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Superconductive Frequency
Control Devices
Report No. 3
Contract DA-36-039-AMC-00036(E)
Electronic Components Research Department
PR&C 63-ELP/R-4511
Third Quarterly Report
1 January 1963 to 31 March 1963
U. S. Army Signal Research and Development
Laboratory

The object of the research is to investigate the performance of superconductive tank circuits and to arrive at design criteria of a tunable superconductive frequency control device.

By

William H. Hartwig
Project Director

EMRL Report No. 122

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PURPOSE

1. General

Previous work of this laboratory has established that loaded Q's in excess of 10^5 can be obtained with superconductive resonant tank circuits. Coupling, radiation, and dielectric dissipation may dominate the ohmic loss in determining Q at HF and VHF frequencies. Such circuits are tunable over a considerable range of Q and frequency. Design of tunable superconducting frequency control devices requires consideration of frequency-temperature effects, means of coupling and tuning, maintenance of a cryogenic environment, geometry, and microphony. More important, however, is a better understanding of the conduction, energy storage, and energy dissipation processes in materials with exploitable properties. The purpose of this investigation is to evaluate the design criteria while carrying out the basic studies.

2. Detailed Requirements:

a. Using bulk and thin films, study the residual impedance of pure metals and alloys with zero field transitions above 4.2°K as a function of

(1) Frequency and temperature and

(2) Signal level and external magnetic field.

b. Using superconducting tank circuits in an oscillator evaluate their performance as a function of

(1) Temperature in the operating range,

(2) Configuration and means of coupling, and

(3) An external magnetic field.

c. Investigate and catalog the physical properties of materials with particular reference to their use in high frequency superconductive circuits.

d. Direct the studies outlined under a., b., and c. above so as to make them of maximum use in establishing a rational basis for the design of tunable superconductive frequency control devices with predictable performance.

I. ABSTRACT

During the third quarter an active experimental program began at 21 mc. with tunable circuits capable of being operated immersed or evacuated. Extensive tests were made with commercial 40SN-60Pb alloy circuits to calibrate the experiment. An identical circuit coated with pure tin having a 5Sn-95Pb shield can was tested for the effects of temperature and magnetic field upon Q and resonant frequency. Residual resistance was higher than expected. A tuning slug resulted in a three fold drop in Q when fully extended.

Construction of an rf amplifier continued which will be in operation at an early date. Several thin-film circuits have been successfully deposited. In parallel a technique for building foil circuits of tin, lead, tin-lead alloys, niobium, tantalum and vanadium has been developed. The alloy foils are rolled in the laboratory after mixing high purity lead and tin in proper proportions and melting.

Theoretical studies continued on the transfer function of an oscillator incorporating one or two coupling probes at the tank. Calculation of inductance is nearing completion. Comparison between experimental residual resistance measurements and theory are discussed.

II. PUBLICATIONS, LECTURES, REPORTS, AND CONFERENCES

Two papers were published. The first entitled "Superconductive Resonant Circuits" was presented at the 1963 International Solid-State Circuits Conference at Philadelphia, Pennsylvania. The paper appeared in the Digest of Technical Papers. The second paper entitled "Q Measurement of Superconducting Tanks" appeared in the February 22 issue of ELECTRONICS magazine.

An abstract was submitted at Dr. Guttwein's suggestion for a paper to be presented at the 17th Annual Frequency Symposium. The title of the paper will be "Application of Superconductivity to Frequency Control." A paper has been accepted at the Southwestern IRE Conference to be held in Dallas in April. It is titled "Magnetic Field Interactions with Superconductive Circuits," by B. G. Slay and W. H. Hartwig.

On February 12 and 13 Dr. John Kunzler of Bell Telephone Laboratories visited the University of Texas and discussed high field superconductors with the project staff.

On February 18 the project director presented an invited symposium on superconductive resonant circuits at the Westinghouse Research Laboratory, Pittsburgh, Pennsylvania and iscussed high field superconductors with their staff including Drs. J. K. Hulm, B. S. Chandrasekhar, and M. Garbundy.

On February 19 the project director visited USASRDL, Fort Monmouth, where he discussed project progress with Drs. Guttwein, Hafner and other members of the USASRDL staff.

Patent disclosures growing out of work on this project were completed in rough draft form, prior to submission to the U. S. Army Signal Patent Agency.

III. FACTUAL DATA

A. Calibration of Equipment

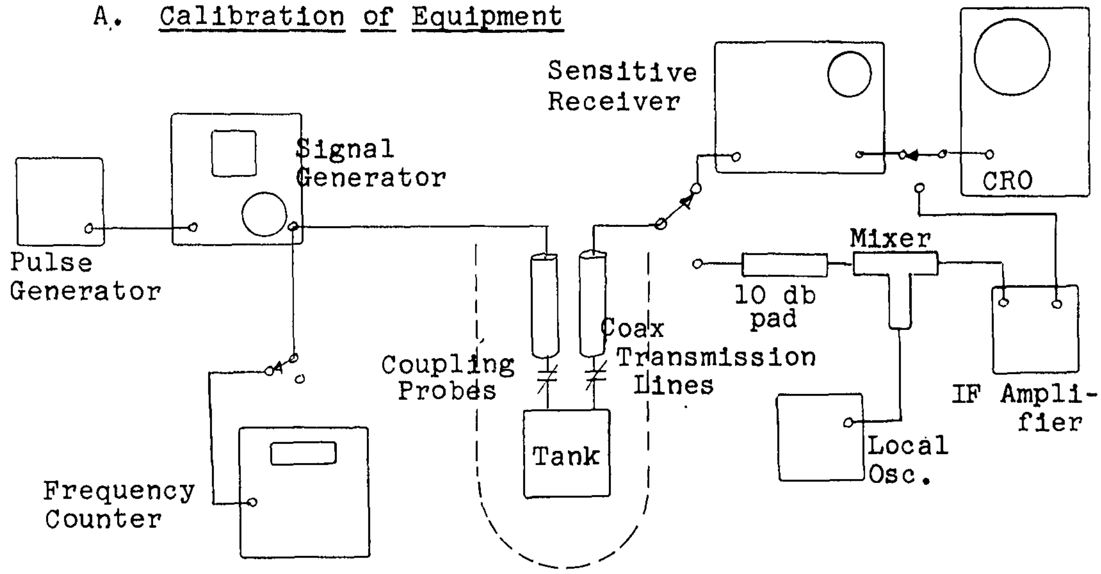


Figure 1. Q and Frequency Measuring Circuits

The components shown in figure 1 were measured to determine their significant characteristics. Figure 2 is a plot of the range of tuning available with the Fine Tuning Adjust of the Hewlett-Packard Model 608-D signal generator. The circuits to be measured were constructed at 21 mc. The narrow bandspread of this adjustment has proved to be helpful in setting a desired frequency.

Figure 3 is the bandspread of the Empire Devices receiver with a T-A/NF-105 Tuner. Its frequency range is 0.15 to 30 mc. The 3 db bandwidth is 16.2 KC at 20 mc. and the response is flat for more than 3 KC. This is an excellent characteristic for using the decrement method where the decay time is in the order of 1 millisecond or

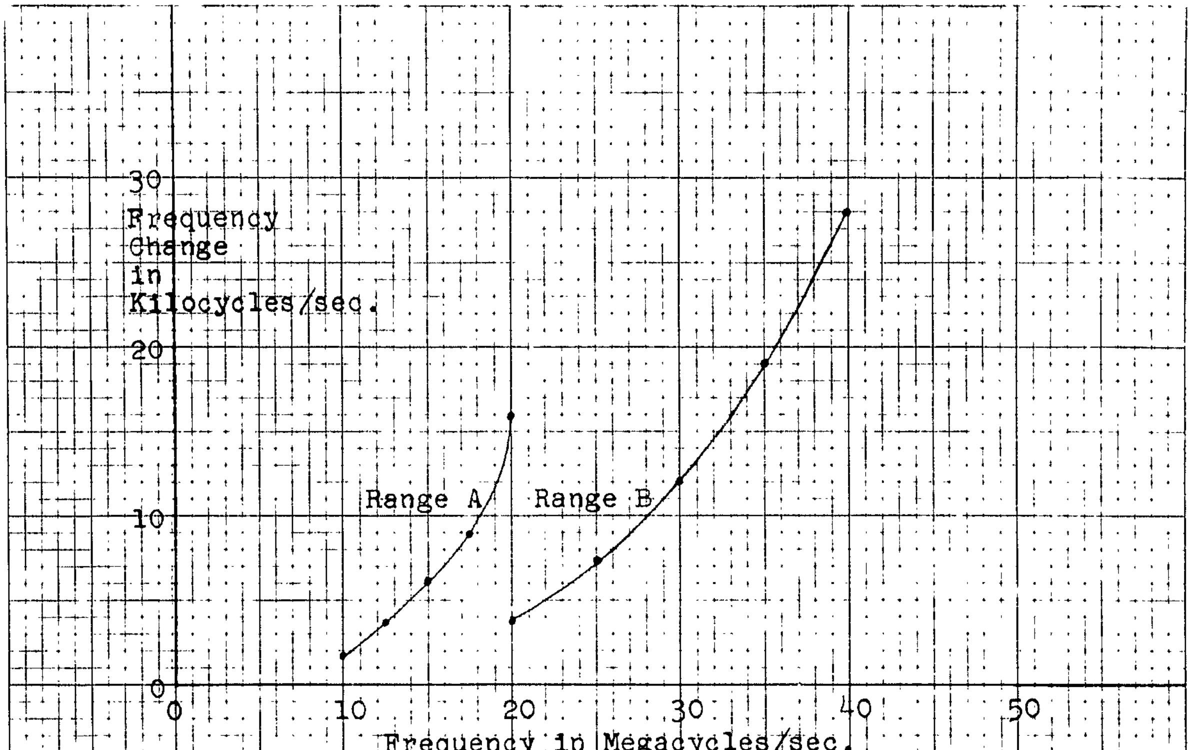


Figure 2. HP 608D Signal Generator Fine Freq. Adjust

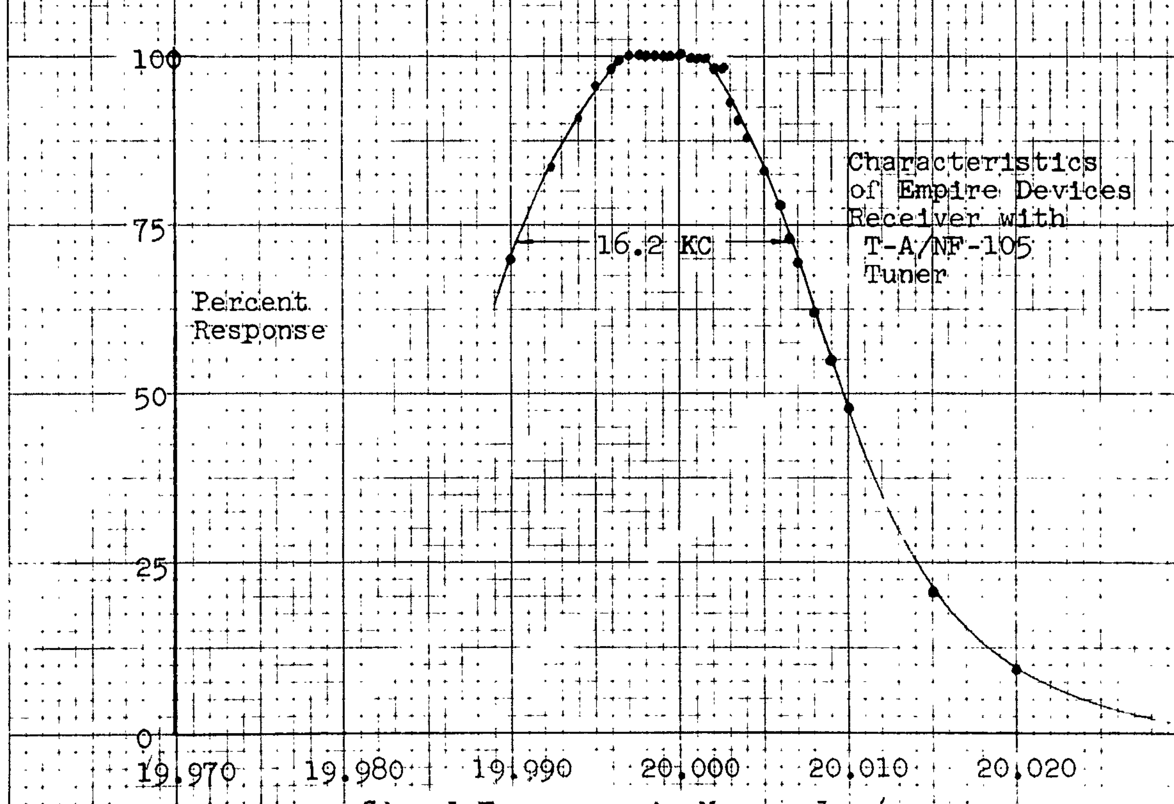


Figure 3. Bandspread of Receiver

greater. This corresponds to Q greater than about 60,000 at 20 mc. The receiver is also very satisfactory for CW measurement of Q below this value when used as an RF vacuum-tube microvoltmeter. Due to its narrow frequency "window," changes in signal generator frequency must be made in small increments to keep the generator, tank, and receiver in the window.

In all other respects the measurement technique is unchanged. It has been sufficient to determinedecay times visually from the CRO trace in most cases. The technique may have to be changed to a faster one when transient and hysteresis effects are studied. Several methods are discussed in a recent paper by the author(1) based upon the work of T. Milner during the first year of the project.

