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Interim Technical Report  
June 1977

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EVALUATION OF SULFOSALTS

Westinghouse Research & Development Center  
Pittsburgh, PA 15235

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Sponsored by Defense Advanced Research  
Projects Agency (DoD) ARPA Order No. 3151

ROME AIR DEVELOPMENT CENTER  
AIR FORCE SYSTEMS COMMAND  
GRIFFISS AIR FORCE BASE, NEW YORK 13441

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of these studies, there has been significant improvement in reducing imperfections in our crystals. Further refinement of composition is expected to lead to further improvements in quality. Work has been started to determine the most desirable composition for crystal growth on the phase relations around the composition  $Tl_3TaSe_4$ . The temperature coefficient of the piezoelectric constant has been remeasured and a new value was found. We have verified, both theoretically and experimentally, the reported ZTCD cut having zero power-flow angle.

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## EVALUATION OF SULFOSALTS

Second Semi-Annual Report  
Contract No. F19628-76-C-0158

### 1. INTRODUCTION

#### 1.1 Program Objectives

This program has two principal objectives, one of which is to determine the optimum conditions for fabrication of reproducible, high-quality crystals of  $Tl_3VS_4$  and, if time permits, of related materials. The other is to determine directions in these crystals which have zero temperature coefficients of delay (ZTCD) for surface acoustic waves, and to assess which of these directions possesses the best combination of velocity,  $k^2$ , and power flow angle for device applications. New determinations of physical parameters (attenuation, velocities,  $k^2$ ) will be made on improved crystals.

In addition, the effects of wider temperature ranges and higher order temperature coefficients of velocity will be examined. Hall measurements will also be made. A bandpass filter will be fabricated to demonstrate the applicability of these materials for surface-wave devices.

#### 1.2 General Approach

The determination of the optimum composition for crystal growth of  $Tl_3VS_4$  is being accomplished by studying phase relations around the stoichiometric composition in the ternary system Tl-V-S. The methods employed include thermal heating and cooling curves, quenching experiments, and directional solidification experiments.

The search for ZTCD directions, in addition to the ones already known, is being done initially using a computer program to locate these directions theoretically. The computer program is being modified and expanded to enable complete calculations to be made. The information thus acquired will be tested experimentally on crystals, and the directions for optimum performance ascertained.

### 1.3 Summary

Our studies of phase equilibria in the system Tl-V-S show it to be complex. Multiple arrests and supercooling presented problems in determining the maximum melting composition of  $Tl_3VS_4$ . We have narrowed the area, however, and are now using directional solidification to approach the best composition for reproducible growth.

We have completed two parts of our studies on crystal growth parameters, rates of growth, and gradient.

During the course of these studies, there has been significant improvement in reducing imperfections in our crystals. Further refinement of composition is expected to lead to further improvements in quality.

The temperature coefficient of the piezoelectric constant has been remeasured and a new value was found. We have verified, both theoretically and experimentally, the reported ZTCD cut having zero power-flow angle.

Work has been started to determine the most desirable composition for crystal growth on the phase relations around the composition  $Tl_3TaSe_4$ .

## 2. COMPOSITION AND CRYSTAL GROWTH STUDIES

### 2.1 Study of Melting Relations in the System Tl-V-S

In the first semi-annual report,<sup>1</sup> we gave the results of our studies of melting relations along the join  $Tl_2S-V_2S_5$ . We found the system to be complex, with considerable supercooling and multiple arrests causing scatter in the empirical data. Our data indicated that the maximum melting compound did not lie along this join, and probably was ternary. They also indicated that there were ternary phases and ternary eutectics off the join which might interfere with growth of high-quality crystals. While the composition of the eutectic found in this study appeared to be sufficiently far away from the stoichiometric composition not to cause problems in growing crystals, we did not know if there were eutectic valleys near  $Tl_3VS_4$  which would interfere with the production of high quality crystals. We proceeded, therefore, to perform thermal analysis experiments mainly along the join TlS-VS, and two along the join  $Tl_3VS_3-S$  to look for eutectics and also to find the highest melting-point compositions. We hoped to be able to map the maxima as an aid in finding the true maximum melting composition. The compositions and temperature ranges of arrests are given in Table 1. A plot of these compositions as well as those reported in the first semi-annual report is given in Fig. 1.

Once again we encountered the problem of reproducibility of data, with multiple arrests at varying temperatures and considerable supercooling (as much as 65°C). Doubled freezing point arrests were encountered in two of the materials ( $Tl_{3.1}V_{0.9}S_4$  and  $Tl_{3.02}V_{0.98}S_4$ ) which may indicate a separation of phases. There may be two ternary compounds with

Table 1  
 Compositions and Arrests of Thermal  
 Analysis Runs in the System Tl-V-S  
 (given in mole %)

<u>Composition</u>	<u>Arrests, in °C*</u>
$Tl_3VS_{4.10}$	520-542
$Tl_3VS_{4.04}$	519-541
	210
$Tl_{3.2}V_{0.8}S_4$	469-496
	240-240.5
$Tl_{3.1}V_{0.9}S_4$	436-451
	407-444
	219.5
$Tl_{3.04}V_{0.96}S_4$	501-534
	350
	226.5
$Tl_{3.02}V_{0.98}S_4$	524-534
	521-523
	373
	237
$Tl_{3.01}V_{0.99}S_4$	521-561
$Tl_{2.98}V_{1.02}S_4$	525-539
$Tl_{2.95}V_{1.05}S_4$	524-539 <sup>†</sup>

\* In the case of arrests corresponding to the liquidus, the observed extreme supercooling would cause the numbers derived from the cooling curve to be low. The range of temperatures given here are therefore taken from both heating and cooling curves.

