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CONTRACTING ORGANIZATION: TETRAD Corporation
Englewood, Colorado 80112

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13. ABSTRACT *(Maximum 200*

The feasibility of building small ultrasound imaging arrays with integrated electronics was explored. These arrays can be used to build laparoscopic, articulated, ultrasound imaging probes for use at forward military surgical locations or in emergency rooms and surgical suites. To achieve this goal, the critical items required are active multiplexer electronics and a multilayer interconnect means which provides for mounting and connection of 128 individual array elements to the imaging system console via a reduced number of signal channels. Methods for making the required interconnect structure were evaluated and evaluation of the overall package with respect to acoustic and thermal performance was performed. The outcome of this research indicates that it is possible to build light weight, articulated intraoperative and emergency surgery probes for use in forward surgical facilities or in field hospitals. Ultrasound imaging in these locations will guide emergency care by identification of bleeding and internal damage while simultaneously reducing surgical exploration. Ultimately, the military gains a new tool which can be used at forward surgery locations or field hospitals to perform quick exploration of wound sites and internal bleeding. Private sector surgeons gain a small, flexible means to guide minimally invasive surgery and therapy.

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Clyde S Alley — 1/22/97

Principal Investigator's Signature — Date

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INTRODUCTION:

This SBIR Contract was focused upon demonstrating the feasibility of building a small ultrasound imaging probe which incorporates integrated electronics. By using integrated electronics and the packaging techniques generally associated with hybrid circuits, the cost and size of the imaging probe will be significantly reduced over currently available devices. These improvements will enable small rugged, high performance, imaging arrays to be built which can be used in forward military surgical locations or in hospital emergency rooms and surgical suites. To achieve these goals, the critical item required is an active multiplexer circuit (MUX) and a means for mounting and connecting the MUX to the 128 internal array elements and the external signal channels. The work performed demonstrated the feasibility of the proposed approach by building a mock-up or prototype of the design. The outcome of this project enables small (5mm diameter) articulated (bendable) surgical ultrasound imaging probes to be built.

EXPERIMENTAL METHODS AND RESULTS OF PHASE I WORK:

The technical objective of the Phase I work was to develop and demonstrate a manufacturable design for an articulated (i.e., bendable) 10 MHz, 128 element acoustic array module with the following properties:

1. An overall package dimensions of 5 mm for use as a laparoscopic imaging probe;
2. A multiplexer integrated into the acoustic module which will allow a probe with many elements (e.g. 128) to be connected to the imaging system via a reduced number of signal leads (e.g. 32);
3. An array with a high level of performance of small enough dimensions to allow the multiplexer to be placed on top of the array stack;
4. Low enough power dissipation and sufficient heat sinking to keep the external temperature of the probe below 41°C under normal invasive imaging conditions.

All of these technical objects were addressed and feasibility was established during the course of the Phase I research program. The research conducted and the results obtained are summarized below and it is felt that the technical feasibility of achieving a fully functional prototype in a Phase II will be high (greater than 90%).

This work was motivated by the fact that the 5 mm cannula is very widely used in laparoscopic surgery. Its use is preferred since the surgical site can be closed with minimal trauma or scarring. The development of a miniature ultrasound probe for use through an opening of 5 mm in diameter could therefore meet the needs of the majority of laparoscopic surgery being performed today and could also enable the new procedures of tomorrow (e.g., guidance of ablative or surgical therapies), exploration of natural body channels, and use in cosmetic sensitive procedures (Ob/Gyn).

