighing 20 to 22 lbs. have been used for the intermediate lapping stage with #600 abrasive. In the final stage of lapping with #303 optical flour, a greatly reduced plate weighing only 15 to 18 lbs. is required if thin linen-base bakelite work-holders are to be used. These values include the weight of a 3 lb. special collar which has been added (see description below). The exact weight does not appear to be critical.

The flatness of the plates can be quickly determined by removing the plates from the lap and lapping by hand one against the other with the same abrasive as is used with these plates for a few minutes. Low areas then become apparent when the plates are separated and the lap surfaces inspected. A flat piece of accurately ground stock laid across the diameter of the plate on four small pieces of paper placed on the inner and outer periphery of the lap surface on both sides of the center hole may be used to measure the unevenness of the plate. If the plate is perfectly flat, the pieces of paper cannot be pulled from under the stock when the latter is held firmly in place. If one or more can be pulled out, the departure from flatness at those points may be determined by using two or more pieces of paper until they cannot be pulled out and then measuring the total thickness with a micrometer.

Before being placed in use, the lap plates are ground flat on a large surface grinder and then lapped-in with the same abrasive as will be used on those plates. For this purpose three gears the same size as the work-holders but about $\frac{3}{4}''$ thick with the center milled out leaving a $\frac{1}{2}''$ ring gear are used. The gears are put in place and the lap run until the plates are flat.

If crystals or work-holders break during lapping, the plates and gears must be thoroughly cleaned with a hard brush and the serrations with an awl. Cloths and towels should not be used on the plates for lint and stringers tend to collect in the serrations.

A bothersome feature of the planetary lap is that the gears which drive the work-holders, particularly the inner gear, become slotted by the work-holders. The position of the lap plate with respect to the gear must therefore be changed after several runs to prevent excessive slotting; the change is required more frequently with coarse than with fine abrasives. A pair of tapped holes in the outer ring of the lower lap plate which will admit a tool to lift the plate from the carriage will expedite the change. The plate is then lifted and turned to the next position, the latter being fixed by a step-like arrangement on the under side of the plate (Fig. 7). In this way the wear on the gear is equalized, and after it becomes worn the gear is turned upside down and used in the same way for only one side of the teeth become worn.

A preferred method of holding the top plate in position is shown in Fig. 5; it permits the ppper plate to float freely on the lower plate. A collar around the inner hole, with a cross-piece with slot and two vertical pins has been added to the lap plate; this adds approximately 3 lbs. to the weight of the plate. A slotted arm fits across the pins and is prevented from resting directly on the upper lap plate by an adjustable stop.

Operation of Lap. It must be emphasized that constant attention to minute details and a set routine such as checking ring depth, setting plates to new gear position, careful washing and inspection of crystals between stages, etc., are required to obtain good results. The work-holders should be checked and evenly spaced in the lap. The crystals are placed against the side of the pentagon, or in the middle if the work-holder is warped. Abrasive is squirted between the work-holders, the top plate and center arm put in position and more abrasive poured through the feed holes in the top plate. The outer gear is rotated counterclockwise by hand several times with the operator listening for any sign of a crack-up. The radio operator runs the lap by means of a foot switch and watches

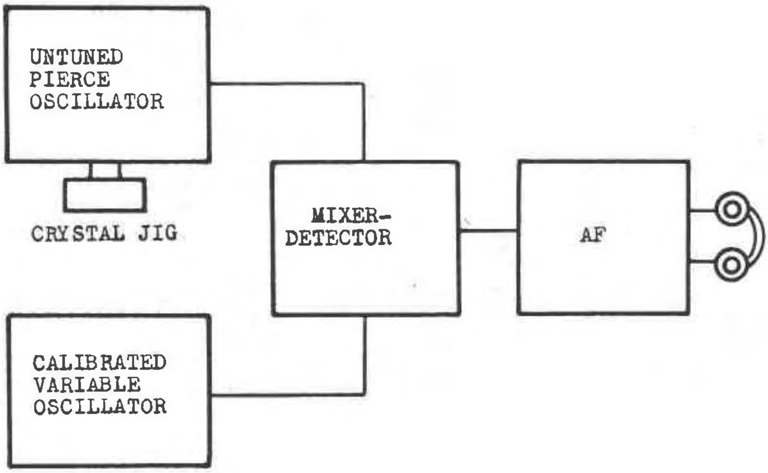


FIG. 8. Simplified block diagram of channel sorter.