† The upper temperatures given here are not those of the highest melting homogeneous melt of this composition. There was a high-melting temperature compound which remained solid throughout the run, so that complete melting did not occur.

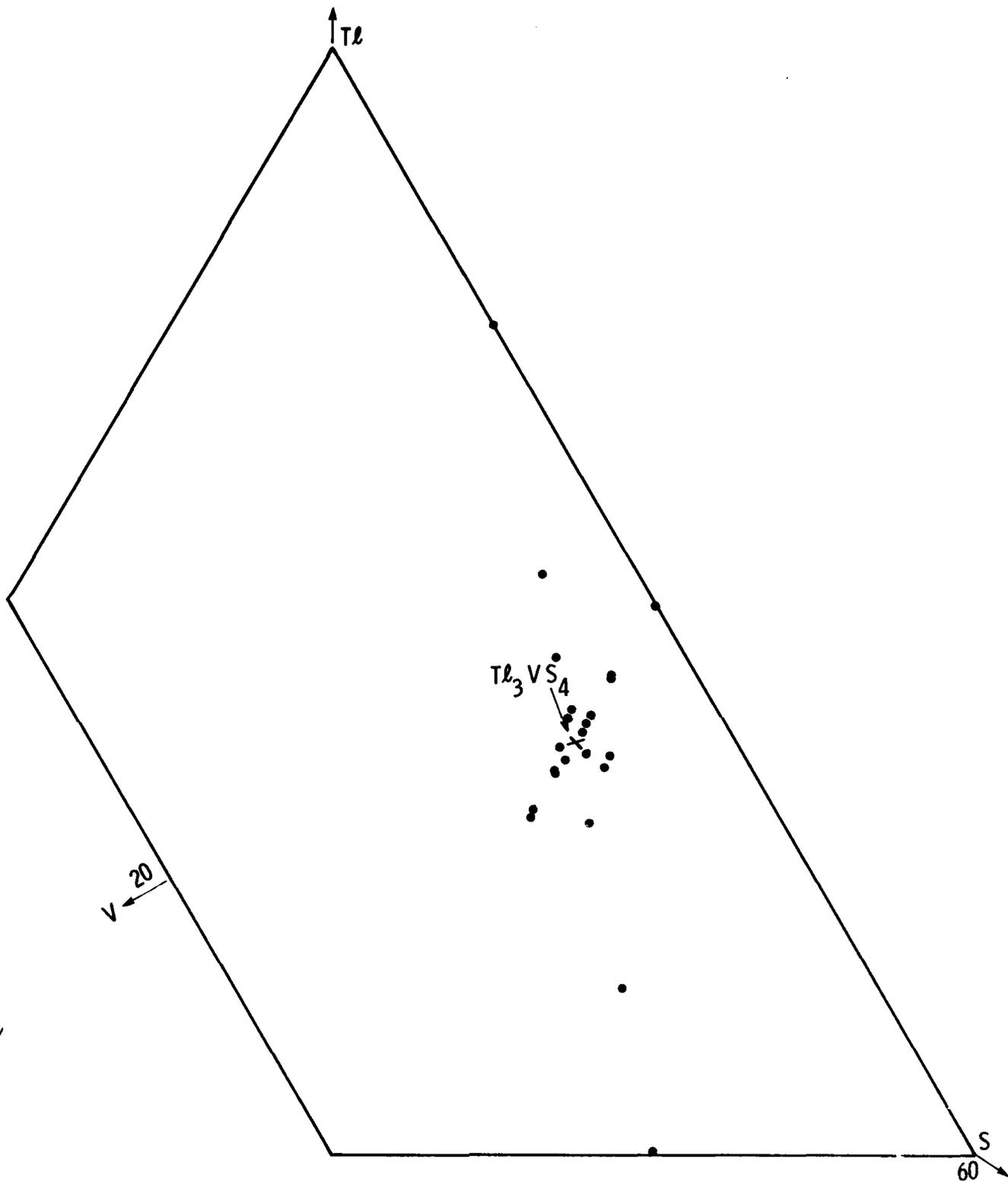


Fig. 1 - Expanded section of the ternary system Tl - V - S in the region of the composition  $Tl_3VS_4$ , showing some of the melting point runs

very close compositions. The liquidus curve along the join TlS-VS near the stoichiometric composition is fairly flat, but the data indicate that there may be a maximum melting compound at the approximate composition  $Tl_{3.01}V_{0.99}S_4$ . The data also suggest the presence of a eutectic valley which may pass within 4 percent of  $Tl_3VS_4$  on the TlS-rich side. The temperatures of the arrests (in the lower 400's) could indicate that this ternary valley includes the eutectic previously found.<sup>1</sup> This composition is near enough to the stoichiometric that the eutectic valley may cause problems in crystal growing. The phase relations in the system Tl-V-S are so complex that, for the purpose of this program, it is not worthwhile to pursue further refinement of the phase relations. Additional phase data will be derived from crystal growth experiments.