B. <u>Design of a 21 mc. Tunable, Evacuable Configuration</u>

Previous measurements at 171, 93, 58 and 36 mc. showed the residual resistance ratio would decrease if the frequency decreased or if the superconductor had more nearly ideal characteristics. Ideal characteristics might be obtained with a smooth surface or with pure metal and probably with both. The losses in liquid helium were not known and this factor continued to be suspected as having a small but uncontrolled influence.

A tunable circuit was designed to operate at 21 mc. having rigid shield can which could be sealed and evacuated, figure 4.

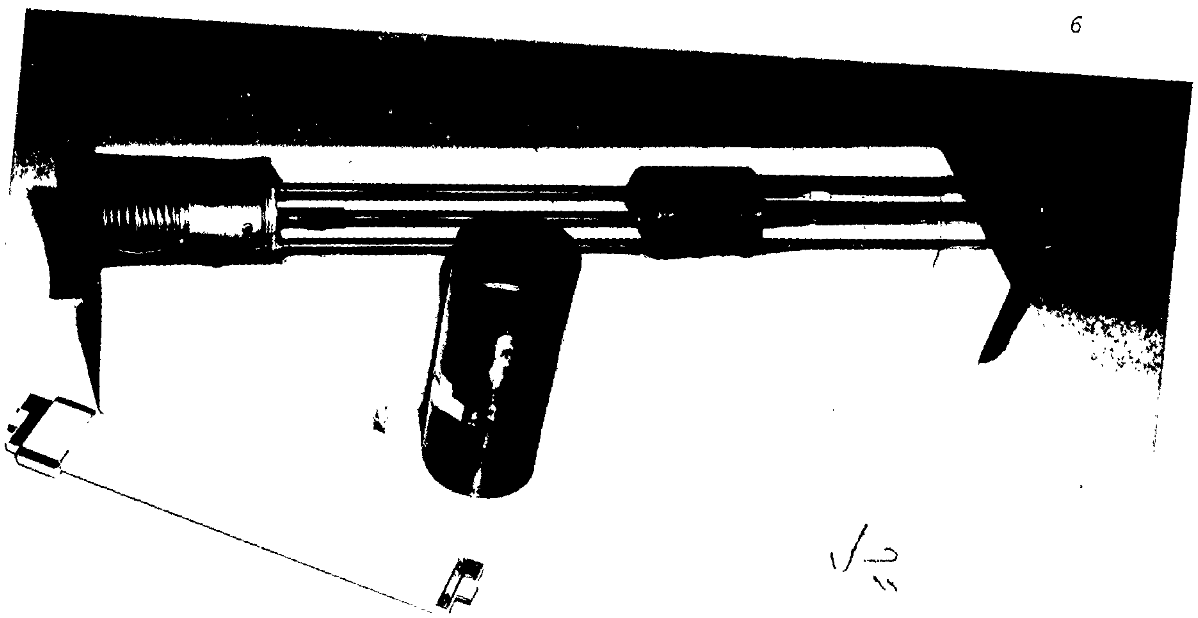


Figure 4. 21 mc. Tunable
Evacuable Configuration

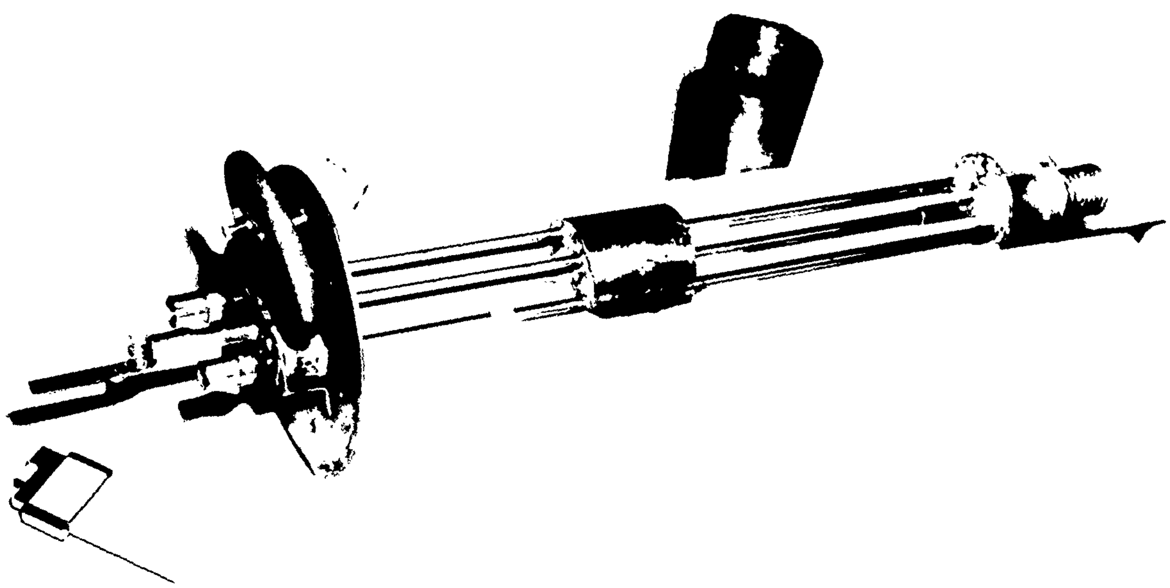


Figure 5. Dewar Header Assembly

1. Seals

To effect a vacuum seal it was necessary to use rubber O-rings at room temperatures for the moving parts. Three were used, two for the coupling probes and one for the tuning rod. The whole chamber to be evacuated, the shield can, circuit and three stainless stell tubes are accessible to pumping from the fitting on the header as shown in figure 5. The shield can is attached to the rest of the circuit with a soft solder seal. Figure 6 is a section drawing of the header showing the seals and means to evacuate the circuit.

2. Circuit Design

The 21 mc. resonant circuit was designed on the same model as the 36 mc. circuit used previously. Several changes were necessary to change the frequency. The capacitor had a double ground plate which the other plate of the capacitor is between. Small teflon spacers kept the plates apart, and additional turns were necessary to increase inductance.

3. Tuning Assembly

The tunability of this circuit comes from a superconducting slug which can be screwed into the inductor or retracted into the grounded capacitor. This design allows a variety of slug sizes and composition to be tested with a single resonant circuit.

An additional design consideration of tuning was to allow heat flow out of the slug and circuit of the evacuated system. rass extension replaced the stainless steel

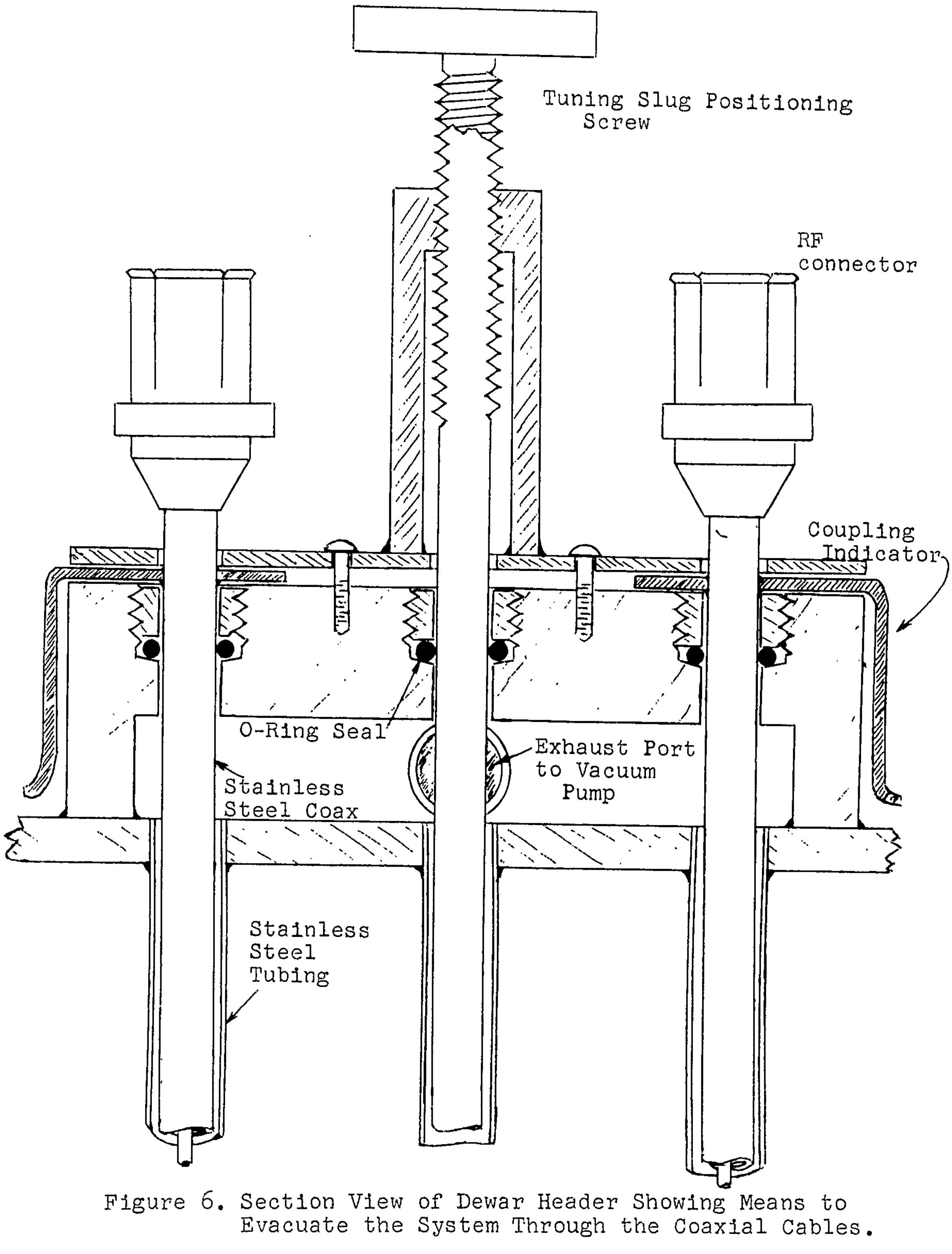


Figure 6. Section View of Dewar Header Showing Means to Evacuate the System Through the Coaxial Cables.

tubing at the shield can top to form a short path for heat to flow out of the slug to the helium bath.

4. Coating Technique

It was found that several procedures in the dipping technique previously used allowed the pure material to be contaminated. Previously the copper circuit was dipped into a pot of molten alloy heated well above its melting point. Copper was dissolved by the tin in the melt, thereby contaminating the superconductor. To achieve a smooth finish it was necessary to shake the hot circuit in the air to remove the excess metal.

The new procedure is to place the circuit in a temperature-controlled electric oven and coat the circuit with a rod of pure alloy. Zinc chloride is used as the flux. The surface is smoothed with a glass rod coated with zinc chloride. This method keeps the temperature constant at a desired value which reduced the copper contamination. The old method required several heating cycles to achieve a satisfactory surface finish, since the ability to get rid of excess metal was unreliable. The new method gets a smooth finish with only one heating. Finally a boiling solution of zinc chloride is very effective in removing trace surface oxidation at a temperature much lower than the melting point of the metal coat.

C. Performance of 21 mc. Tunable, Evacuable, Configuration

A number of identical 21 mc. tanks were made for constant-frequency tests on the lead-tin system. The first tests were conducted on 40 Sn - 60 Pb commercial solder to calibrate the equipment. Following that a 99.99$^+$% pure tin circuit, dip-coated, was tested. No evacuated tests were made due to difficulties in sealing.

1. Tuning

The tuning slug is 5/8" in diameter and can be inserted into the coil which is 1-3/8" in diameter, 2" long, and has 10 turns. Experimental results, figure 7 and 8, show the slug is capable of a 10% increase in resonant frequency. In addition, when it is almost fully retracted a second resonance may occur at the low end of the frequency range. In this mode the slug is acting capacitively which results in a higher Q.

2. 21 mc., 40 Sn - 60 Pb

Preliminary superconducting tests were made with a lead-base alloy to permit operation at atmospheric pressure. The Q was 0.2×10^6 with coupling apparently not a significant factor. The lower Pb concentration may have been the principal reason for Q not being higher. Possible contamination by copper, as discussed in a later section, may also be involved. Figure 9 is a plot of frequency as a function of slug position at 77°K and 4.2°K. Q values are noted on the curve for 4.2°K showing a 15% reduction in Q when the slug was fully extended.

TABLE 1

Amplitude of Signal Through Pure Tin Circuit versus Slug Position for Three Frequencies at Liquid Helium Temperature:
A is relative amplitude in db with constant input.
d is displacement of slug in millimeters from retracted position.