the progress of the lap by turning the main tuning dial of the receiver back and forth across the signal while the lap operator feeds abrasive at regular intervals. At the end of the run, the spread may be determined by measuring one crystal from each work-holder with the channel sorter.

MISCELLANEOUS LAPPING EQUIPMENT

There has been no published extensive study of the lapping procedures in current use in the crystal industry. The following descriptions are based upon observations of several dozen plants mainly in the East. Space and time limitations allow a brief description of only a few of these.

Optical-Type Lap. The crystals are cemented to a flat plate and one side is lapped (Fig. 10). The crystals are then removed, the lapped side cemented to a plate and the second side is lapped. This type of lap has certain disadvantages for quartz work and is used by only a few plants in the crystal industry. It may prove to be useful in the preparation of very thin plates, which have been previously lapped by the usual procedures to approximately 0.010″.

The "machine employs a $15\frac{1}{2}''$ diameter cast iron lap rotating at a speed of 17.2 r.p.m. against which is driven at a speed approximately 99 r.p.m. the crystal mounting plate. For the average crystal work this

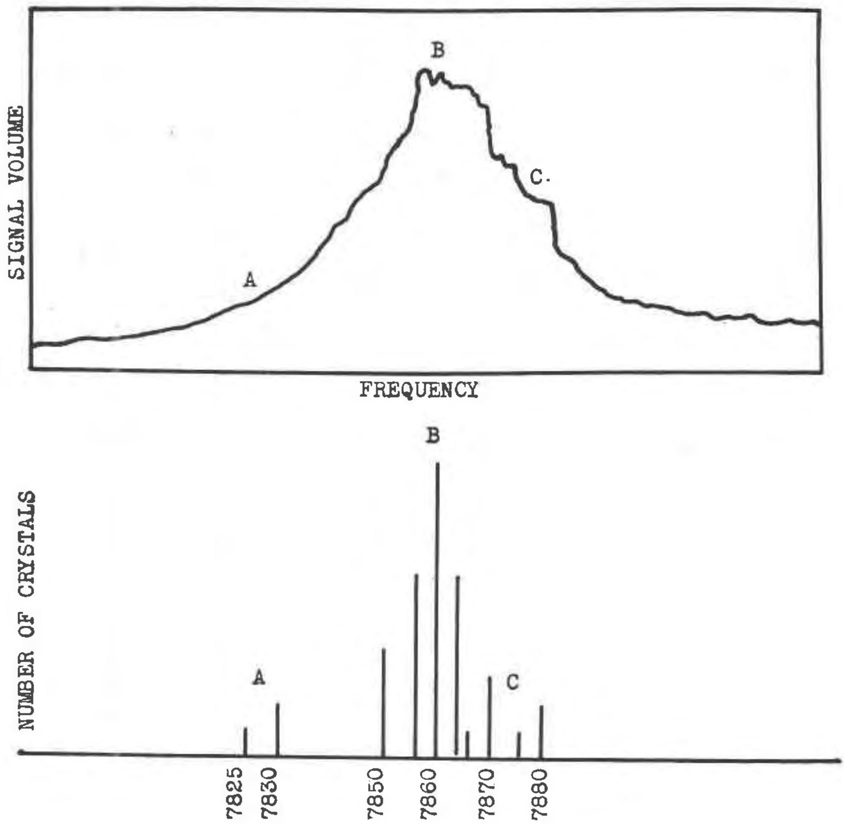
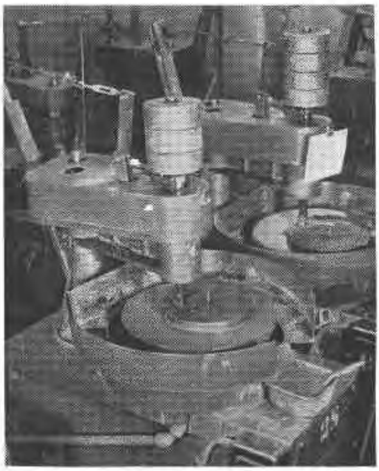