The research conducted during the Phase I portion of this project was aimed at evaluating the feasibility of building a 5 mm miniature probe by performing a detailed evaluation of the following issues:

1. Specification of MUX size and electrical performance.
2. Acoustic performance of an array in a small package as well as the effect of MUX electrical properties on array performance.
3. Mechanical packaging issues
4. Heat control and dissipation

Mux Evaluations:

A review of commercially available MUX chips suitable for use with an ultrasound imaging array was completed early in the project. For switching of the transmit voltage usually used in ultrasound imaging, the MUX must be able to operate at moderately high voltage levels (30-45 volts). While there are many vendors of MUX chips for voltages less than 20 volts, there are very few vendors for the range of 20-50 volts. Two vendors were identified who supply high voltage MUXes which can switch up to 100 volts: AT&T and Supertex. Evaluation of the AT&T chip was performed by our TRP partner (Siemens) and this device was found to be unsatisfactory for the low-noise application of ultrasound imaging. TETRAD conducted an evaluation of the Supertex HV202 and has found it to be satisfactory, however, the smallest available package (4.1 x 4.6 mm) is too big to fit in the 5mm laparoscopic probe package. The commercially available HV202 has the following summary specifications:

8 channels / MUX
200 V max voltage
25 Ohms ON-resistance

Using the HV202, the area required for 128 active channels was estimated to be approximately 310 mm^2. This is approximately twice the area which was estimated to be available in the 5mm acoustic module with the element pitch of 0.2 mm required for high frequency imaging.

Tetrad obtained from Supertex guidelines on the tradeoff which can be made among, area, ON-resistance, voltage, and the number of channels per chip in a realizable custom MUX circuit. Using these guidelines, TETRAD has developed specifications for a custom MUX chip which will meet the program requirements:

16 channels / MUX
50 V max voltage
50 Ohms ON-resistance
3x6 mm die size.

Figure 1 summarizes the area requirements for the original MUX chip and the proposed custom MUX using the modified specifications. The area required for controls, level shift, and MUX switch area in each design is shown. Either the "full logic" or the "reduced logic" designs will be capable of meeting our requirements for the 5 mm package.

The MUX will fit in the 5 mm package only if the dimension of the final device are about the same as the dimensions of the die itself. The surface mount parts currently available are almost an order of magnitude too large. Recent articles related to the packaging of hybrid circuits and multi-chip modules were reviewed to evaluate packaging technologies. These included articles from trade publications such as *Electronic Packaging & Production* and *Circuits Assembly* and scientific documents such as *Joint Industry Standard: Implementation of Flip Chip and Chip Scale Technology, J-STD-012.* Additionally, numerous contacts were made with leading consultants and companies within the packaging industry. From this review, only two viable alternatives for MUX attachment emerged; "flip chip" and "chip-scale" packaging.[1,2] A third method, Chip-on-board, requires too much additional area for pads associated with wire bonding. The two viable alternatives would be further investigated in a Phase II program.

Acoustic Performance of Array:

The acoustic performance of the miniature array probes down to 7 mm in diameter without a MUX has already been demonstrated by Tetrad. Arrays down to 5 mm with space for the MUX were evaluated theoretically and experimentally.