Frequency Megacycles	20.500		20.470		20.440	
	A	d	A	d	A	d
	0	19.3	20	12.5	19.5	12.5
	8	16.3	24	11.3	24	10.5
	18	13.6	32	10.0	30	9.7
	30	11.5	39.2	9.5	35	8.8
	40	11.1	40	9.0	40	7.4
	40	10.5	37.5	8.5	42	7.0
	32	10.0	30	7.5	40	5.9
	26	8.5	26	5.8	40	5.3
	22	7.3	30	3.1	42	4.4
	23	3.0	38.0	2.0	38	3.5
	30	1.3	41.0	1.7	38	2.3
	38	0.5	40.0	1.6	33	2.1
	41	0.1	33.0	.9	28.5	1.7
	40	0	26.5	0	26.7	1.3
					23	0

TABLE 2

Resonant Frequency versus Slug Position for Pure Tin Circuit

Temperature °K					
4.2°		77		300	
d(mm)	f(mc)	d	f	d	f
25.5	21.200	28.5	21.950	33.0	22.100
24.2	21.110	21.5	21.500	31.5	22.000
22.5	21.000	16.5	21.250	28	21.750
14.2	20.600	12.5	21.110	23.5	21.500
.3 & 10.5	20.500	.3 & 11.0	21.070	20.5	21.250
1.5 & 8.5	20.470	1.5 & 10.5	21.050	18.1	21.200
4.4 & 7.0	20.440	3.0 & 9.0	21.030	13.5	21.000
				11.0	20.900
				6.0	20.850
				5.7	20.800
				5.5	20.700

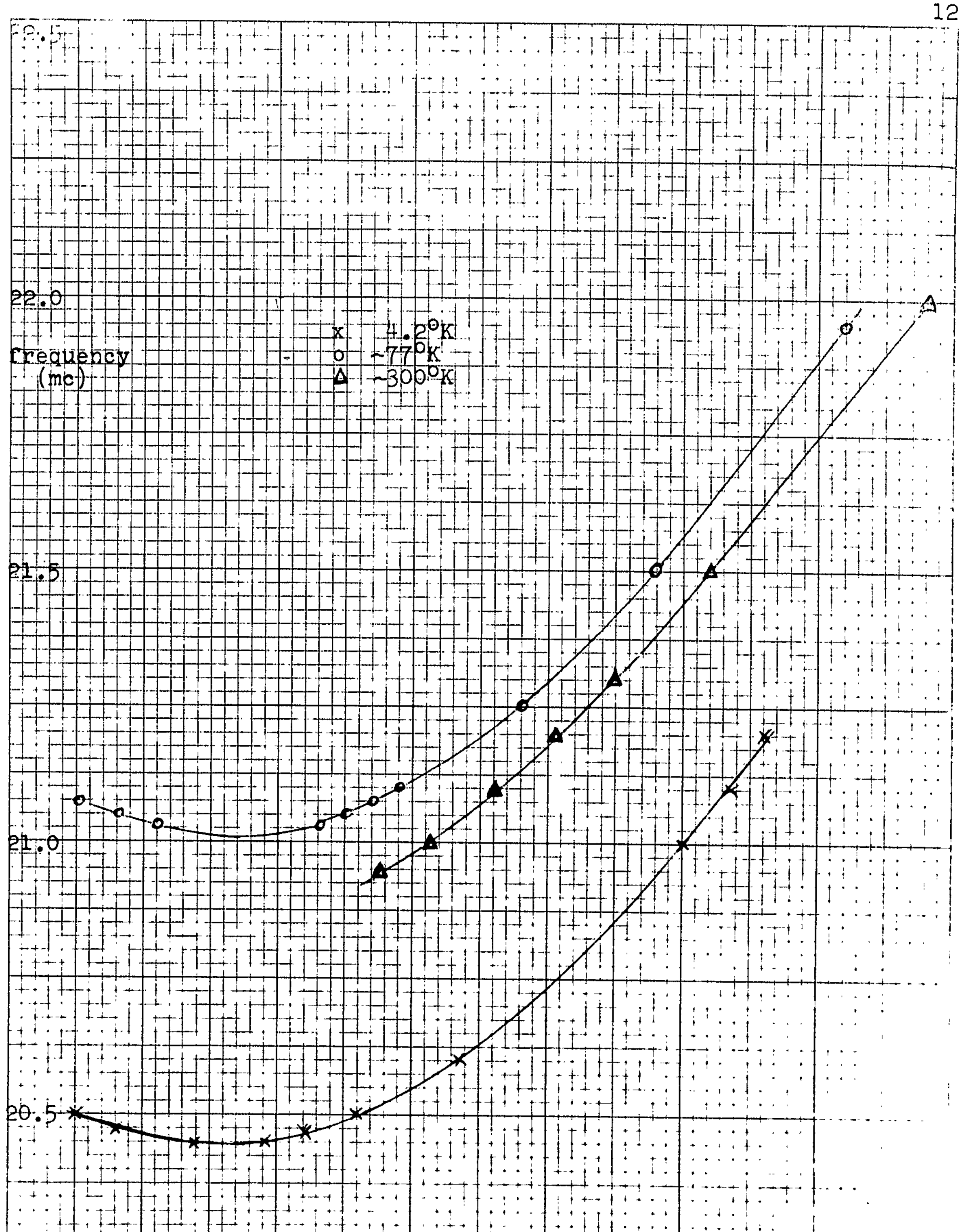


Figure 7. Resonant Frequency vs Slug Position
For Pure Tin Circuit at 3 Temperatures.

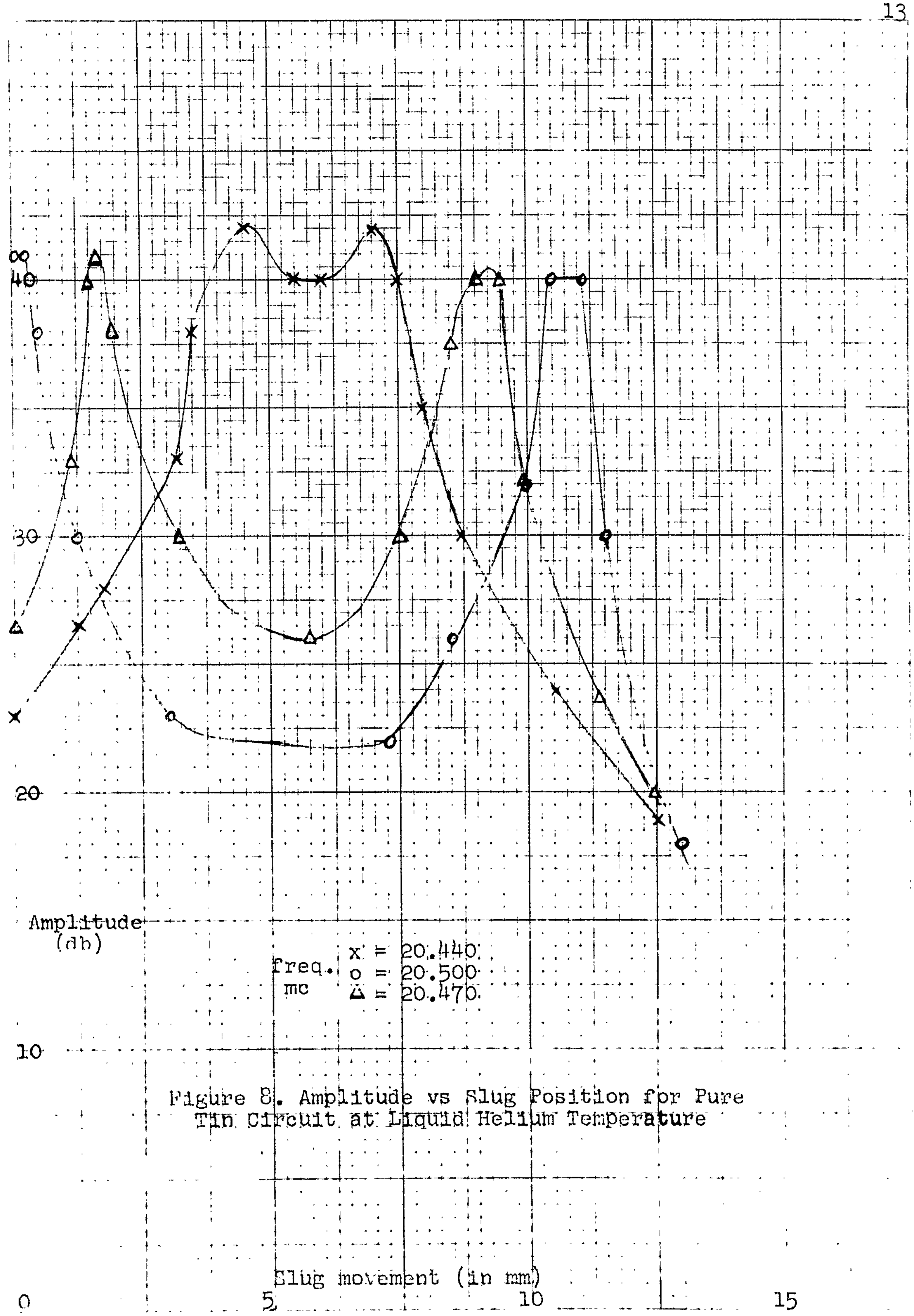


Figure 8. Amplitude vs Slug Position for Pure Tin Circuit at Liquid Helium Temperature

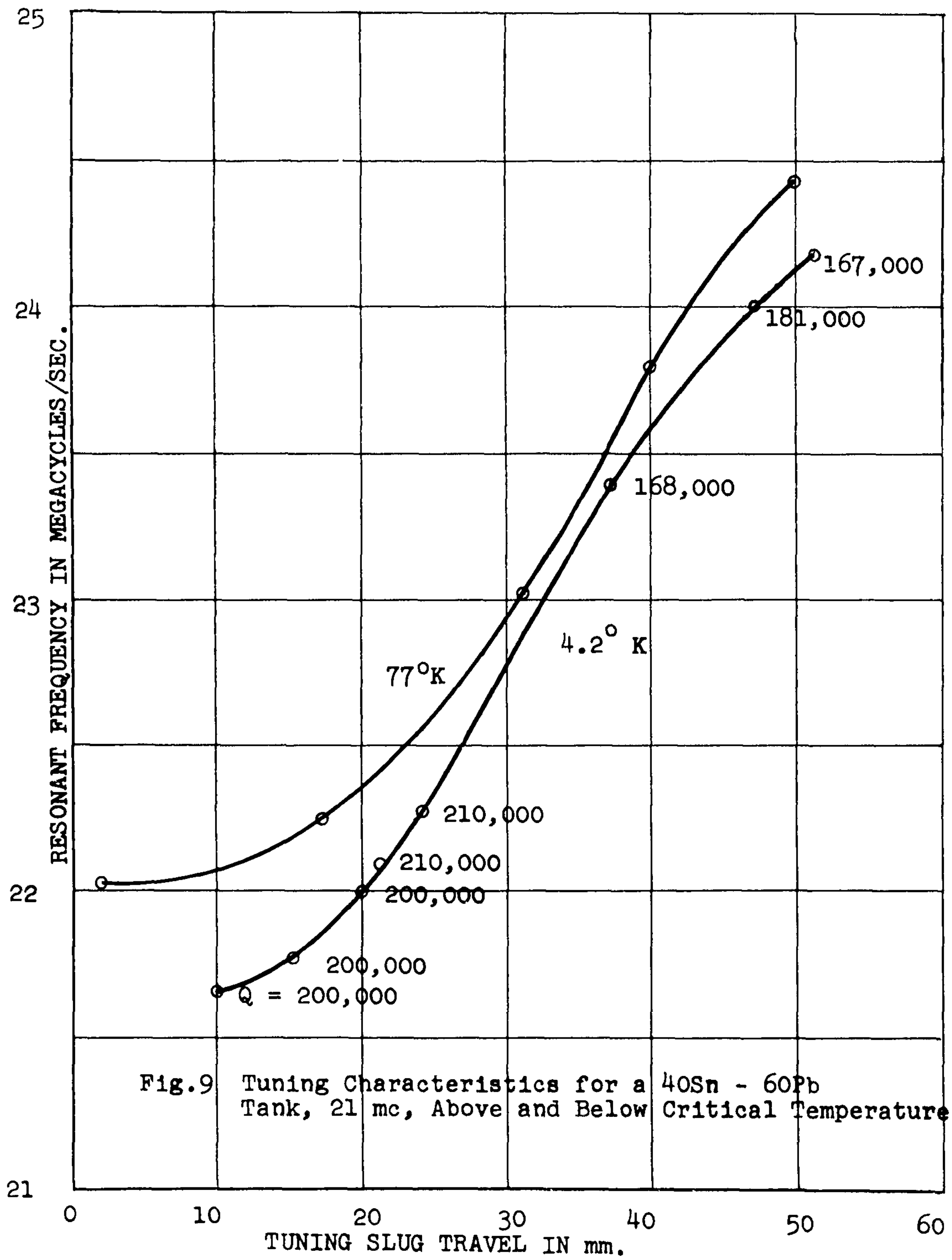


Fig.9 Tuning Characteristics for a 40Sn - 60Pb Tank, 21 mc, Above and Below Critical Temperature

3. 21 mc., Pure Tin, Evaporated Lead Shield

The shield can shown in figure 4 was coated with pure lead by evaporation in a vacuum. The losses in the shield should have been much lower and Q would be dominated by the residual resistance of Sn at a higher reduced temperature. The Q was much lower than expected. The film was suspected and a new test run with a dip-coating of 05 Sn - 95 Pb on the shield. Since no difference was observed, it was concluded the evaporated film technique was successful.