FIG. 9. Graphic recording (above) of crystal signals from final stage of planetary lapping with #303 optical flour. Receiver dial set at frequency B. Lap stopped immediately after recording and individual crystals measured with frequencies shown below. Smallest vertical line represents one crystal.

mounting plate is $9\frac{1}{2}''$ diameter and approximately $1\frac{1}{8}''$ thick and is also made of cast iron and is lapped flat on both sides and parallel to approximately .000010″ over the entire usable surface.

"The crystals are mounted on this plate with paraffin, taking care on the last side lapping especially to have an absolute minimum quantity of paraffin on the surface and carefully controlled heating. In this way we can control the mounting error so that only a very small percentage of the crystals on the plate will be out of parallel by more than .000020″ from corner to corner. The mounting plate is driven by means of a crank pin engaging a hardened steel center insert in the mounting plate. The throw of the crank as well as its center of rotation in relation to the lap are varied to maintain a flat working surface on the lap as well as to control the flatness across the mounting plate and the contour of each individual crystal. The work on the mounting plate is measured by means of



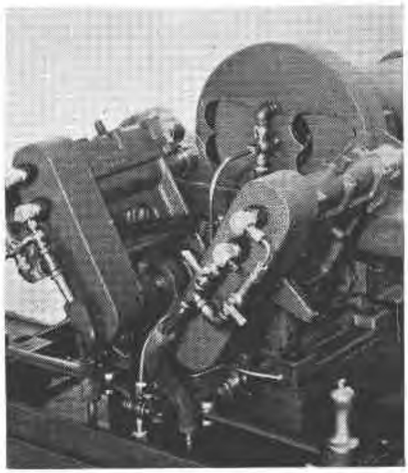


FIG. 10. Optical-type lap. (Courtesy of Bliley Electric Co., Erie, Pa.)
FIG. 11. The Q-lap. Crystal is held by vacuum chuck on rocker arm which oscillates across face of diamond grinding wheel.

a specially designed ring gauge employing a Pratt-Whitney Electrolimit Comparator Head."[20]

Q-Lap.[21,22] This unique lap employs two rocker arms, each holding two crystals, which slowly oscillate over the face of a diamond abrasive wheel (Fig. 11). One side of the crystal is held by a suction device on the face of the rocker arm while the other side is lapped. The angular position of the crystal is slightly displaced with each successive cycle of the rocker arm and the rotation of the crystal holder at 16 r.p.m. produces a uniform grinding of the crystal surface. A stop nut which can be set in steps of 0.00025″ prevents grinding beyond the set thickness, after which

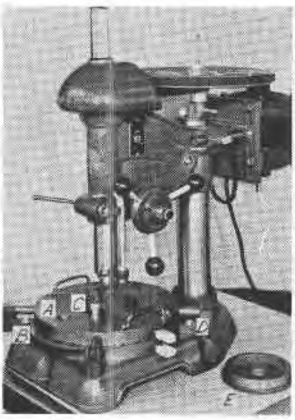
[20] Personal Communication, C. C. Collman, Bliley Electric Co., Erie, Pa., Feb. 12, 1945.

[21] Schaffers, T. W. M., The Q lap: *Communications*, **24,** 40–42, 80 (1944).

[22] Manufactured by Hammond Machinery Builders, Inc., Kalamazoo, Mich.

the handle is retracted and the rocker arm locked in the idling position. Best results were obtained with a resinoid bonded diamond wheel, $8\frac{1}{2}''$ diameter, 100-grit size, #50 concentration, running at 1750 r.p.m. and a mixture of 20–30% turpentine and 80–70% kerosene by volume for coolant.