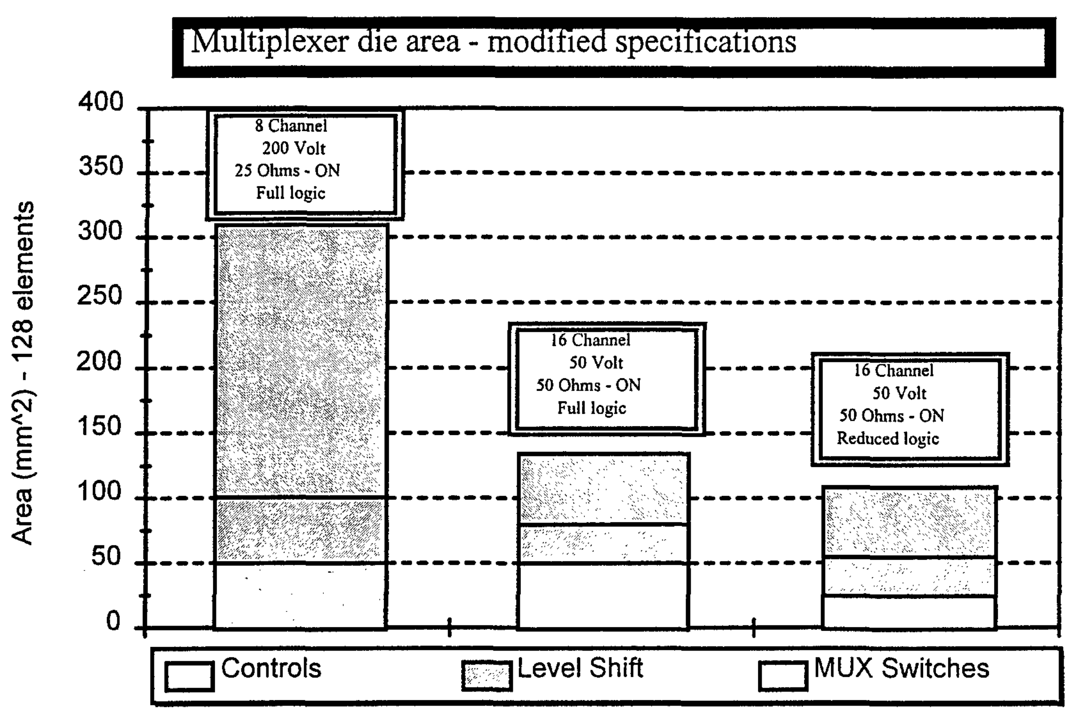

Figure 1. Summary of MUX area required for three different MUX configurations. Left shows area usage in commercial part, center shows area usage for custom configuration with full logic parts on-board, right shows area usage with reduced on-board logic circuitry.

Theoretical Array Evaluation

The industry standard method for modeling the acoustic performance of a transducer element is to use the KLM[3] equivalent circuit approach. This model was originally developed to estimate the effects of matching layers, and backing materials on transducer bandwidth and efficiency. During the course of this project, we have extended the use of this model to allow the following effects to be modeled:

- effect of MUX electrical properties on array performance (ON-Resistance, ON-Capacitance, OFF-Capacitance).
- effect of equivalent noise sources on transducer Signal-to-Noise Ratio (SNR), for both round trip and receive only.
- effect of cable electrical properties on losses and bandwidth
- Estimates of power dissipation in each mechanical and electrical component; i.e., matching layers, ceramic, backing, MUX, and cables. The estimates of power dissipation, provided the input data required for thermal modeling to be described later.

Using this modified KLM modeling approach, a 10 MHz linear array was modeled making the following assumptions: PZT-5H active material, 2 matching layer system, good preamplifier (1nV/√Hz and 3pA/√Hz equivalent noise sources), 4 meters of miniature coax cable, and MUXes of varying properties.

Table 1. KLM Modeling of 10 MHz Array element and effect of MUX

Case	Bandwidth	SNR-RT	SNR-Rec
No Mux	68%	91 dB	96 dB
25 Ω On	69%	89 dB	94 dB
50 Ω On	71%	88 dB	94 dB
100 Ω On	72%	87 dB	94 dB

These results indicate that the performance of the array is not severely degraded by the presence of the MUX and that the SNR achievable with the proposed 50 Ohm MUX is nearly identical to that achievable with the commercially available 25 Ohm MUX.

Experimental Array Evaluation

To test this result, a linear array module was built which incorporates a fully functional 128 element array. This array was built with the same dimensions that are expected in the final 5 mm module; i.e., 3 mm elevation dimension and 0.2 mm center-to-center spacing of elements. A silicone lens was bonded to the surface of the array to provide a slight amount of "out-of-plane" focusing. Because of the size constraints, a limited number of these elements were connected to 46 AWG micro coax and 4 of these elements were also connected to a pi-network which