4. 21 mc., Pure Tin, 05 Sn - 95 Pb Shield

a. Figure 10 shows the residual resistance of the pure tin circuit. It is very much higher than hoped for on the basis of theory described below in section III. D. 2. While Pb - Sn alloys have been characteristically lossy, the effect was expected to be less for pure tin. A closer look at method of coating the circuit revealed a distinct possibility copper was dissolved into the tin at the temperature of molten tin. A review of previous test shows the Q dropped as the tin content increased, even though the lower frequency would have had the opposite effect.

b. Figure 11 shows the circuit Q when a DC magnetic field was applied. The temperature dropped during the test from 2.447^{o} to 2.19^{o} due to variations in the pumping rate. This is not felt to have an important influence on the results. The Q was measured at 29 values of H as it was varied from 0 to +3800 gauss then back through 0 to -5000 gauss and again

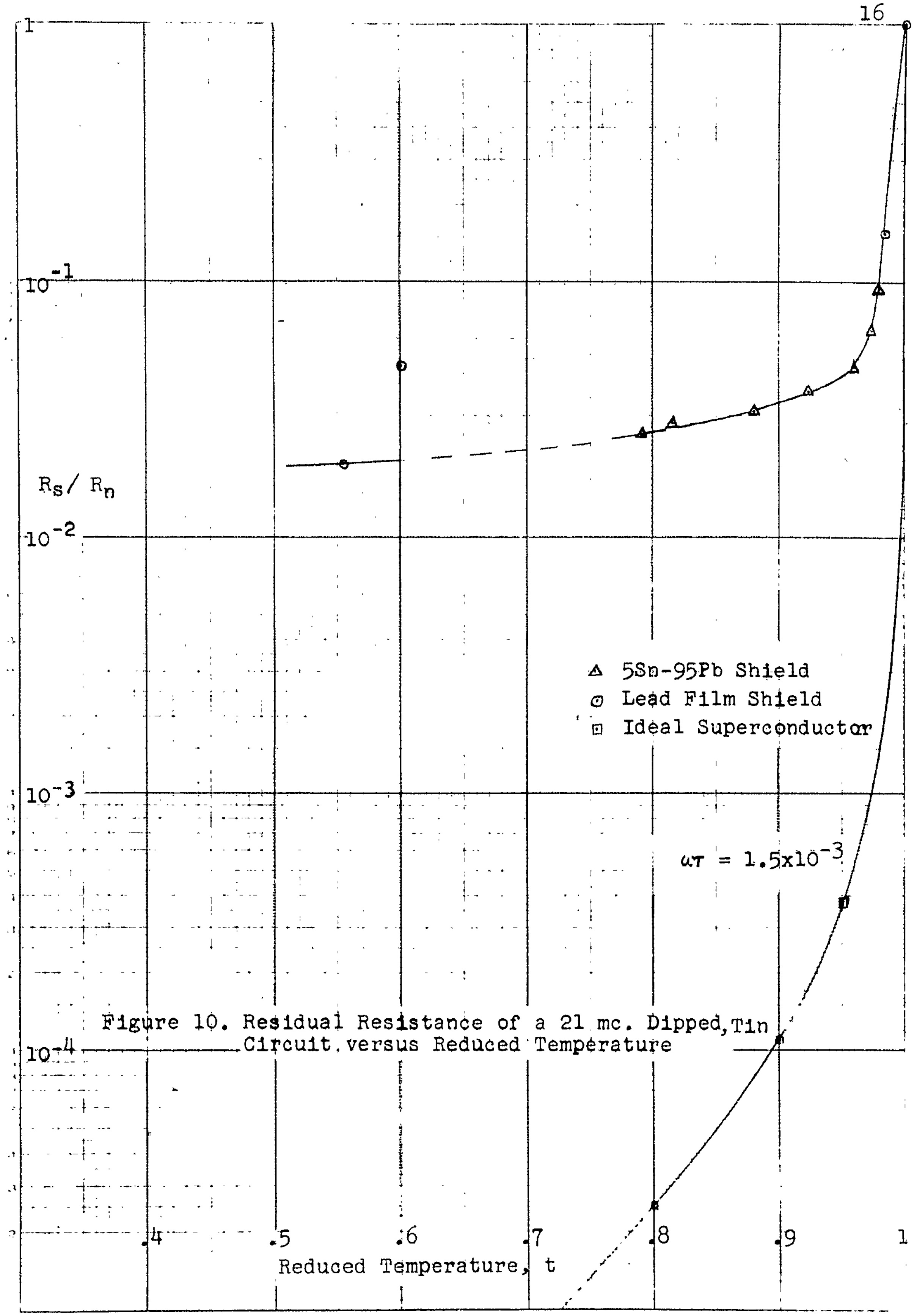


Figure 10. Residual Resistance of a 21 mc. Dipped Tin Circuit versus Reduced Temperature

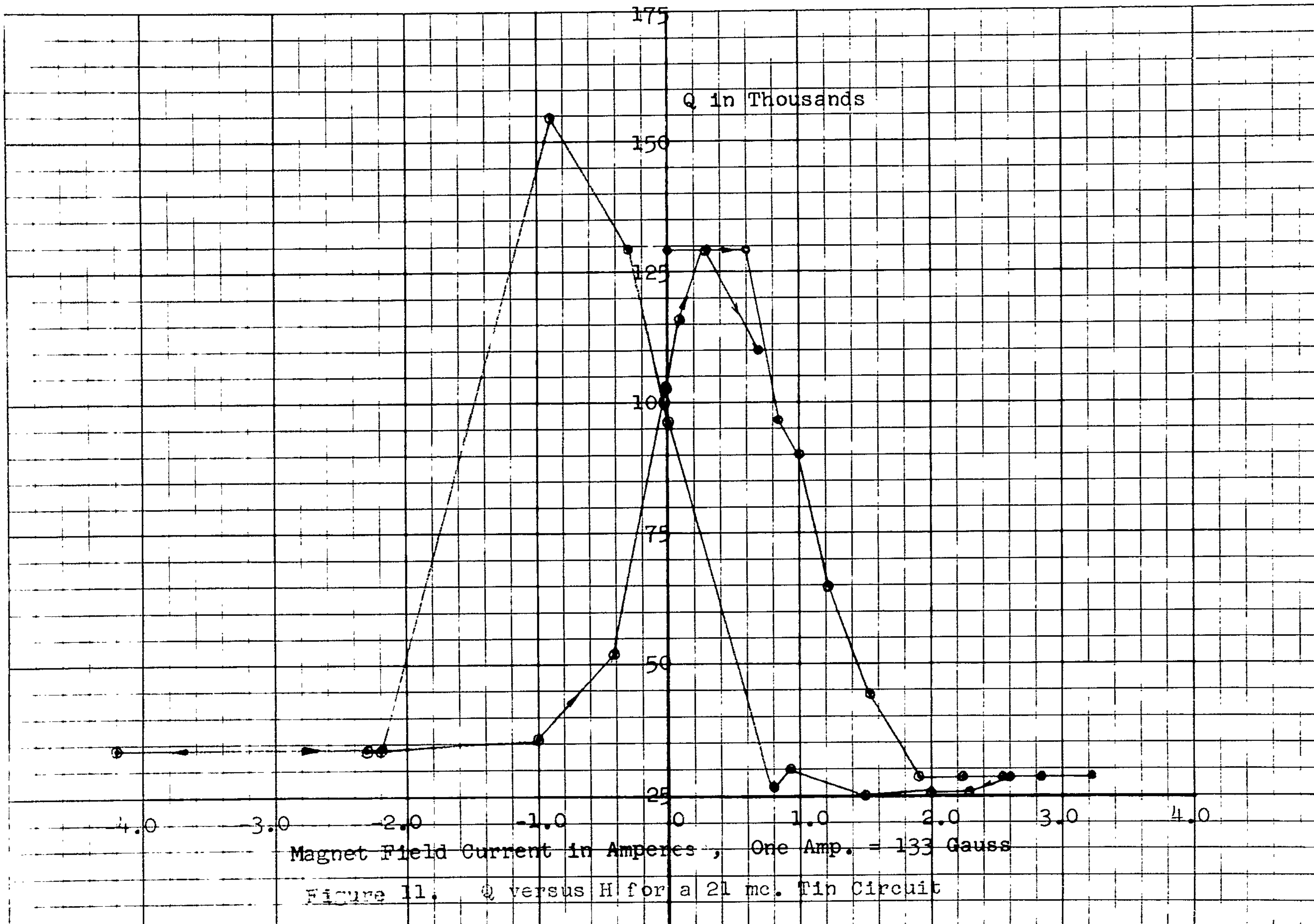


Figure 11. Q versus H for a 21 mc. Tin Circuit

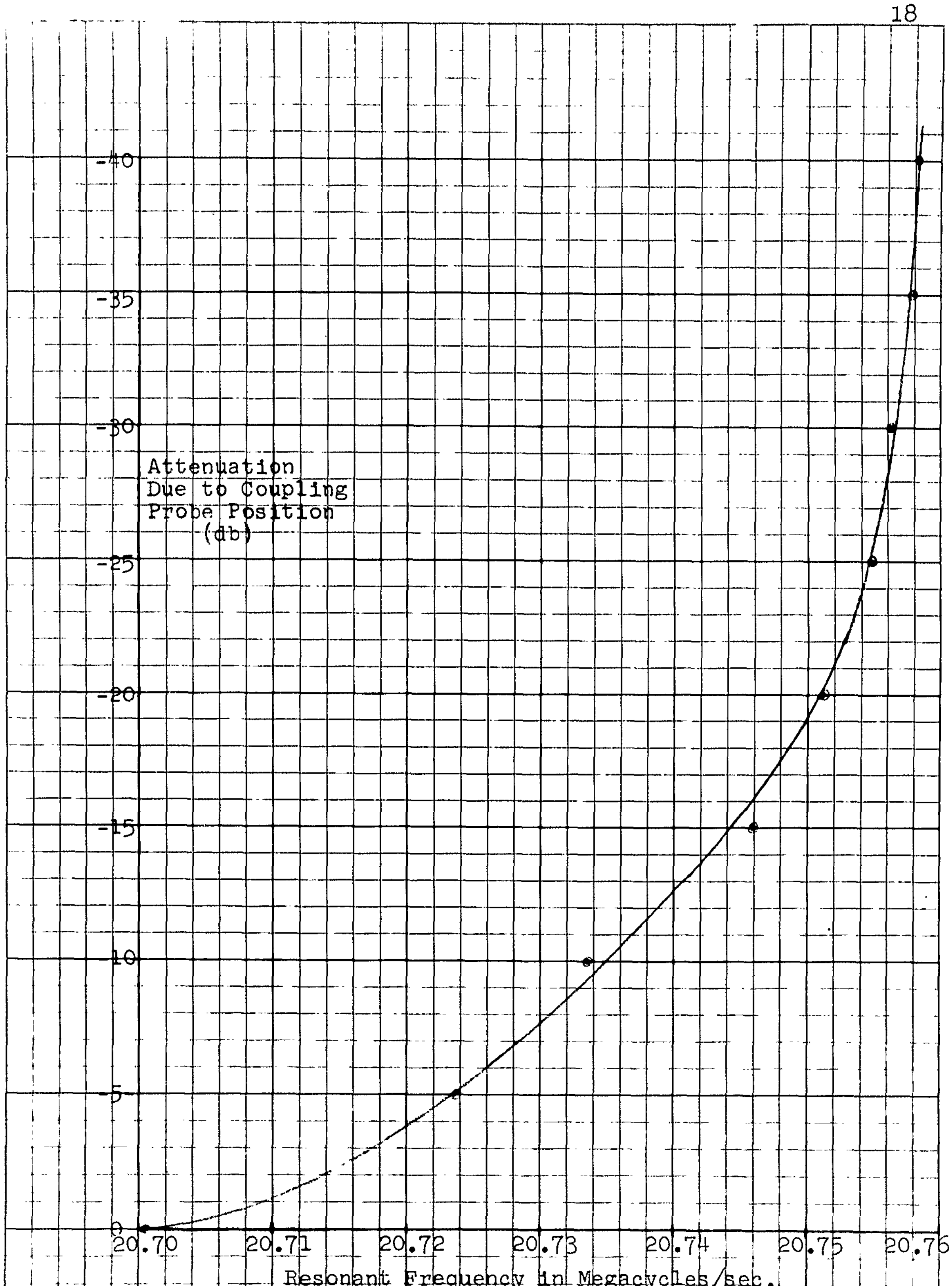


Figure 12. Coupling vs Frequency for a 21 mc. Tin Circuit at 4.2 Degrees

increased through 0 to about 900 gauss. The hysteresis effect is very strong and extends over a range much greater than the critical field for tin. The increase of Q in a reversed field over the zero-field case is very interesting and not understood at this time.

c. Figure 12 shows the coupling versus frequency relation for the 21 mc pure tin circuit at $4.2^{o}K$. No difficulty exists in interpreting this data on the same basis as described in the First Quarterly Report(2).

D. Residual Resistance

To date sufficient data and experience has been acquired to support some pertinent conclusions. Residual resistance measurements with alloys and lead show these materials followed the theoretical curve for Rs/Rn[2] for temperatures near T_c but became independent of temperature below about t = 0.9. It is felt much lower residual resistance and much higher Q can be realized. By carefully subtracting this temperature-independent asymptote the corrected curve can be made to agree with the theory for an ideal superconductor. The relaxation time used in the theory was calculated from published data on conductivity of pure lead and pure tin. The agreement may be fortuitous, although the corrected curves have the expected frequency dependence. A closer look at lead-tin alloys is now under way to permit the fundamentals fo the problem to be illuminated by a consistent series of tests. Magnetic field measurements yielded an unexpected increase in Q after the field was reversed.