The Q-lap has been employed by only one crystal manufacturer. Its principal uses have been in grinding thick wedge-shaped blanks to parallelism with a reference surface, reducing extra thick cuts to a nominal thickness for lapping and in correcting off-angle blanks. In making test-



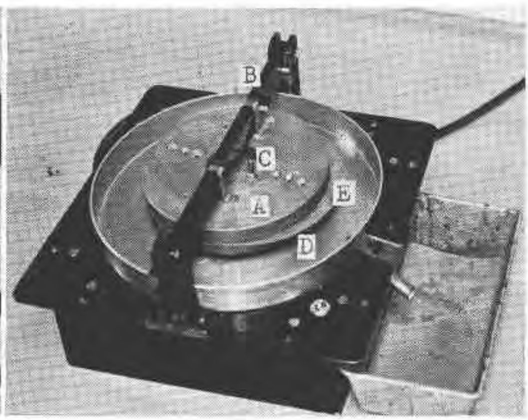


FIG. 12. Drill press lap. The most widely used type of lap in the crystal industry. (A) Lap plates, (B) work-holder, (C) offset arm, (D) rods for holding upper lap plate, (E) disc for lapping-in plates. (Courtesy of Atlas Sales Co., Chicago, Ill.)

FIG. 13. Calibrating machine lap. (A) Lap plates, (B) arm for holding upper lap plate, (C) offset arm, (D) abrasive guard shield.

cuts in wafering, the first wafer is usually wedge-shaped with the outer surface off angle and the inner surface on angle. The correct surface is attached to the crystal holder and the off-angle surface lapped to parallelism with the correct surface. Where both surfaces are off-angle, an adjustable head whose surface may be varied with respect to that of the diamond wheel is slipped on the rocker arm for making the correction indicated by x-ray measurement.

Drill Press Lap.[23] A conversion of a standard bench type drill press (Fig. 12) has become the most widely used lap (about 2000) in the crystal industry. The adaptation was made several years ago by Western Electric Co.

[23] Manufactured by Atlas Sales Company, Chicago, Ill., and William A. Hardy Co., Inc., Fitchburg, Mass.

The standard movable table and drill chuck are eliminated and the steel column holding the motor mount has been shortened. The lap plates are stationary and a single work-holder carrying from 12 to 20 crystals (depending on the size of the crystals) is driven between the plates by an off-set arm from the main spindle. The length of the offset arm is adjusted so that the crystals in the work-holder slightly overlap alternately the inner and outer edges of the lap plates. The bushing holding the work-holder (not visible in Fig. 12) fits loosely so that the latter rotates slowly about its own axis during lapping. The motion of the crystals is less complicated than in planetary lapping. Speeds varying from 30 to 100 r.p.m. have been used but 55 r.p.m. has been the average. The lap plates are serrated, $10\frac{3}{4}''$ diameter with $4\frac{3}{4}''$ central hole. The upper lap plate, weighing approximately 16 lbs., is held in place by four rods in U-shaped holders which alllow it a slight amount or no lateral play. Abrasive is fed through holes in the upper plate. An adapter disc fitting into the central hole of the lap plate is used to lap in the plates. The top and bottom plates may be interchanged a few times when lapping-in to obtain flatter surfaces.

Several complications have been introduced in attempting to improve the quality and speed of the drill press lap but they have not been generally adapted. In one of these, the upper and lower plates were made to revolve counter to each other at different speeds. This caused more to be lapped off one side of the crystal than the other and often saw marks remained on one side of the crystal. The radio receiver method of controlling the stopping point has been applied successfully to this lap when an insulated work-holder such as linen-base bakelite was employed and the four rods holding the upper lap plate are insulated so that the two lap plates are not shorted. Transpositions decrease the frequency spread and improved quality.