## 2.2 Directional Solidification Studies

Because we could not determine the exact maximum melting composition using methods of thermal analysis, we proceeded to conduct directional solidification experiments, varying the composition of the charges by small increments around (and including) the stoichiometric composition. Five compositions were chosen for the initial runs,  $Tl_3VS_4$ ,  $Tl_{3.01}V_{0.99}S_{3.98}$ ,  $Tl_{3.01}V_{0.99}S_{4.00}$ ,  $Tl_{2.99}V_{1.01}S_{4.00}$ , and  $Tl_{2.99}V_{1.01}S_{4.02}$ .  $Tl_{3.01}V_{0.99}S_{3.98}$  was the maximum melting composition on the join  $Tl_2S-V_2S_5$  as reported earlier.<sup>1</sup>  $Tl_{3.01}V_{0.99}S_4$  appeared to be the high-melting composition on the join TlS-VS. The other two compositions are on the V-S rich side of  $Tl_3VS_4$ . Although the data from thermal analysis experiments indicate that the maximum melting composition probably lies on the Tl-S rich side of stoichiometry, the evidence is not conclusive. In our study of the join TlS-VS, the data gave overlapping freezing-melting point temperatures immediately near  $Tl_3VS_4$ , and the curves for  $Tl_{3.01}V_{0.99}S_4$  and  $Tl_{2.98}V_{1.02}S_4$  were about equally clear. The maximum melting composition along this join is uncertain. We must also consider the possibility of interfering eutectics. Should they prove to be a problem, it may

become necessary to grow crystals from a composition slightly rich in V-S to avoid the melt composition falling into the valleys. Our decision to include vanadium-rich materials was also influenced by information given to us by Dr. Dickinson<sup>\*</sup> regarding an analysis made in his laboratory on some of the impurities in a sample supplied under this contract. The analysis did not show vanadium in the particles examined. This finding is consistent with our most recent thermal data along the join T1S-VS. Our choices were made in part to gain information as to relative amounts and types of impurities at compositions around and including the stoichiometric. This might enable us to discern a trend which would help in determining the optimum composition. The first few experiments were performed in our silica-glass crystal-growing furnaces. The boules showed numerous imperfections such as banding, inclusions, excessive cracking, and even some polycrystallinity indicating interface fluctuation and breakdown. These results were primarily influenced by adverse external factors, namely, ambient temperature variations and irregularities in line voltage. We decided to transfer this work to the semi-automated controlled growth furnace where these fluctuations would not present serious problems. However, first priority was given to determination of the parameters for growth rate and gradient in this system. These tasks were completed in March (see Section 2.3), and the refinement of composition is now being undertaken under controlled conditions.

### 2.3 Study of Crystal Growth Parameters

We have completed two parts of our investigation into the effects of growth parameters on crystal quality. The first was concerned with rate of growth, using rates of 0.94, 1.9, and 4.7 cm/day. The boule grown at the fastest rate was polycrystalline throughout its entire

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\*Verbal communication from Dr. Stanley K. Dickinson, RADC, Hanscom AFB.

length. The boule grown at the intermediate rate was a single crystal, but it was cracked into several pieces and contained some widely disseminated particles which were clearly visible in reflected light under the microscope. The boule grown at the slow rate was a single crystal and had only a few widely scattered particles which we could see under the microscope in the polished section. There were two cracks in it from hanging up in the growth tube. We found, therefore, that the moderately slow rate of 0.94 cm/day gave the best results. The second part was to ascertain the best gradient at this growth rate, using constant charge composition. Various settings for the two furnaces were used, and the gradients were determined. Figure 2 gives the plots for a number of them. All of the runs to determine the best growth rate were made using a gradient of about  $100^{\circ}$  per cm (represented by curve c on the figure). In our first run to investigate gradients, we lowered the gradient to about  $80^{\circ}$  per cm (curve b). The boule from this run was polycrystalline throughout its length. Apparently, it is necessary to maintain a steep gradient in order to prevent continuous nucleation because of the large amount of undercooling present in this system. The next run was made at a gradient of approximately  $115^{\circ}$  per cm (curve d), and the boule was a single crystal. But it contained some widely disseminated fine inclusions. We wanted to further steepen the gradient, but did not wish to do so by raising the temperature in the upper furnace; higher temperatures markedly increase the problem of boule hang up in the tube. We could not further lower the temperature in the bottom furnace as it was at 55% of the melt temperature. The best approach, therefore, was to separate the two furnaces, and several distances between  $1/4$  and 1 inch were tried and the gradients determined. A separation of 1 inch proved to be too great, producing a depression in the curve (curve f). We found that a separation of  $3/4$  inch produced the steepest useful gradient,  $130^{\circ}$  per cm (curve a). The boule grown at this gradient was the best quality of all those produced in this furnace, and in this entire investigation thus far.