1. D. C. Resistivity of the Lead-Tin System

At room temperature the resistivity of lead-tin alloys in crudely a linear relation of the relative composition, figure 13.[5,8] Below room temperature[4] the temperature dependences of pure Pb and Sn are very symmetrical above 10^oK, as shown in figure 14. Below 10^oK they become anomalous, with ρ/ρ_{273} being independent of T well above T_c for tin and somewhat below T_c for lead. The exact curve will depend heavily upon the sample and its purity. The

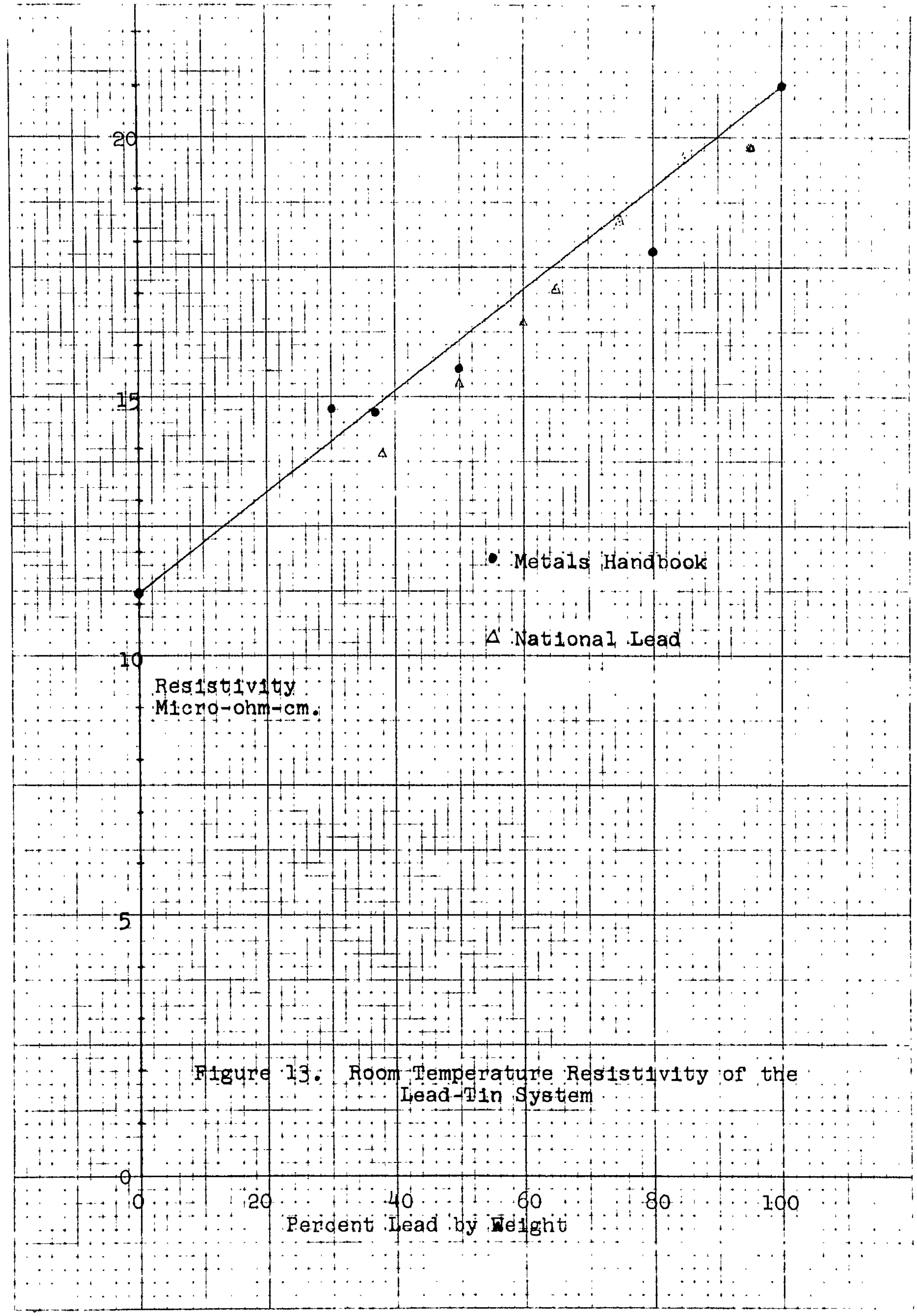


Figure 13. Room Temperature Resistivity of the Lead-Tin System

curves give no clue as to how a particular alloy might behave, but we have ample evidence they will not be ideal soft superconductors (6)(11).

The conductivity of a normal metal is

$$ {}_n = (e^2 \tau N_n/m^*) $$

as previously described. The most sensitive parameter is the relaxation time, τ, above the critical temperature, T_c. Below T_c, N_n drops rapidly as superelectrons become the dominant carriers. The function $\phi(t)$, has been taken as

$$ (N_n/N_s) = \phi(t) = (t^4/1-t^4) $$

although several references (9)(10) can be found for slightly different functions. Electronic charge is a constant. The effective mass, m*, cannot be regarded as well defined in polycrystalline materials, but is still a valid concept. More data is needed from the literature, but for the present we will assume m* is independent of temperature (except for the thermal contraction effects which will be well-behaved for all the Pb - Sn alloys) without apology. This puts all temperature variation as a measure of changes in relaxation time.

Using the values from Table 4 and the resistivity-temperature plots, figure 15 is a calculated relaxation-time versus temperature.

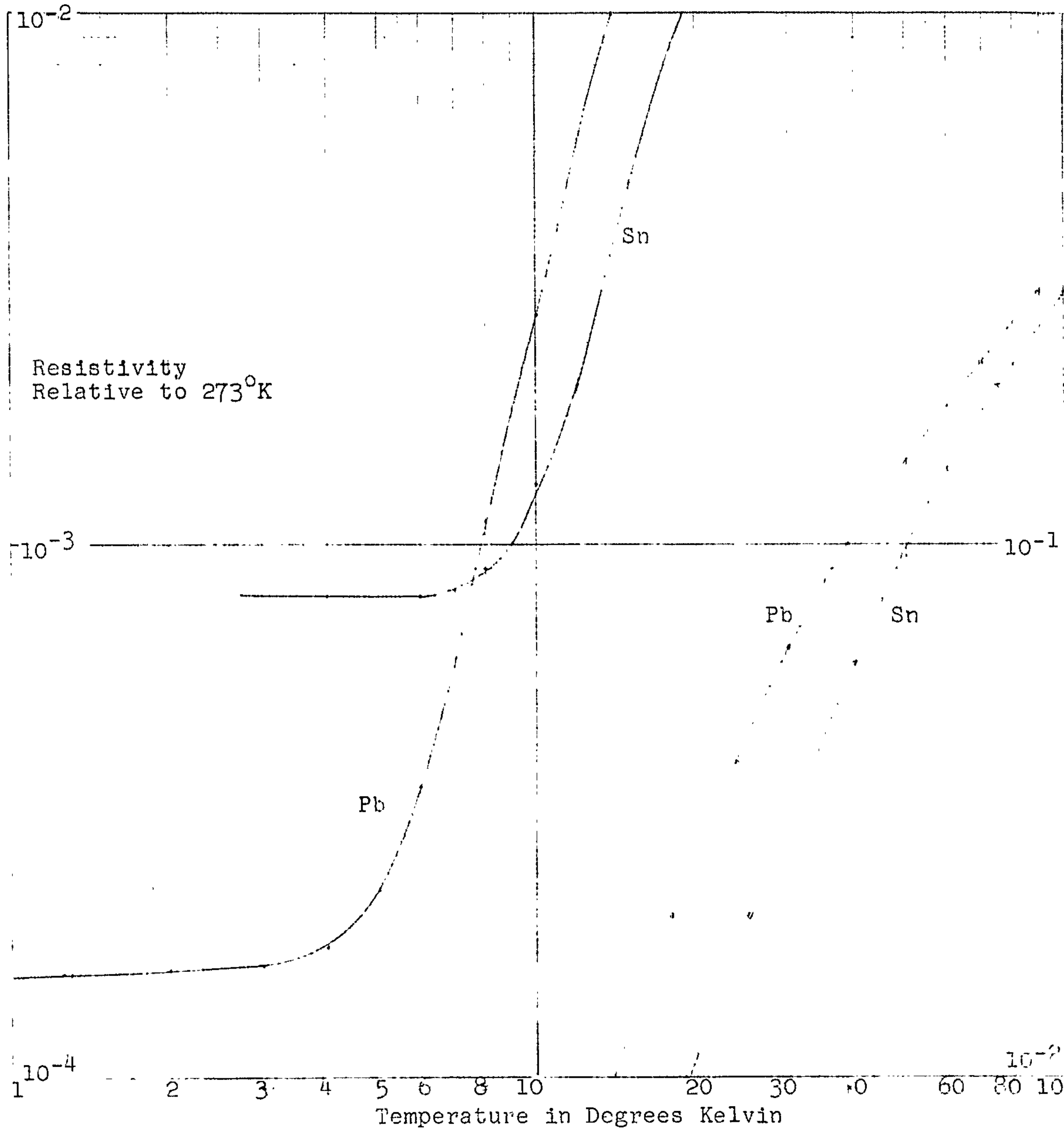


Figure 14. Low Temperature Resistivity of Lead and Tin

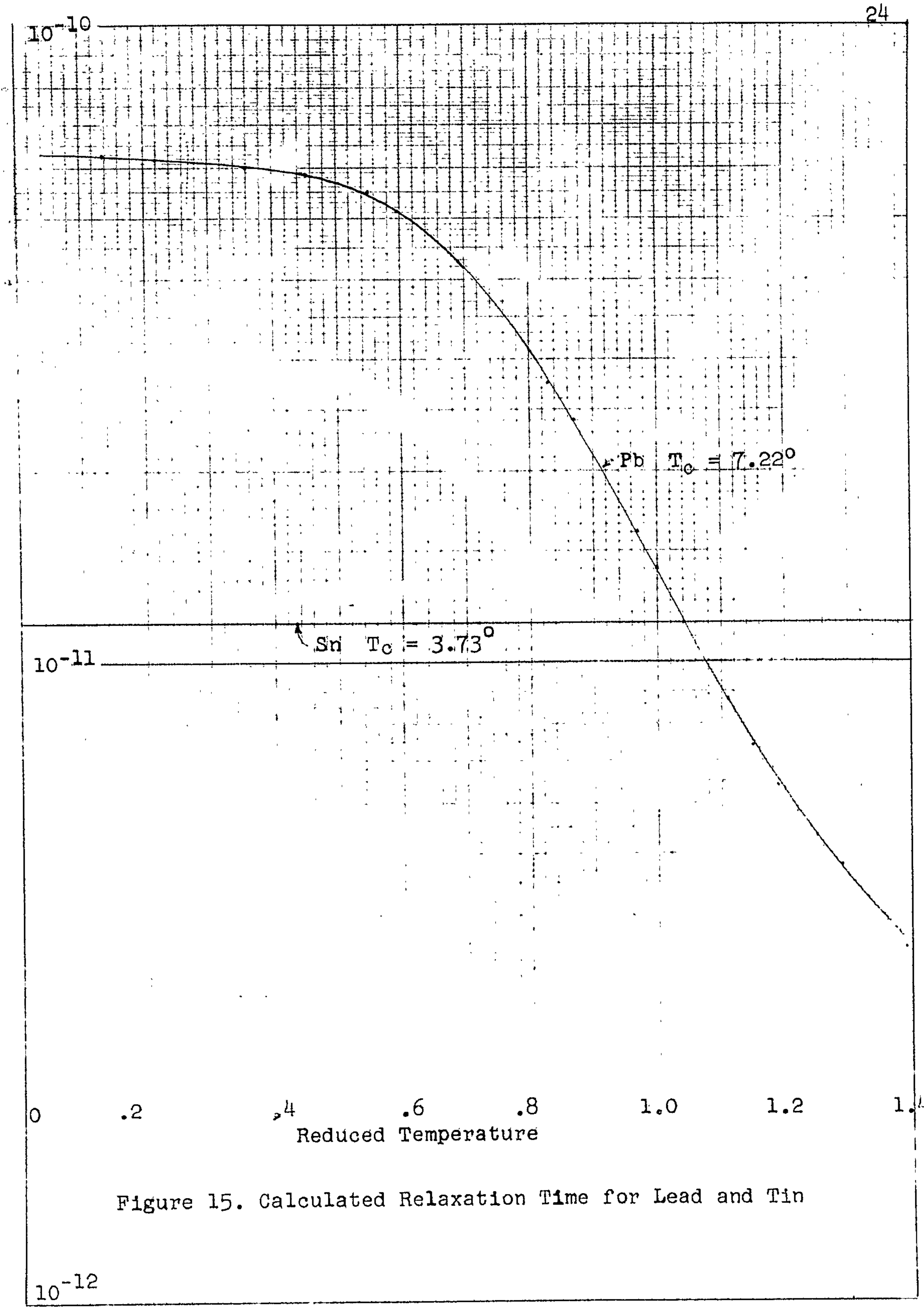


Figure 15. Calculated Relaxation Time for Lead and Tin

TABLE 4

Properties of Lead and Tin at Low Temperatures

Property	Pb	Sn	Remarks
n_e electrons/atom	1.24	1.12	R. G. Chambers
N_a atoms/cc	3.3×10^{22}	3.7×10^{22}	Metals Handbook(5)
density, gm/cc	11.34	7.298	@ 20°C
n_n, electrons/m^3	4.092×10^{28}	4.15×10^{28}	$N_n=n_eN_a\times10^6$ (MKS)
ρ_{273} ohm-meters	19.2×10^{-31}	11.15×10^{-8}	Stewart & Johnson(4)
m*/m	2.1	1.2	Kittel (7)
m* kgm	19.1×10^{-31}	10.92×10^{-31}	Stewart & Johnson(4)
T_c °K	7.22	3.73	
τ_{273} Relaxation time, sec.	9.61×10^{-15}	9.33×10^{-15}	$m^*/q^2n_{n(273)}$

2. Theoretical Rs/Rn

The residual resistance ratio has been derived as

$$Rs/Rn = \sqrt{\frac{\omega\tau\phi}{1+\omega^2\tau^2\phi^2}\left[\sqrt{1+\omega^2\tau^2\phi^2}-1\right]}$$

where no assumption has been made except the validity of the London two-fluid model. Whether $\phi(t)$ has been selected properly remains to be seen. The product $\tau\phi$ may be determined if Q_n/Q_s is measured and ω is fixed and known. As a start on this phase we have made a digital computer analysis of Rs/Rn vs $\omega\tau$ for constant values of reduced temperature, assuming $\phi(t) = t^4/(1-t^4)$. They form families of curves with an $(\omega\tau)^{3/2}$ dependence for t below about 0.95. These curves will be used to solve for τ for a given superconductor and to examine its departure from the ideal soft superconductor. All previous experiments will be examined, but the most useful information is expected to come from the study of foils described in Section E of this report.