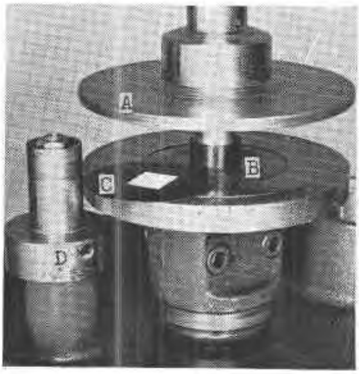
Several manufacturers are of the opinion that the drill press lap is not capable of the enormous production and high quality crystals obtained from the planetary lap.

Calibrating Machine Lap.[24] The principal of this lap is the same as that employed in the drill press lap described above but it is smaller (Fig. 13). The lap plates are serrated, $6\frac{1}{2}''$ diameter with $2''$ central hole. One work-holder is driven at 95 r.p.m. by an offset arm attached to the motor drive. By changing the length of the arm, the overlap of the crystals on the inner and outer edges of the lap plates may be varied. The work-holder carries 6 to 10 crystals depending on their size. Since the upper lap plate weighs only $3\frac{1}{2}$ to $5\frac{1}{2}$ lbs., thinner work-holders may be used with this type of lap than with the planetary or drill press so that it may be useful

[24] Manufactured by Empire Electronics Corp., New York City.

for thin crystals. A disc fitting into the central hole of the upper lap plate is attached to the eccentric arm for lapping the plates together when the work-holder is removed.

Seco Precision Crystal Finisher Type F.T.[25] This small slow speed lap was developed for finishing single crystals (Fig. 14). The lap plates have a smooth disc-like plateau which is slightly narrower than the width of the crystal and is slightly above and extends around the entire lap plate.



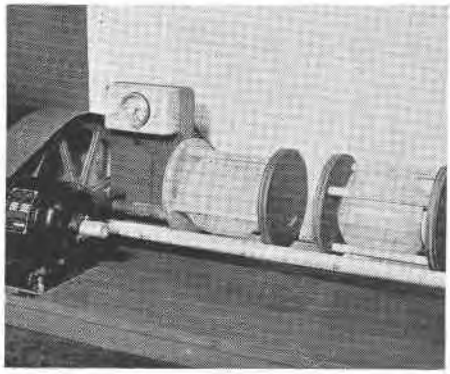


FIG. 14. Seco precision crystal finisher type, F.T. lap for single crystals. (A) Upper lap plate raised from lapping position, (B) lower lap plate, (C) work-holder with crystal, (D) post.

FIG. 15. Milling equipment for tumbling several jars.

The crystal is contained in a circular work-holder with a square hole just large enough to hold the crystal. The lap plates and post rotate clockwise and the work-holder counterclockwise. A timer is generally used to control the lapping time but the lap may be adapted for use with the radio receiver method. It is used after the standard lapping procedure (with planetary or drill press laps) to bring crystals to the same starting frequency for etching and to eliminate hand finishing at the finishing positions. It is also useful when only a few crystals of special frequencies are required.

MILLING TECHNIQUE

An ingenious approach to several of the problems in lapping, edging and finishing was developed by Galvin Manufacturing Corp. by an adaptation of the familiar ball mill technique.[26] A large number of blanks (as

[25] Manufactured by Sipp-Eastwood Corp., Optical Division, Paterson, N. J.

[26] Fruth, Hal F., Crystal finishing: *Radio-Electronic Engineering* (*Radio News*), **3**, 3–7, 26, 44–45 (1944).

many as 1000 in a two-quart jar) previously lapped by conventional methods such as those described above, are sorted into groups on the basis of thickness, or frequency, and each group placed in a jar containing a mixture of abrasives. A motor driven device such as the one shown in Fig. 15 may be used to rotate several jars at a time.[27] The usual speeds are from 35 to 60 r.p.m. Higher speeds may cause excessive breakage.