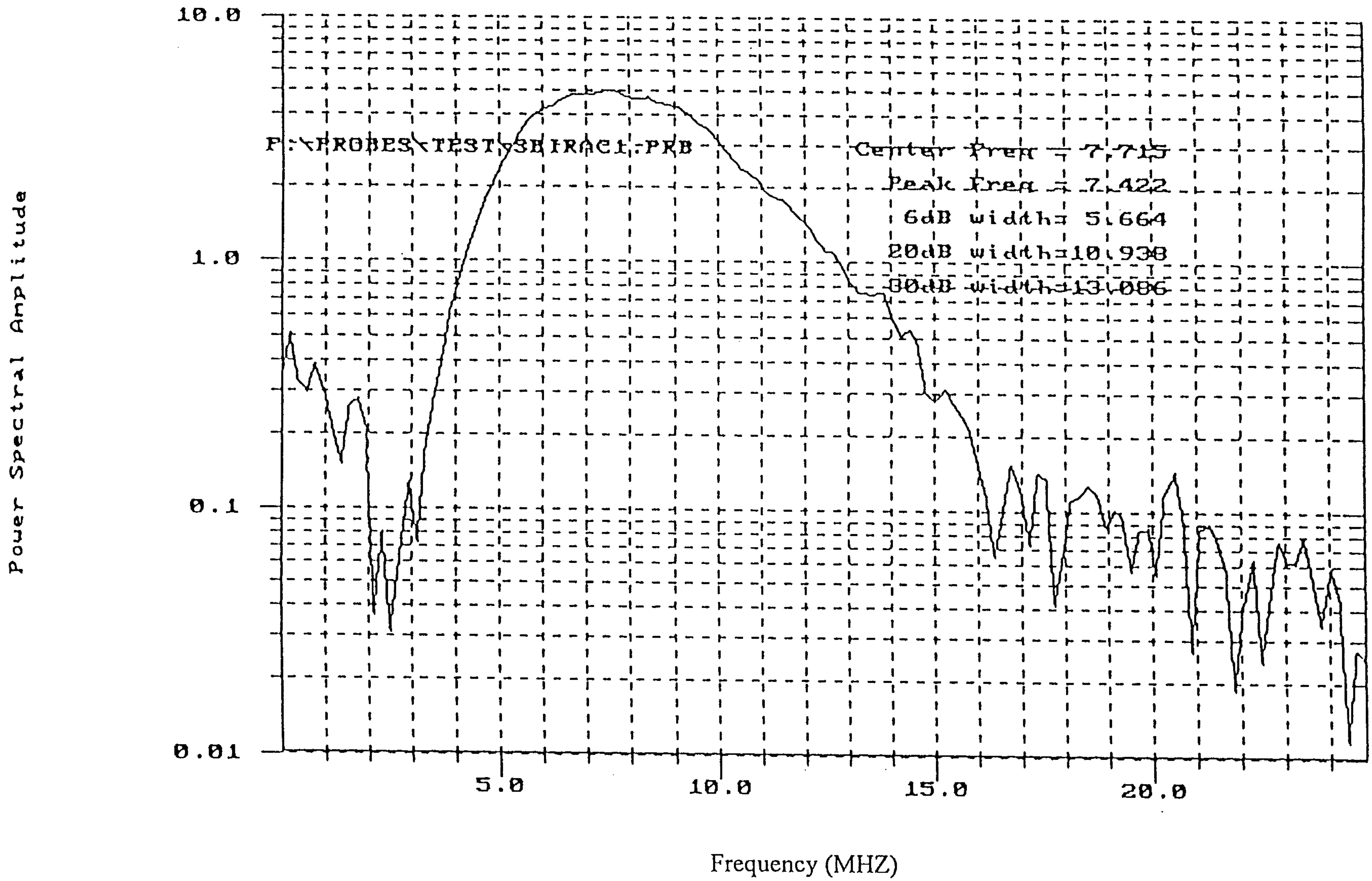

Figure 2. Experimental time-domain response of single array element with no MUX. Abscissa is time from 11 to 18 microseconds, ordinate in signal strength from -.6 to +.6 volts.