3. Experiments on 40 Sn - 60 Pb and Pure Tin

Q measurements during the quarter were made on two 21 mc circuits as reported above. The results appear to indicate the Q is being depressed more as tin content increases. The solution of copper in tin (and lead) may have a significant effect upon the superconducting properties of lead-tin alloys. The dip-coating method may be a means to distribute copper atoms from the interfacial alloy of copper and tin to the surface particularily. If this occurs, Rs/Rn may become adversely affected, since Rn would not be greatly changed but Rs may be significantly increased.

This is an important observation since it calls attention to a factor which is separable from surface finish in determining Q_o. The presence of copper may provide a means to reduce the coherence length for superelectrons. As a first step, the use of foils will prevent contamination.

4. Magnetic Field Effects

The existence of a hysteresis effect, as shown in figure 11, and discussed in the previous section, is readily attributable to incomplete removal of persistent currents when H is restored to zero. The increase in Q when the field was reversed will have to be examined closely. It should be pointed out the increased Q was measured at a lower temperature, 2.19^{o}K, instead of 2.447^{o} when the test commenced.

E. Superconducting Foil Configuration

During the third quarter efforts to roll thin foils of lead-tin alloys on a precision rolling mill were successful. This opened the possibility of direct comparison of tin, lead, lead-tin alloys, plus niobium, vanadium, tantalum, and any other metal or alloy. The foils are relatively easy to roll and have a very smooth surface with a shiny finish. They can be cut to form a superconducitng resonant circuit using a quartz tube form.

1. Technique of Rolling Foils

Lead-tin alloy foils are desired for dc resistivity measurements and for construction of foil circuits. For the dc resistivity measurements a long thin strip is required. (See Section III. H on transition timperature measurements for more details.) For constructing a 21 mc foil circuit, a strip two inches wide and seven feet long is required.

The Oliver rolling mill, figure 16, which is used, elongates the material with very little increase in width. A piece of commercial solder 1/8" in diameter and about twelve inches long was rolled in a strip 1/4" wide, .0025" thick, and a length of over 20 feet.

The material to be rolled is prepared by weighing out the correct proportions of lead and tin for the desired composition. The lead is melted first since it has the highest melting point, then the tine is added. Zinc chloride

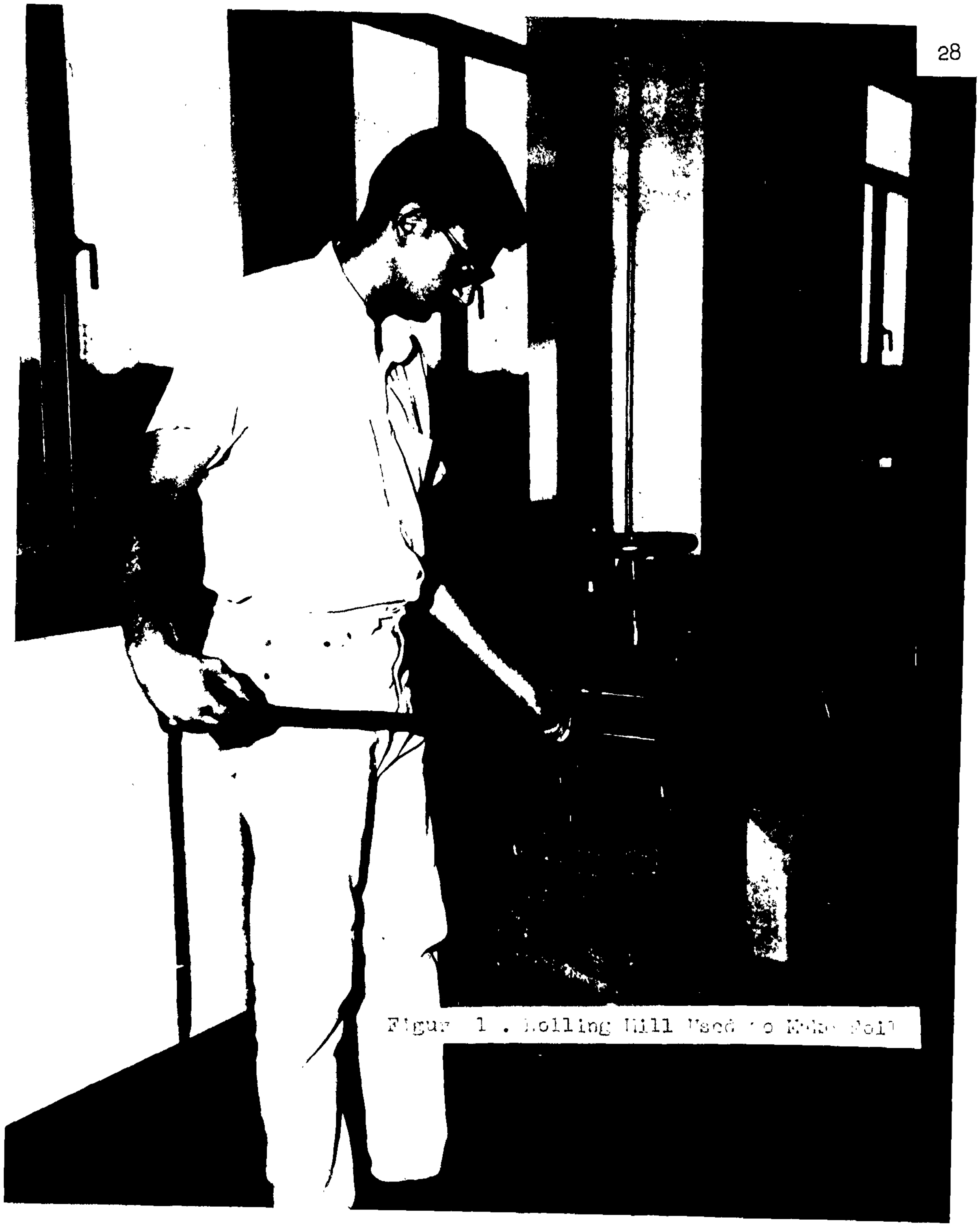


Figure 1 . Rolling Mill Used to Make Foil

had been used to keep the mixture from oxidizing. Ammonium chloride will be substituted to prevent zinc contamination at high temperatures. A pyrex test tube and stirring rod are used.

The pyrex test tube is broken off after cooling and the solder is washed to get rid of the flux. The solder is then flattened or cut by hand to the proper width since the rolling mill has little effect on the width. The rolling to final thickness takes place in several passes, the number depending on thickness and the desired final thickness. No annealing is required between passes, but low temperature annealing will be carried out before the circuit is tested.

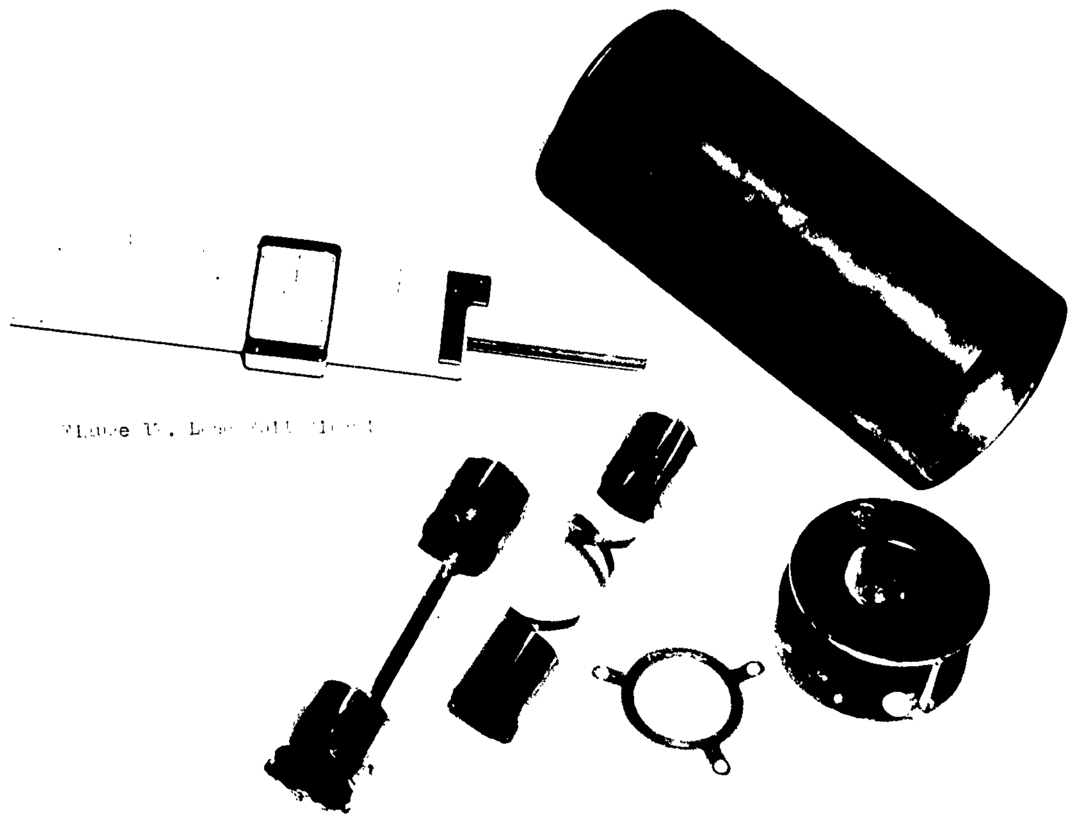
2. Construction and Use of Foil Circuits

A major effort has been put forth during the last quarter toward the development of a workable metal foil circuit. The primary objective in this area is a study of the so-called "hard" or type 2 superconductors. Preliminary tests are to be made using a "soft" superconducting foil. This will be useful in determining what, if any, drawbacks exist for this particular circuit configuration. These tests will be followed by a series of tests with niobium, tantalum, and vanadium.

A study of the properties exhibited by circuits made of "hard" superconductors is desirable for several reasons. First, it may expose a-c properties attributable only to the hard superconductors. This may, in turn, shed light upon the basic differences in the conduction processes in hard and soft superconductors. Secondly, the hard superconductors are capable of operation under very high magnetic fields. This property suggests use of superconducting resonant circuits to problems of r-f interference and other high energy level applicatons.

The circuit configuration used is that of a metallic foil wrapped on quartz tubing to form an inductor and cylindrical capacitor plates. This is shown in figure 17. The particular circuit shown here is of lead foil and is to be used in preliminary tests. A picture of the assembled circuit with the mounting bracket is given in figure 18.

A foil circuit is desirable for several reasons. The first is a result of the difficulty encountered in getting a smooth surface for the circuit. Dipping techniques are awkward and do not always provide a good surface. Also, the high melting points of the type 2 superconductors make this impractical. Electroplating may be feasible for some, but is virtually impossible for such materials as niobium. Metallic foils made from the hard superconductors are quite smooth, and the working of the material as a result of rolling enhances some superconducting properties. A second advantage is the inherent convenience of the foil circuit. The circuit consists of two continuous pieces of foil, as shown in figure 19, and may be assembled or disassembled at will. Thus the same quartz forms may be used many times and with different types of foil.



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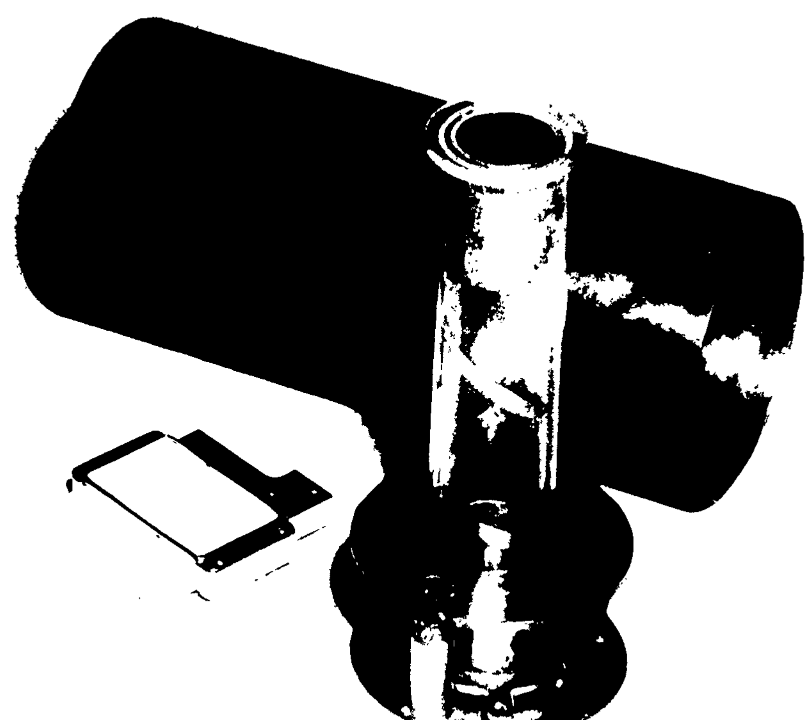

This allows the handling, by the same methods and with the same geometry, not only the hard superconductors, but all the materials investigated thus far. Another advantage lies in the study of the niobium-tin system in particular. A series of tests is planned where in both niobium and niobium-tin foils will be used. Tests on niobium will be run first, then the circuit disassembled and the foil re-acted with tin. This will allow a second test with an Nb_3Sn foil at almost exactly the geometry and frequency.