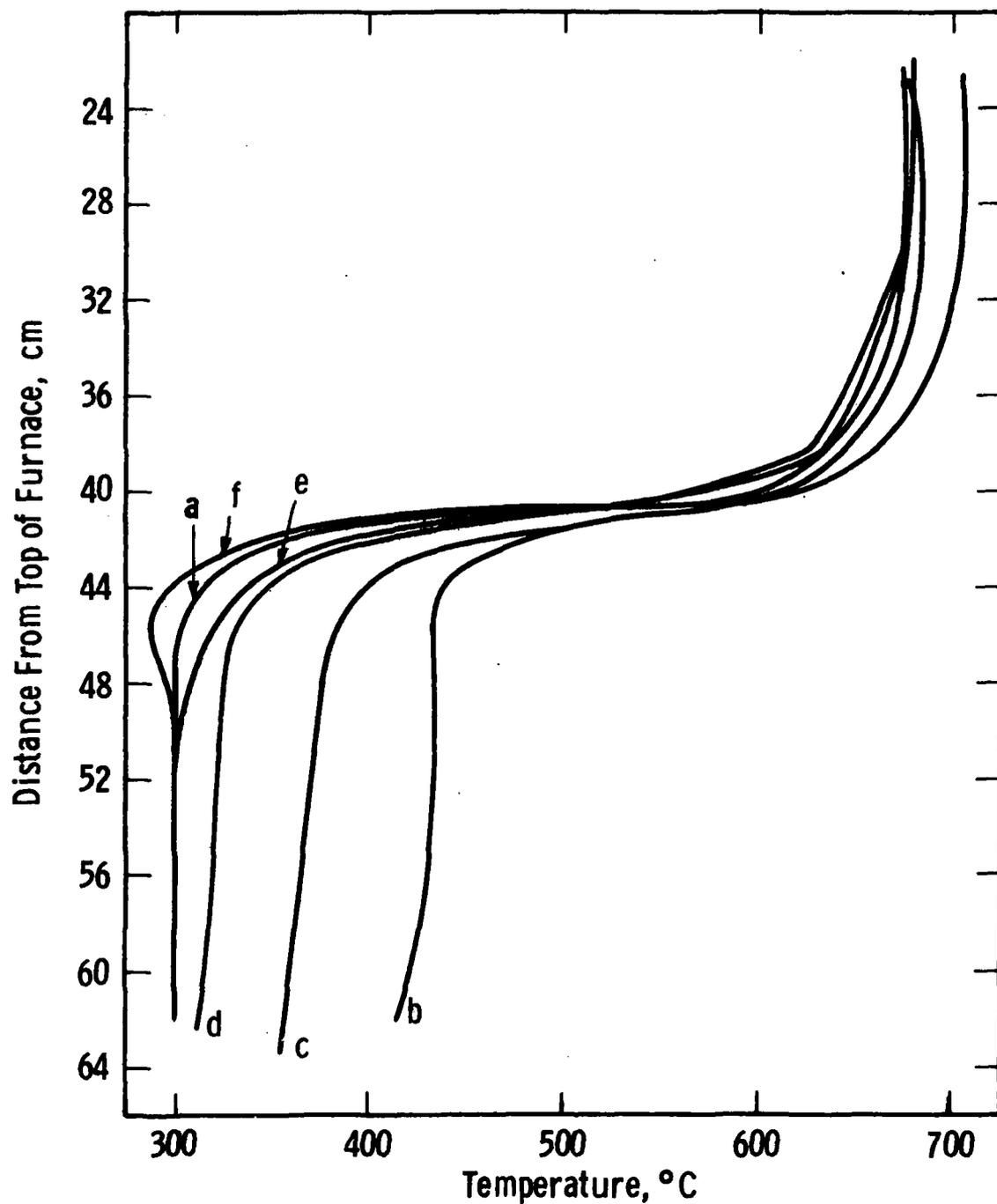


Fig. 2 - Temperature profiles of crystal growth furnace at various settings

It had a 5 cm section of good quality single crystal, of which the central portion of the bottom 4 cm was of high quality (see Section 2.4).

The third part of this study of growth parameters, the effect of various rates of cooling upon crystal quality, will be undertaken after we have completed our optimization of composition.

#### 2.4 Microscopic Studies

Results of some of our crystal growth runs have been examined under the infrared microscope. While imperfections were still visible, there has been a marked improvement in quality. This is illustrated in Plate 1 where sections from two crystals are shown as seen under 100X magnification. The top photographs are of a crystal grown in April 1975, while the bottom photographs are of the most recent crystal grown in our semi-automated controlled growth furnace.

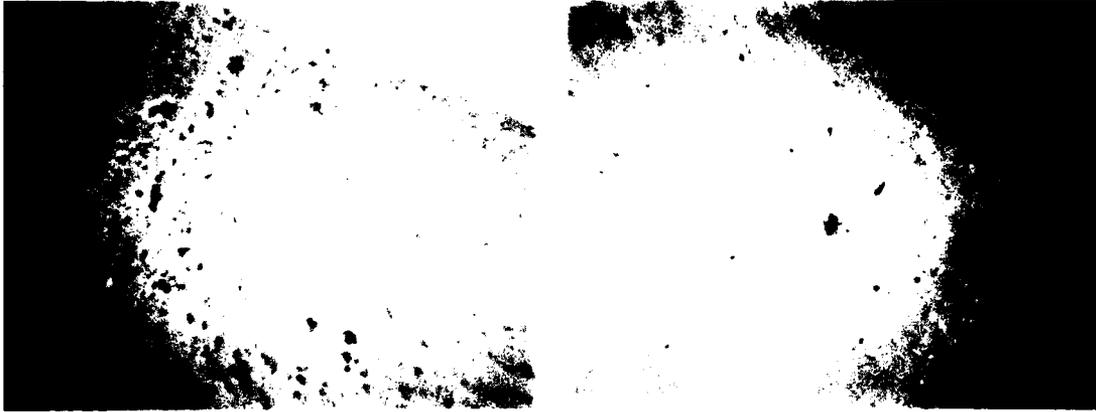
A serious problem with crystals of the family  $Tl_3BX_4$  has been the presence of numerous widely dispersed inclusions and other imperfections, as illustrated by the two upper photographs. We see here that defects comprise approximately 4 percent of the area observed. Typically, they were in the range of 3 to 6 percent in these early crystals. A major goal of this program has been to reduce significantly the percentage of these imperfections. The results of our studies of composition and growth parameters to date on one member,  $Tl_3VS_4$ , show that this has essentially been accomplished, as is seen in the bottom photographs. This boule was of high quality in its central portion over a length of about 4 cm. The amount of imperfections has been reduced to approximately 0.2 percent in this portion. The sections near the perimeter, however, were of lesser quality where the percent of defects increased to where they made up from 1 to 2% of the material at the edge.