A two-quart glass jar, 6″ in diameter with four straight sides, rotated in a horizontal position was found to give the best tumbling and mixing

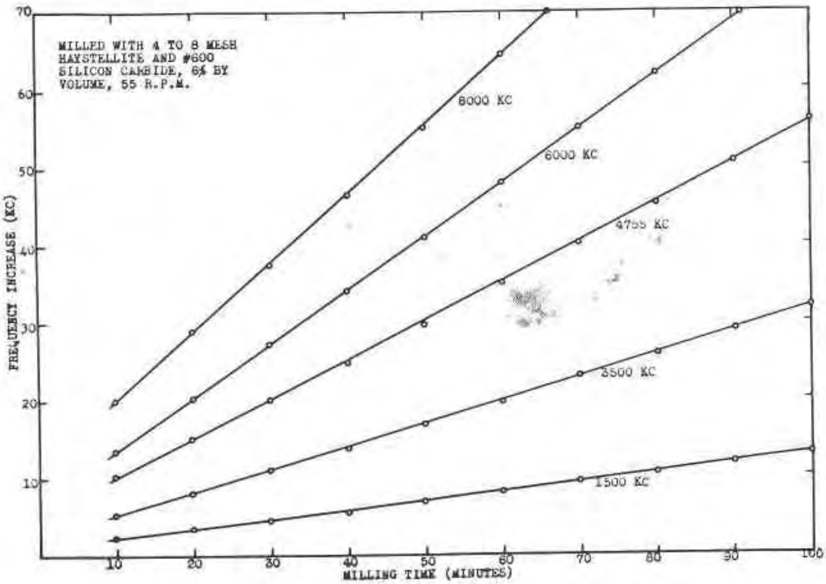


FIG. 16. Frequency increase with milling time. (Courtesy of Galvin Mfg. Corp., Chicago, Ill.)

action for the abrasive. Cylindrical jars do not turn over the crystals and the position of baffles placed in cylindrical jars to accomplish this are critical and not convenient. Devices for rotating the axis of rotation of the jar as well as the jar itself have been used. Various combinations and types of abrasives have been used for the milling methods. A jar about one-half to five-eighths filled with solids and the remainder with water containing a wetting agent was found to give good results. Two types of abrasives are used simultaneously in the mill. #320 to #800 silicon carbide or aluminum oxide comprise approximately one-tenth by volume of the

[27] Manufactured by Jenkins Engineering Co., 2301 East 48th Street Terrace, Kansas City 4, Mo.

solids and do the grinding while a dense material such as garnet or corundum in the form of pebbles (5–10 mesh) supplies the pressure. The amount of quartz removed is linearly related to milling time and due to the extremely small pressures, the method is much slower than the usual lapping techniques. The rate of frequency increase will depend among other factors on the frequency-thickness curve and the starting frequency as shown in Fig. 16. When such factors as velocity of rotation, shape of container, type of abrasives, etc., are controlled the results are reproducible within very close limits. The method does not equalize thickness differences. In practice, the crystals are channelled (frequency grouped) within very close limits if a small frequency spread is desired at the end of milling. If this procedure is not followed, all the crystals are removed from the mill at stated intervals and channelled. Those that are within the frequency tolerance are removed and those below the specified range are returned to the mill for further milling and the process repeated. An alternative procedure is to start the mill with the group of crystals which is furthest away from the final desired frequency and then to add the channelled groups one at a time in progressively increasing frequency of the next channelled group.

The method is used to increase the frequency only a small amount, approximately a few hundred KC being the maximum for a 6 MC BT-cut while 25 KC is the usual amount removed. The rate of removal of quartz is very small and the contour and edges of the crystals may seriously deteriorate if milled for long periods. The method is said to be subject to such control that most of the abrasion is on the major surfaces of the blanks, or if desired, the edges can be made to abrade relatively more rapidly.

The method has been employed by several crystal plants and has been most successful where large production quantities of closely spaced frequency channels are required as in the present crisis. The mass etching procedures which are now used as standard finishing practice and the high speed precision lapping techniques available today are capable of huge precision-controlled production so that it is difficult to evaluate its importance as a technique that will be useful in the future. A possible application of the method is in the manufacture and final frequency adjustment of very thin crystals. The method has been useful in edging and washing crystals.