Several factors were considered in the circuit design. Quartz was chosen as a circuit base because of its very low loss tangent. This is approximately $2(10^{-4})$ at room temperature and is of the order of 10^{-6} at liquid helium temperatures. The circuit is so designed that there is no dielectric directly between the capacitor plates. The only dielectric loss will result from "end" effects where the fields will exist in a small volume of quartz. The loss here will be held to a minimum because of the low dielectric loss of quartz. A secondary advantage of quartz is its low thermal conductivity, which goes from 10^{-3} cal./cm.-^{o}K-sec. at room temperature to 10^{-4} cal./cm.-^{o}K-sec. at liquid helium temperature.

A second important feature of the design is the use of both inductive and capacitive coupling. This forces all the transmitted energy to go through the resonant circuit so there is no chance of direct feed-through. This may also simplify the problem of designing an oscillator around the circuit.

The circuit is simply constructed, and the procedure is as follows: Quartz tubes of the appropriate length and diameter are cut, and slits are made on one side in each end. The foil is then cut in the pattern as shown in figure 19 to give the desired frequency. End plates are made by cutting two concentric grooves, of the same radius and thickness as the tubes, into flat quartz plates. The foil is then wrapped on the tubes with one piece on the outside of the inner tube, and the other on the inside of the outer tube. The plates are slipped over the ends and the circuit is completed. The whole assembly is then mounted on a shield bracket as shown in figure 18. The primary function of the shield is to separate the capacitive coupling from the outer cavity. This leaves the inner cavity near ground potential and prevents the introduction of secondary modes. The circuit is fastened to the shield bracket with the use of a mounting collar held by the mounting screws.

Perhaps the most critical parts of the circuit assembly are the end plates. They must hold the quartz tube rigidly, so that the resonant frequency will not charge. These plates are grooved with a special tool on an ultrasonic grinder. A diagram of this tool is given in figure 20.

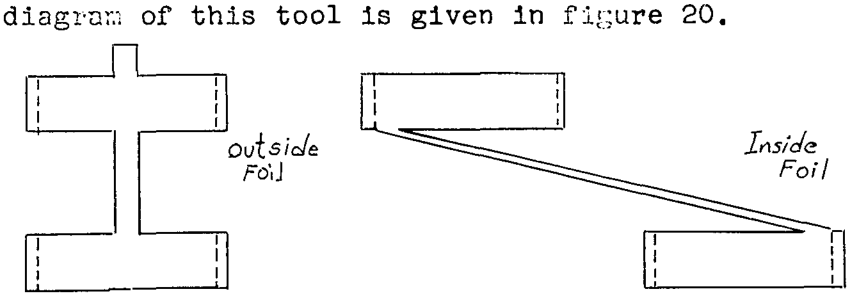

Figure 19. Foil Pattern Cut to Give Desired Frequency

Only half the groove may be formed at a time because of the relatively large grinding surface. The tool is then lifted, rotated 90°, and a second cut is made. In this way, two exactly concentric grooves are obtained. The tolerances are such that the tubes are held rigidly in position.

The circuits designed thus far have been at 171 mc, which is a considerably higher frequency than used recently. This was done to decrease the size of the foil needed for the circuit. The design of circuits in the neighborhood of 20 mc. is planned, however, in order to make full use of the measurement facilities available and permit a close comparison with dipped circuit performance.

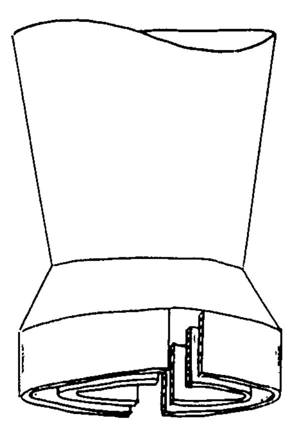

Figure 20
Ultrasonic Tool To Groove Mounting Plates

F. Oscillator Design

The design of an oscillator using a superconducting tank has proceeded along two separate paths. The impedance characteristics of the tank, associated stainless steel co-axial cables, and coupling probes are being studied theoretically. In addition an rf amplifier is being built for use in the forward loop.

The basic problem is to combine a high gain amplifier and a tank circuit which is loosely coupled. The attenuation in the feedback loop will be high due to the loose coupling.

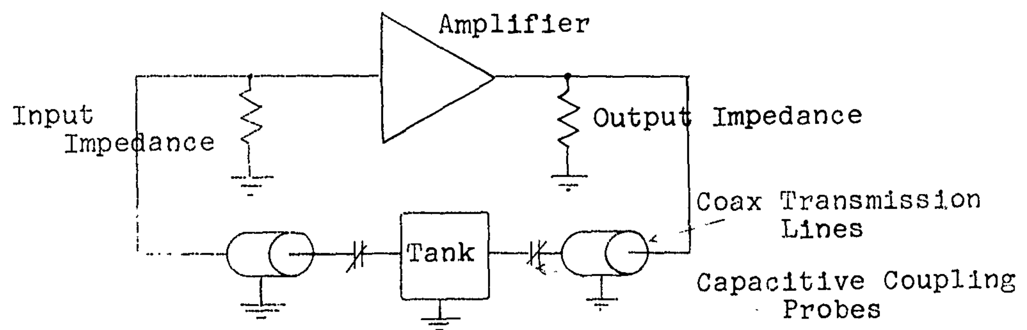

Figure 21

As a consequence the amplifier gain must exceed the attenuation. This forces a compromise on amplifier bandwidth, which in turn requires considerable effort to control phase shift introduced in the forward loop. Ideally the tank should be the dominating phase-shifting element to insure the oscillator operates at the resonant frequency of the tank and takes maximum advantage of the high Q. The schematic circuit of figure 21 is symbolic only. The optimum configuration may require only one coupling probe.

1. <u>Introduction to the Transfer Function and Impedance</u>

The superconductive tank is part of the feedback loop when combined with an amplifier to operate as an oscillator. An analysis is being carried out to evaluate the effects of the coupling probes upon the resonant frequency, frequency stability, and the amplifier characteristics. The total feedback equivalent circuit, figure 22, consists of an input probe transmission line capacitively coupled to the tank, the tank itself, and the output probe inductively coupled to the tank coil. The output probe transmission line is terminated in the input impedance R_{in} of the amplifier. The output of the amplifier is represented by its output voltage E_o and impedance R_o' connected to the input probe. Z_3, Z_2, and Z_1 are input impedances as indicated while Z_{32} are Z_{1in} are the transfer impedances of the transmission lines. R_o is the line characteristic impedance.

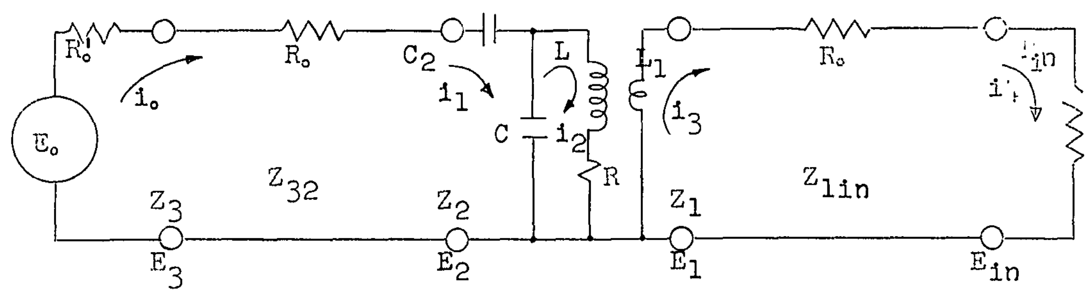

Figure 22. Equivalent Circuit of Feedback Loop

$Z_3=E_3/i_o$, $Z_{32}=E_3/i_1$, $Z_2=E_2/i_1$, $Z_1=E_1/i_3$, $Z_{1\ in}=E_1/i_4$

The feedback voltage transfer ratio $\beta = (E_{in}/E_o)$ is derived considering the transmission lines to be lossless t· simplify the derivation.

Thus, $$\beta = \frac{E_{in}}{E_o} = \frac{R_{in}}{Z_{1in}} \; \frac{MZ_1}{C\Delta} \; \frac{Z_2}{Z_{32}} \; \frac{Z_3}{R_o' + Z_3}$$

where; $$Z_{1in} = R_{in} \cos \beta l + jR_o \sin \beta l$$

$$Z_1 = R_o \frac{R_{in} \cos \beta l + jR_o \sin \beta l}{R_o \cos \beta l + jR_{in} \sin \beta l}$$

$$Z_2 = \frac{\Delta}{(R + j\omega L + \frac{1}{j\omega C})(Z_1 + j\omega L_1) + \omega^2 M^2}$$

$$Z_{32} = Z_2 \cos \beta l + jR_o \sin \beta l$$

$$Z_3 = R_o \frac{Z_o \cos \beta l + jR_o \sin \beta l}{R_o \cos \beta l + jZ_2 \sin \beta l}$$

$$\Delta = \begin{vmatrix} \frac{1}{j\omega C_s} + \frac{1}{j\omega C} & -\frac{1}{j\omega C} & 0 \\ -\frac{1}{j\omega C} & (R + j\omega L + \frac{1}{j\omega C}) & -j\omega M \\ 0 & -j\omega M & (Z_1 + j\omega L_1) \end{vmatrix}$$

After substituting and simplifying one gets:

$$\beta = \frac{MR_o{}^2R_{in}}{j\cos^2\beta l\left[R_o+jR_{in}\tan\beta l\right]\left[\left(R+j\omega L+\frac{1}{j\omega C}\right)(Z_1+j\omega L_1)+\omega^2M^2\right]\left[R_o'(R_o+jZ_2\tan\beta l)+R_o(Z_2+jR_o\tan\beta l)\right]}$$

where Z_1 and Z_2 are left as indicated. Making the following substitutions in the expressions for (E_{in}/E_o) and Z_2

$x=C_2/C$, $Q_o=\omega L/R$, $k=M/\sqrt{LL_1}$, $\omega_o{}^2=1/LC$, $y=\omega/\omega_o$, $Q_1=\omega L_1/R_1$, $Q_2=\omega L_1/R_o$

one gets:

$$\beta = \frac{j\omega R_o{}^2k\sqrt{LL_1}}{y^2\cos^2\beta l\left[R_o+jR_{in}\tan\beta l\right]\left[\left(j\frac{1}{Q_o}-1+y^{-2}\right)(Z_1+j\omega L_1)+j\omega L_1k^2\right]\left[R_o'(R_o+jZ_2\tan\beta l)+R_o(Z_2+jR_o\tan\beta l)\right]}$$

$$Z_2 = \frac{1}{j\omega Cx}\,\frac{\left[(1+x)\ (Z_1/\omega L_1)(1/Q_o)+(k^2-1)\ +y^{-2}\right]+j\left[(1+x)(1/Q_o)+(Z_1/\omega L_1)-y^{-2}(Z_1/\omega L_1)\right]}{\left[(Z_1/\omega L_1)(1/Q_o)-k^2+y^{-2}\right]+j\left[(1/Q_o)+(Z_1/\omega L_1)-y^{-2}(Z_1/\omega L_1)\right]}$$

One can examine the expressions for E_{in}/E_o and Z_2 for two cases. The first considers $R_{in}\gg 1$, hence $Z_1 = (-jR_o/\tan\beta l)$. Considering Z_2 to be very large in the vicinity of resonance simplifies the denominator of E_{in}/E_o in both cases. The second case considers $R_{in} = R_o$ and thereby $Z_1 = R_o$.

<u>First</u> <u>Case</u> R_{in} large, Z_2 large, $Z_1 = (-jR_o/\tan\beta l)$

$$\beta = \frac{\omega R_o^2 k\sqrt{LL_1}}{jZ_2 y^2 \sin\beta l \cos\beta l\left[\, j(1/Q_o)-1+y^2 \;\; -(R_o/\tan\beta l)+\omega L_1 \; +\omega L_1 k^2\right]\left[jR_o'\tan\beta l+R_o\right]}$$

$$Z_2 = \frac{1}{j\omega Cx}\;\frac{\left[(1+x)(-jR_o/\omega L_1 Q_o)+(k^2-1)\tan\beta l+y^{-2}\tan\beta l\right]+j\left[(1+x)\left(\frac{1}{Q_o}\tan\beta l-j(1/Q_1)\right)+j/(Q_2 y^2)\right]}{\left[-(j/Q_2Q_o)-k^2\tan\beta l+y^{-2}\tan\beta l\right]+j\left[(1/Q_o)\tan\beta l-j/Q_1+j/(Q_2y^2)\right]}$$

<u>Second</u> <u>Case</u> $R_{in} = R_o$, Z_2 large, $Z_1 = R_o$

$$\beta = \frac{j\omega R_o^2 k\sqrt{LL_1}}{Z_2 y^2\cos^2\beta l\left[1+j\tan\beta l\right]\left[\left(j(1/Q_o)-1+y^{-2}\right)(R_o+j\omega L_1)+j\omega L_1 k^2\right]\left[R_o+jR_o'\tan\beta l\right]}$$

$$Z_2 = \frac{1}{j\omega Cx}\;\frac{\left[(1+x)\left((1/Q_2Q_o)+k^2-1\right)+y^{-2}\right]+j\left[(1+x)\left((1/Q_o)+(1/Q_2)\right)-(1/Q_2y^2)\right]}{\left[(1/Q_2Q_o)-k^2+y^{-2}\right]+j\left[(1/Q_o)+(1/Q_2)-(1/Q_2y^2)\right]}$$

At this point one can examine $\beta = |\beta|\underline{/\phi}$ as a function of ω, Q_o, k and x. A look at the rate of change of $|\beta|$ with respect to these variable can yield much design information. The same thing goes for ϕ, the phase angle, since $d\phi/d\omega$ is a measure of the stability of the system. The frequency stability S_f is, in fact, defined by the relation $S_f = \omega_o(d\phi/d\omega)$ where ω_o is the main frequency of the oscillator.