We believe that there was some reaction between the melt and the silica-glass container, which affected the quality of the outer part of the boule. This appears to be a problem in growing crystals of this

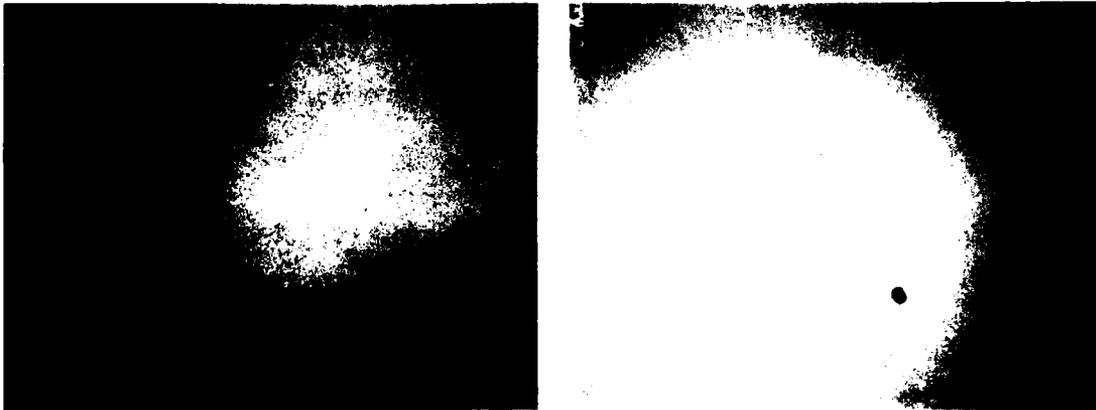
material, and is more severe when the containers are made from synthetic rather than natural quartz, as was the case with the tube used for the run mentioned above. The silica-glass made from synthetic material contains an appreciably higher amount of water than does that made from natural quartz, and it is extremely difficult to remove it. We believe that the water has a deleterious effect on our crystals, at least near the perimeters. We also think that there may be some reaction with the silica itself. But silica-glass is the only suitable container which we have found for this work. We tried coating the inside of a tube with graphite, and the results were even worse, as some vanadium carbide was formed, and the graphite partially pulled away from the wall of the container.

While we plan henceforth to use only silica-glass made from natural quartz, we realize that this step will merely lessen the problem, but not end it. The container still will not be water-free, and it will have bubbles which may contain undesirable vapors (water and others) which could migrate under elevated temperatures to interior surfaces. We plan to try a high-temperature reworking technique used a few years ago at this laboratory to improve the quality of silica-glass. In this method, the tube is flamed to a white heat using a hydrogen-oxygen torch. The torch is moved rapidly around the tube to avoid forming hot spots which could distort the cylindrical shape. This treatment tends to collapse near surface bubbles, to drive off adsorbed water from surfaces, and to polish the interior surfaces. We do not know at this time how much of a beneficial effect this treatment will have, but its effects will be evaluated in the next work period. Should it prove useful, we shall not only use it for our crystal growing tubes, but also for our reactant tubes to prevent contamination during the synthesis stage.

Parenthetically, the silica-glass container problem is not unique to our family of materials; it also exists for silicon and gallium arsenide, and quartz investigations are being pursued in other laboratories.



Crystal Number 207057-9



Crystal Number 207057-125

Plate 1

Photographs of sections of two crystals illustrating progress in quality improvement studies. The top two photographs are of an early crystal while the bottom are of a recent crystal.

## 2.5 Phase Equilibria in the System Tl-Ta-Se

The compositions of compounds in the system Tl-Ta-Se can be described in terms of a phase diagram (Fig. 3) on which known binary and ternary compounds are plotted. There are three compositional phases along the binary Tl-Se, and two along the binary Ta-Se; the compound  $\text{TaSe}_2$  has four polymorphs. There are two ternary compounds,  $\text{Tl}_3\text{TaSe}_4$  and  $\text{Tl}_{0.33}\text{TaSe}_2$  ( $\text{TlTa}_3\text{Se}_6$ ).

We have begun our study of melting relations in this system around the composition  $\text{Tl}_3\text{TaSe}_4$ . Our approach will be similar to that for  $\text{Tl}_3\text{VS}_4$ , although we shall not conduct as extensive thermal analysis determinations because of the large supercooling found in these systems. Our initial experiments involve freezing (melting) point determinations along the possible join  $\text{Tl}_2\text{Se-Ta}_2\text{Se}_5$ , where  $\text{Ta}_2\text{Se}_5$  is a hypothetical compound. We realize that the optimum composition probably is ternary and therefore will not lie on a join, but the maximum melting composition on this join will give us a starting point for further determinations. We are also looking for possible eutectics near this composition which may affect crystal growth.

Several runs have been made using selected compositions along this join, and the compositions and thermal arrests are given in Table 2, and also are shown in Fig. 3. There was considerable supercooling (as much as  $80^\circ\text{C}$ ), and some lower temperature arrests. The arrests at  $383.5^\circ\text{C}$  suggest the possibility of a eutectic at this temperature. Further exploration will be necessary to determine whether it does indeed exist and, if so, its compositional location. Thus far, we have not observed the multiplicity of thermal arrests which we encountered with  $\text{Tl}_3\text{VS}_4$ . It is possible that this system may prove to be less complicated. We have not as yet conducted enough experiments to determine the approximate maximum melting composition along this join, but the data indicate that it probably is near the stoichiometric composition. Once this has been located, it can be used as a starting point in determining the optimum composition for crystal growth by directional solidification studies using the controlled growth furnace.

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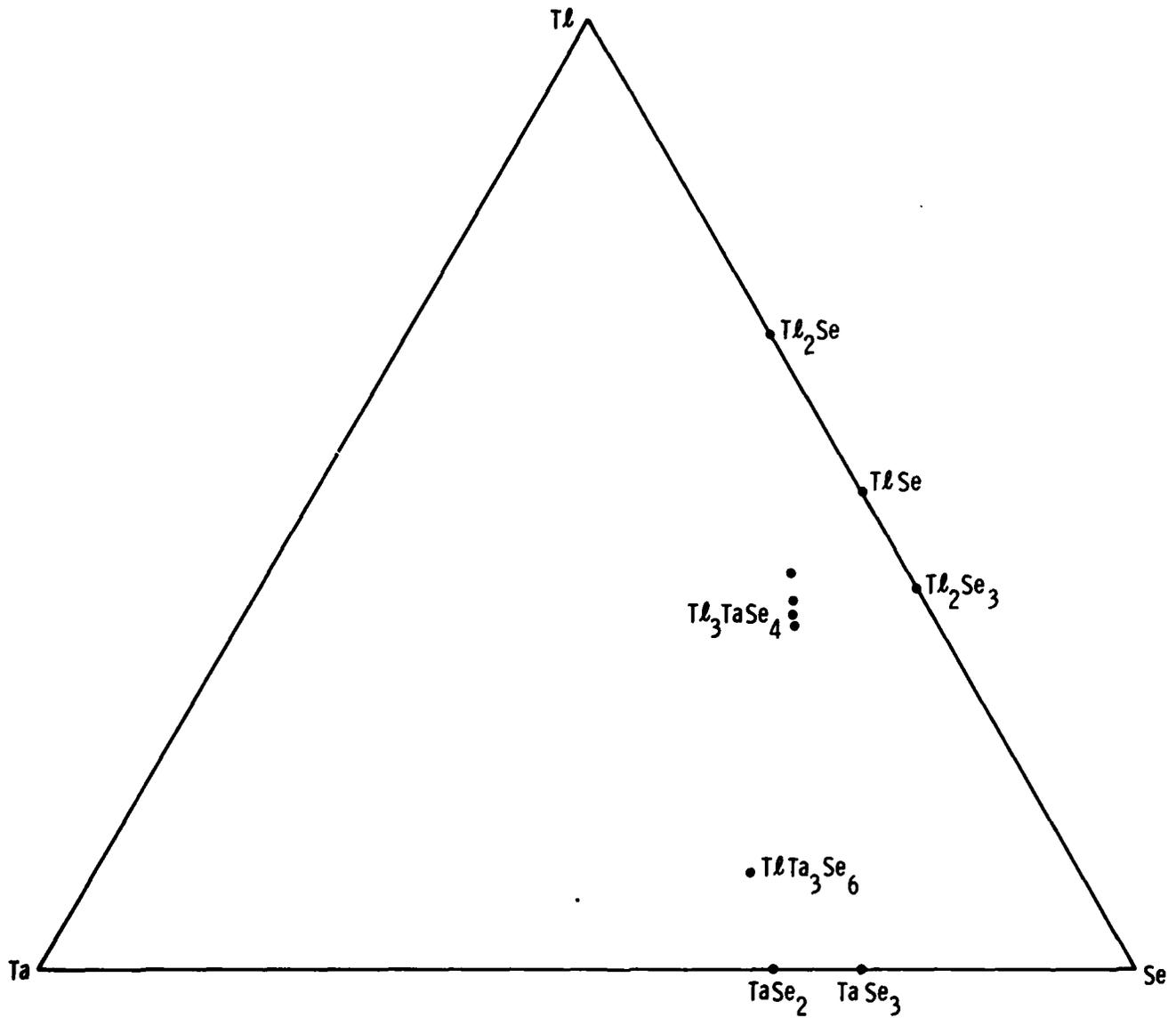


Fig. 3 - The system Tl - Ta - Se showing known binary and tenary compounds

Table 2  
 Compositions and Arrests of Thermal Analysis  
 Runs Along the Join  $Tl_2Se-Ta_2Se_5$   
 (given in mole %)

<u><math>Tl_2Se</math></u>	<u><math>Ta_2Se_5</math></u>	<u>Arrests, in °C*</u>
80	20	592-629 383.5
76	24	602-634 383.5
75	25	632.5-643
74	26	628-639

\* The temperature ranges are taken from both heating and cooling curves.

### 3. STUDIES OF ACOUSTIC PROPERTIES

#### 3.1 Overall Objectives

The acoustic work comprises two areas of study. The first involves the measurement of material constants such as the elastic, piezoelectric, dielectric constants, the density, and the temperature dependence of these constants. These numbers are then used to calculate surface wave velocities in various cuts and propagation directions as a function of temperature. Orientations are considered useful when the temperature coefficient and power flow angle are small and the effective surface electro-mechanical coupling factor is large.

The second area of study involves SAW device fabrication and testing on the sulfosalt materials. This work is concerned with techniques of cutting, polishing, and photolithography, and in general the surface quality of a finished crystal device.

During this six-month period, the acoustic work has been oriented mainly towards device applications. We were concerned with surface quality, specific cuts and directions, and there were also some further studies on physical properties.

#### 3.2 Remeasurement of Temperature Coefficient of the Piezoelectric Constant

Our first determination of the temperature coefficient of the piezoelectric constant had a large error factor, and we have therefore remeasured it. This is done by measuring the temperature coefficient of the stiffened elastic constant,  $\bar{c}_{44}$ , and then calculating the temperature coefficient of the piezoelectric constant,  $e$ , from the known values of the temperature coefficients for the unstiffened  $c_{44}$  and of

the dielectric constant. This calculation was discussed in detail in our first semi-annual report. The new value for the first order piezoelectric constant temperature coefficient is  $-6.1 \times 10^{-4}/^{\circ}\text{C}$ ; the old one was  $-3.2 \times 10^{-4}/^{\circ}\text{C}$ . We consider the more recent value to have greater validity as there was much less scatter in the experimental data. We believe that the first measurement may have been made on a damaged crystal, the imperfection being small and therefore not noticed. This hypothesis is suggested by the large scatter of experimental points. We shall do another set of measurements on a new crystal to verify the second value.