2. RF Amplifier

The circuit shown in figure 23 is that of two-tube cascode rf amplifier. It is unique in that band switching has been added. This type of circuit is extremely stable and uncritical in adjustment. At 50 mc and higher its overall gain is equal to the best single stage pentode amplifier and its noise figure is much lower. In addition the new nuvistor tube is used, which, from manufacturers figures, is capable of a noise figure improvement of from 2 to 4 db over conventional tube types.

Neutralization is accomplished by the neutralizing coils which resonate at the signal frequency with the grid-plate capacitance which is approximately 4 pf for the 6cw4. The value of the inductance is not at all critical and may be eliminated without having the stage oscillate. However, by including it, a much better noise figure is possible.

The major problem encountered was solely a construction problem. However, at this time the amplifier has not been tested, therefore additional problems may be anticipated. The gain of the amplifier must be sufficient to counter the losses in the band switching network, in addition to other losses in the feedback loop. Although conventional wafer switches are used it is felt the losses introduced will not be too much higher than if specialized switches had been used.

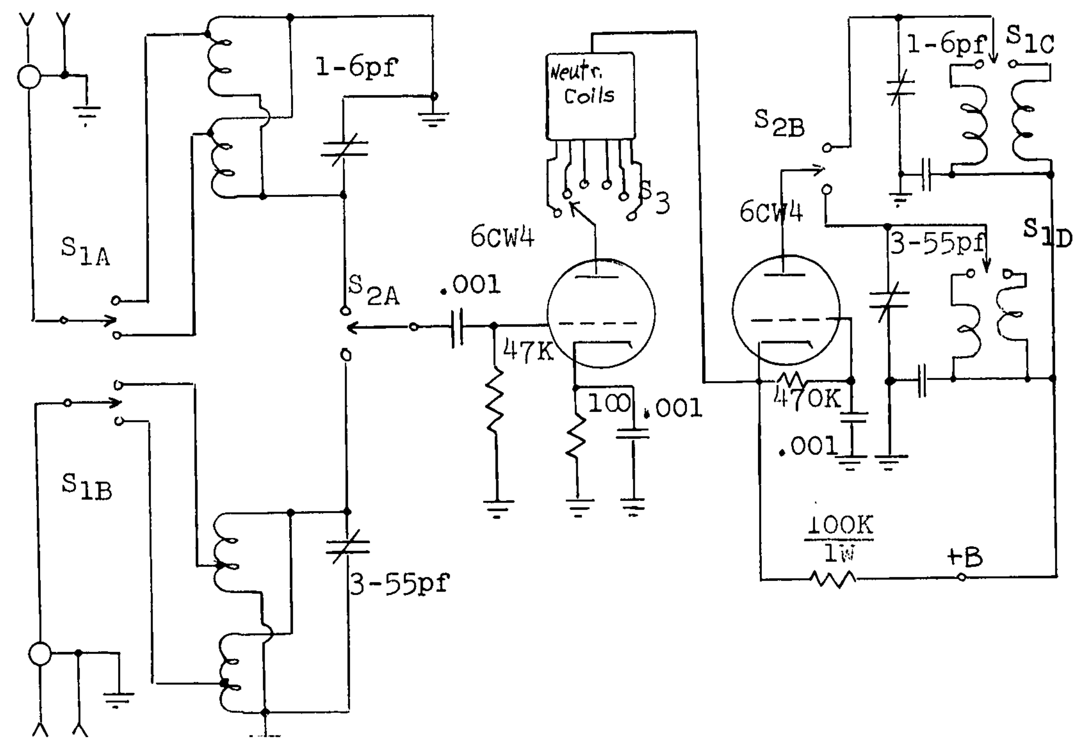

Figure 23

Two Tube Cascode RF Amplifier Circuit Diagram

G. Thin Film Circuit Fabrication

The purpose of the activity has been to develop a lead film tank circuit resonant at about 175 mc. The circuit was to be made on concentric glass or quartz cylinders; two capacitor plates joined by an inductor on the outside of the inner cylinder, and two matching capacitor plates, in series, on the inside of the outer one. It would duplicate the foil circuit configuration very closely.

To date efforts have been limited to developing the technique without particular regard to its precise circuit configuration, resonant frequency, or film thickness. These studies lie in two main areas; developing suitable means for masking the cylinders; and, developing techniques for depositing a uniform lead film in three dimensions.

The first area has proven a difficult one. Fairly satisfactory results are being obtained using a brass mask on the inside of the outer glass cylinder. "Scotch" tape on the outside of the inner one has not been impressive.

A rectangular brass sheet is bent into the form of a cylinder, of diameter slightly greater than the outer glass cylinder, with edges folded inward leaving a "slot." These edges allow the mask to be pinched together with long-nosed pliers (the resulting diameter of the cylindrical mask is slightly less than the glass cylinder) and inserted into the glass cylinder. When the pliers are released the mask springs open holding it in place, and leaving a narrow strip exposed for depositing which joins the capacitor at each end.

After depositing, the mask can be pinched together and carefully removed without damaging the deposited capacitor plates. When the mask is in place the entire cylinder is wrapped in aluminum foil, leaving the ends open, so no depositing will take place on the outside of the cylinder.

The inner cylinder is completely wrapped with "Scotch" tape and the ends are sealed. This insures no depositing will occur on the inside of this cylinder. The circuit pattern is drawn on the tape and cut out with a razor blade. The areas to be covered with lead film are peeled away exposing the glass underneath.

The second major area of investigation has been the depositing of the film itself. Nickel wire coated with pure lead is used as a material source. A suitable length of this wire is bent into a spiral somewhat larger in diameter than the inner masked cylinder and of approximately the same length. One end of this spiral becomes an electrical connection and the other continues in a straight segment long enough to pass through the middle of the outer glass cylinder. The inner masked cylinder is placed on end on a platform within the evaporator and the spiral is fashioned about it. The outer cylinder is placed on its side and the straight segment of the nickel-lead wire is passed through its center. The wire is heated only slightly at first, to out-gas it, and as soon as the pressure has again dropped to the desired value of about 2×10^{-6} mm it is heated to a dull orange glow for approximately five to ten seconds. This requires about ten amperes current.

Difficulty has been encountered with slight bits of gum from the tape adhering to the glass cylinder both during peeling of the mask from the area to be film covered, and during removal of the mask after evaporating has taken place. This effect is slight one time, severe another, and appears not to be a function of the technique with which the tape is applied. No satisfactory means, such as a solvent, has been discovered for removing this gum without also damaging either the mask before, or the film after, depositing has taken place. For this reason a new masking technique is to be investigated. A mask of paper or foil is to be constructed and wrapped around the inner glass cylinder for the inductor-capacitor portion of the circuit. This technique was tried and abandoned previously because no satisfactory method of making the mask adhere to the glass was discovered. It is hoped that using small bits of double coated "Scotch" tape will achieve this aim. The brass mask appears to be quite satisfactory, however.

Most of the basic problems appear to either be solved or have a solution in sight. Next, film thickness and circuit configuration for the desired resonant frequency will be investigated, so that models for actual testing may be produced.

H. Transition Temperature Measurements

Previous measurements of Q versus temperature for lead-tin alloys revealed no discontinuity in properties on either side of the transition temperature of tin. It is desirable to know the transition temperature of the lead-tin alloys as a function of composition. While information has been scarce in the literature one expects a reasonably continuous curve from 7.2^{o} to 3.73^{o}.

With the simple circuit shown below, figure 24, the voltage across a sample and the current through the sample can be measured.

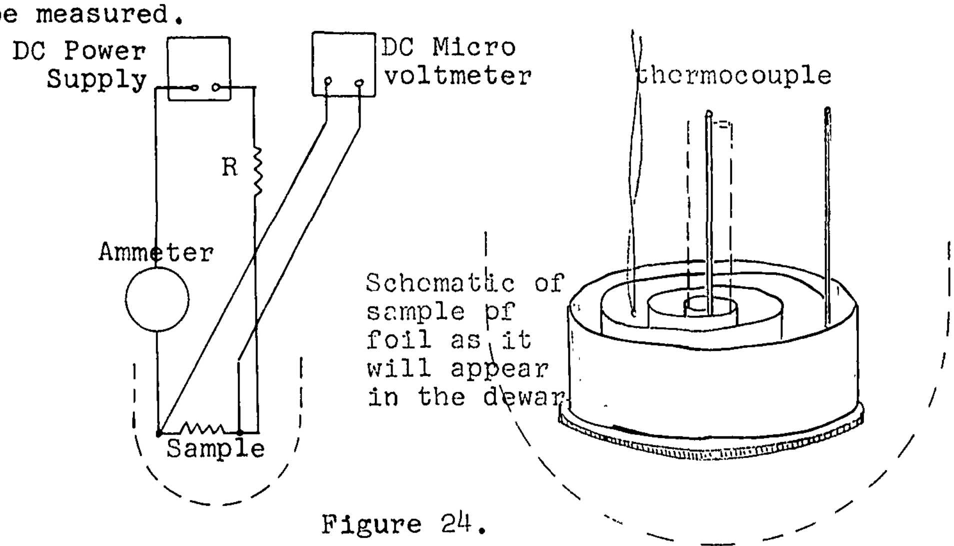

Figure 24.

This design makes it possible to measure the transition temperature and the dc resistance of the test sample. From this data it is possible to plot a relative resistivity versus temperature curve. The effect of current density can be determined by changing the amount of current with the variable resistor, magnetic field transitions and magnetoresistance effects can also be measured.

To enable an accurate reading of voltage with the microvoltmeter it is necessary to have large enough resistance to measure. From the dc resistivity curves[4] (of lead and tin) the room temperature resistance of fifty ohms would decrease to a normal resistance of approximately 0.005 ohms at liquid helium temperature. With a current of only ten milliamperes, this would be a voltage of fifty microvolts which is easily read on the microvolt meter.

This experiment has been in the planning stages during the third quarter. The problem still be to solved is obtaining satisfactory temperature variation and simultaneously having a uniform temperature throughout the sample. The sample will be a thin ribbon of the metal with a transparent tape on a glass spool. Thermocouples will be imbedded at several points to obtain information on temperature uniformity.

IV. CONCLUSIONS AND RECOMMENDATIONS

Development of the foil circuit configuration has been carried out in a very brief time and has several advantages over dipping, bulk, and film techniques. Identical circuits can be quickly assembled from all the superconductors of interest at low cost. This permits an accurate comparison of the properties of these metals as a function of frequency, temperature, and magnetic field. Their surface finish will have uniform high quality. Sources of contamination are reduced since the foil will not be exposed to elevated temperatures as the dipped circuits are.

Film techniques have been successful as far as they have been tested. Additional information has to be obtained on the loss tangent of quartz. If $\tan\delta$ is less than 10^{-6}, evaporated film circuits on quartz substrates should be very satisfactory frequency control devices. Foil circuits can be used as models for a wide variety of metals and alloys. Thin film tanks of hard superconductors or alloys would require a great deal of development effort. Many laboratories are working on Niobium thin films in two dimensions using exploding wire and electron beam techniques with limited success. Before starting such a program it should be studied with foils first.

The use of an external magnetic field to modulate Q is bounded by the hysteresis effect. No way to "start over" is known other than raising temperature above T_c. This cannot be done quickly except with tantalum circuits. The critical temperature for Ta is 4.4°K which is obtainable at a slightly elevated pressure, about 1.25 atmospheres. Tantalum circuits should be studied carefully from this point of view. Superconductors with T_c less than 5°K are all potentially useful in this application. Helium will not remain liquid above about 5.19°K or under pressure of about 2.25 atm.

Residual resistance can now be studied in detail. The contributing factors can be separated, identified, and measured. Continued work on a larger variety of superconductors will show which is best suited for a particular application. In addition, considerable basic physical data on metals will become available.

The scope of the project should be enlarged to maintain an adequate pace. The widespread use of superconducting resonant circuits cannot be confidently predicted at this writing. When a lower cost, closed cycle, cryogenic refrigerator is developed, however, the inherent advantages of superconductivity will be enhanced. Several companies are pressing this development. Their representatives are very confident there will be substantial reduction in refrigerator size and cost in the next few years. As this takes place the interest in superconductive resonant circuit theory and practise will grow rapidly. The efforts of this project will be more clearly defined to anticipate earliest possible use of research results while maintaining a steady flow of new basic knowledge. An increase in the size of the project appears warranted in the near future.

V. PROGRAM FOR THE FOURTH QUARTER

During the fourth quarter experiments will continue. We anticipate more definite information concerning the most suitable superconductor and its fabrication in a resonant configuration. This will include the measurement of Q and frequency measured at 21 and 171 mc. for lead, lead-tin alloys, tin, niobium, tantalum, and vandium in foil form. Lead and tin circuits in thin-film form having the same configuration will be included.

Application studies will begin with incorporation of a superconductor tank in an oscillator using a nuvistor amplifier in the forward loop operating at room temperature. This program will supply design data for a tunable oscillator using a superconductive resonant circuit lightly coupled to preserve a high loaded Q. Effects of a magnetic field can be investigated in tests incorporating the circuits described above.

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Report No. 3 (Third Quarterly Report), 1 January 1963 to 31 March 1963, 52 pp., 24 Illus., Signal Corps Contract DA-36-039 AMC-00036(E), Unclassified Report.

During the third quarter an active experimental program began at 21 mc. with tunable circuits capable of being operated immersed or evacuated. Extensive tests were made with commercial 40Sn-60Pb alloy circuits to calibrate the experiment. An identical circuit coated with pure tin having a 5Sn-95Pb shield can was tested for the effects of temperature and magnetic field upon Q and resonant frequency. Residual resistance was higher than expected. A tuning slug resulted in a three fold drop in Q when fully extended.

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