### 3.3 Determinations of Temperature Stability

We investigated, both theoretically and experimentally, the (110) cylinder cut in  $\text{Tl}_3\text{VS}_4$  having surface wave ZTCD with zero power-flow angle reported by Jhunjunwala et al.<sup>2</sup> Computer calculations were initially performed which verified their finding, and we then prepared a crystal for experimental studies on the temperature coefficient of delay for surface waves. The Euler Angles which describe the direction in our study are  $45^{\circ}$ ,  $54^{\circ}$ ,  $90^{\circ}$ , whereas those given in Ref. 1 are  $45^{\circ}$ ,  $53^{\circ}$ ,  $90^{\circ}$ . The slight difference between them is brought about by our including the temperature variation of the dielectric constant and the piezoelectric constant in our calculations.

The crystal used in this study was of composition  $\text{Tl}_{3.01}\text{V}_{0.99}\text{S}_{3.98}$ . It was cut to a size of approximately 1 cm square and 0.2 cm thick; the top surface was polished, and the bottom one left finely ground. A pair of I.D. grids were put down on the polished surface, and a comparison was made of the phase of a signal going through the device with that of a reference signal while varying the temperature of the crystal. The phase difference was kept constant by varying the frequency of the signal. The crystal orientation and the results of this study are shown in Fig. 4. We found a temperature stable region

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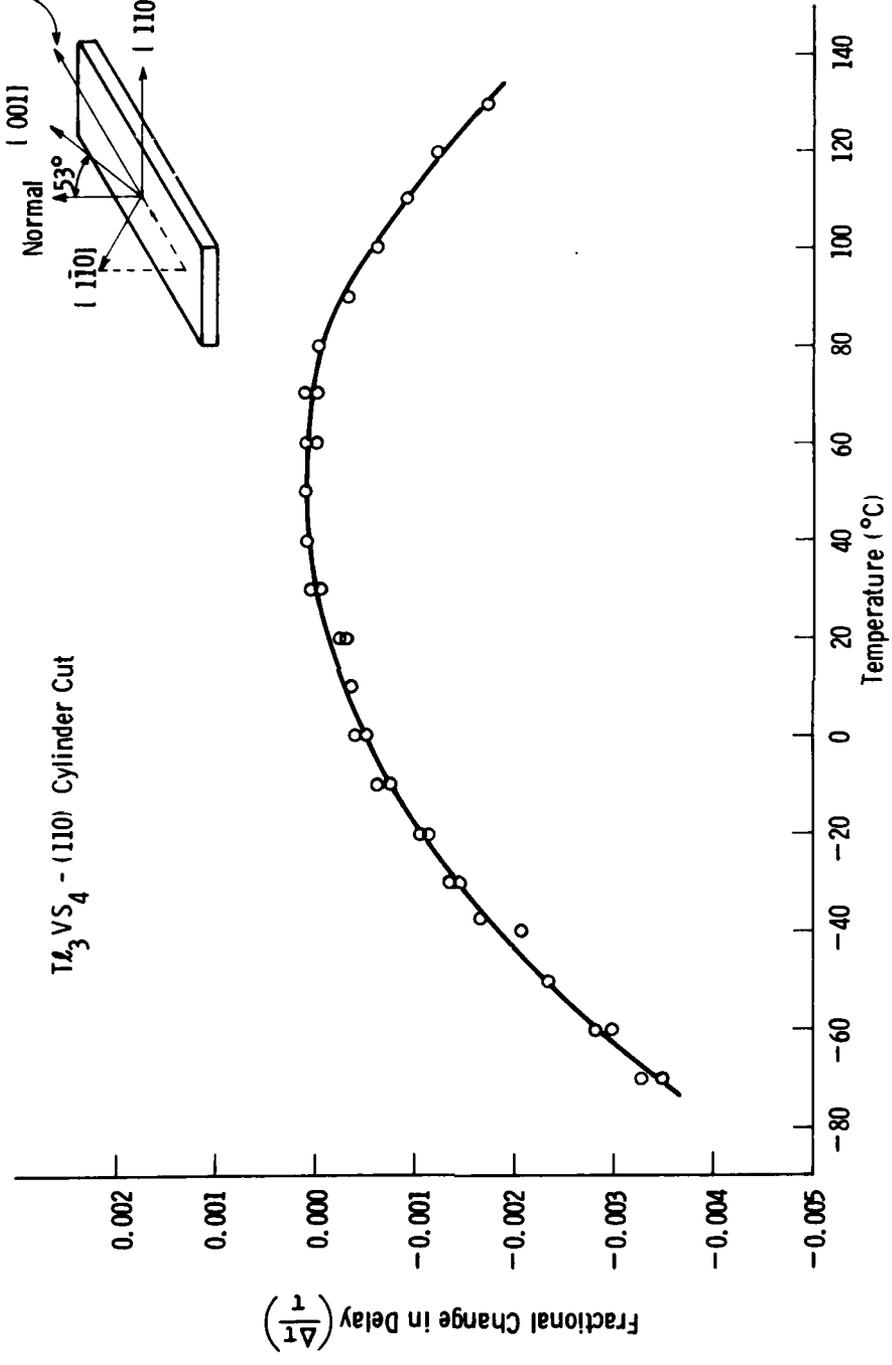
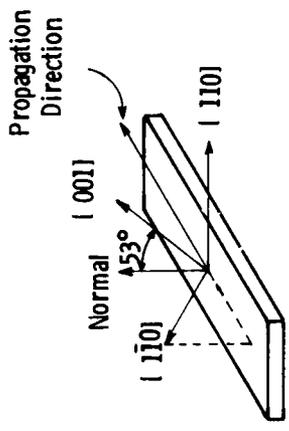


Fig. 4. Fractional change of delay vs. temperature for surface waves propagating on a (110) cylinder cut of  $Tl_3VS_4$ .

of 30 to 80°C, within which the fractional change in delay time was  $\pm 50$  ppm. This figure translates into a temperature coefficient of delay of  $\pm 1$  ppm/°C.

This cut will be useful for device applications. Not only does it have a zero power-flow angle, but also a theoretical  $k^2$  of  $\sim 0.8\%$  (we measured  $\sim 0.6\%$ ) which is 10 times that of the temperature stable direction of quartz. Also, the surface wave velocity for this direction in  $Tl_3VS_4$  is approximately 3 times smaller than that of quartz.

#### 3.4 Study of Surface Effects of Polishing

In our previous report,<sup>1</sup> we discussed the effect of our then current polishing techniques on the quality of the surface of the crystal. We found that the damaged layer extended to over 20 $\mu$ . Ion beam milling was used to remove this layer and give a smooth surface. We have worked out a polishing procedure which eliminates the need for this last step. We now polish the crystals in steps, changing the size of the grit with each step down to a grit size of 0.1 $\mu$ . At each grit size a layer of material is removed which is at least as thick as twice the previous grit diameter. After the final polish with the 0.1 $\mu$  grit, we found the damage layer to be less than 0.2 $\mu$ . With this small damaged layer, the ion milling step could be eliminated for low frequency devices. Current determinations indicate that the effective surface wave  $k^2$  for 10 MHz I.D. Grids is not (measurably) diminished by the thin 2000 Å damaged layer as compared to a damage-free surface.

#### 4. DEVELOPMENT OF THE COMPUTER PROGRAM<sup>†</sup>

##### 4.1 Introduction

A computer program for the determination of the acoustical properties of anisotropic crystals has been designed and is currently in the debugging stage. It is to be used to locate propagation directions of bulk acoustic waves which minimize the temperature coefficient of velocity and have zero or small power flow angles. The importance of these conditions stems from application of ultrasonic devices in signal processing, where temperature stability to 1 part in  $10^6$  is often required.

The program is designed to generate four maps: propagation velocities (or slownesses) of normal modes, power flow directions, temperature derivatives of velocities (slownesses), and temperature derivative of power-flow directions. These maps will ultimately be produced in the form of three dimensional representations drawn on a CALCOMP plotter. The first version of the program, however, will provide only the tabulated data from which the plots will be made.

When a direction with the desirable properties is identified by the user, the program will then be rerun using a finer scan to obtain the optimum direction.

We believe that this approach, using the pattern recognition capabilities of the sophisticated user, is far superior to one which requires the computer program to search for the solution from an initial set of guesses.

##### 4.2 Program Design

A structural Fortran package purchased from Caine, Farber and Gordon, Inc., was employed in writing our program. This is a preprocessor

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<sup>†</sup>The computer program is being developed with Westinghouse funds.

that converts, and eventually translates the input into Fortran V language, and compiles using the standard Fortran compilers. The package is important in that it provides a convenient way to make Fortran programs modular. The program can thus be expanded simply by writing new modules and inserting them into existing slots.

The acoustic program, entitled BULKWV, has been designed to process crystals of all crystallographic types which are of interest in application to acoustic devices. The user will specify crystal symmetry on one of his input cards (e.g., TRIGONAL (32), the symmetry of  $\alpha$ -quartz). There is a set of masks within the code which contain information on the elastic, piezoelectric and dielectric constants the program needs to run with this symmetry. We enter into it only those independent constants that are found by running along the rows of matrices. The program fills in all of the other constants. The minimum set of constants required for the program to function is the set of elastic constants. The temperature coefficients of the constants must be entered to run the temperature derivative portion.

Several options are available with respect to the type of run to be made. These are labeled PIEZØ, PIEZØT, and TEMP. If none of these is entered as true, the program assumes a non-piezoelectric run without temperature dependence. Should PIEZØ be entered as true, a piezoelectric case is assumed and the coefficients are entered. Should TEMP be true, the temperature derivatives are requested for acoustic properties. The minimum entry would be the temperature coefficients of the elastic constants. If PIEZØT is false, we use the constant values of the piezoelectric coefficients as the piezoelectric coefficients are not available. If PIEZØT is true, however, the temperature coefficients of the piezoelectric constants are entered as well as the temperature coefficients of the dielectric constants.

The program has scanning options which permit the user to specify that he wants 1) the desired velocity (slowness) and power-flow

angle at a fixed propagation direction, or 2) to scan within a fixed plane, or 3) to scan over a set of planes which are rotated with respect to a pole. The scanning ranges, both within a plane and over a set of planes, are set on input to enable a narrowing down of scans to be accomplished. This permits closer observation. The approximate angular increment within a scan is also set on input.

#### 4.3 Adaptation to Surface Waves

The surface wave program developed by Campbell and Jones has the disadvantage of not permitting the user to see the development of the solution. Much computer time therefore is wasted on runs which terminate on maximum time without producing results. Options to limit the number of iteration steps also have only given minimal information.

We plan to interpose into the program a map which will be in the form of a computer plot showing the characteristics of the surface wave boundary condition determinant as a function of the velocity. We can determine from this plot the likelihood of finding pseudo surface waves which decay in the direction of propagation.

When a real surface wave cannot propagate in a given direction in a plane, a change in the orientation of that plane may result in an allowed surface wave. We plan, therefore, to generate a map of the minimum value of the boundary condition determinant as a function of propagation direction. The propagation velocities at which these minima occur will be tabulated. The regions in which real surface waves can exist as well as those where only pseudo surface waves can exist will be determined from the map. Information about velocities of bulk waves which may interfere with surface waves in a given direction will be obtained from the bulk wave program.

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