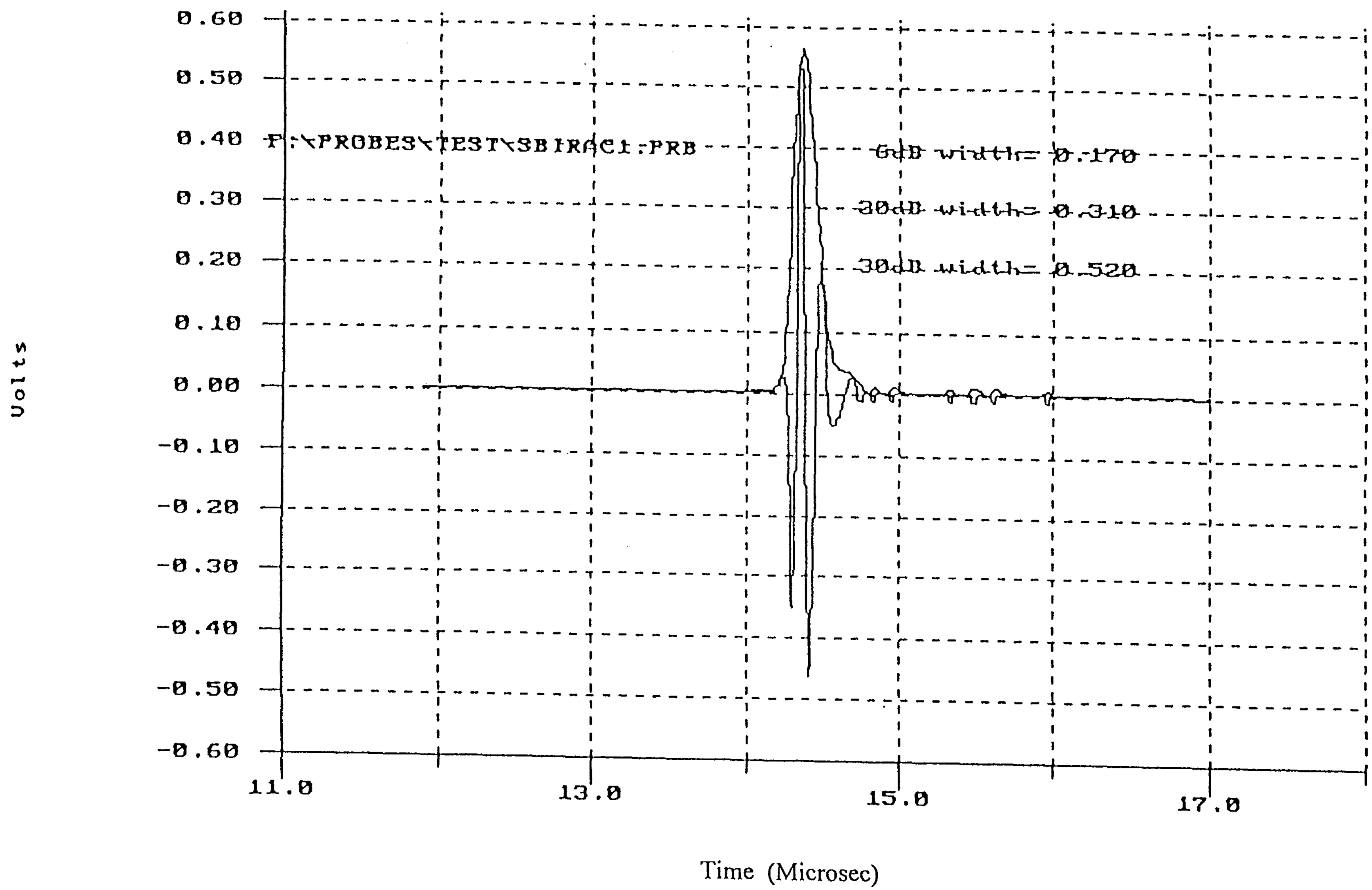

Figure 3. Experimental spectrum of the signal from Figure 2. Abscissa is Frequency from 0 to 24 MHZ, ordinate is Power Spectral Amplitude from -2- to -90 dB.

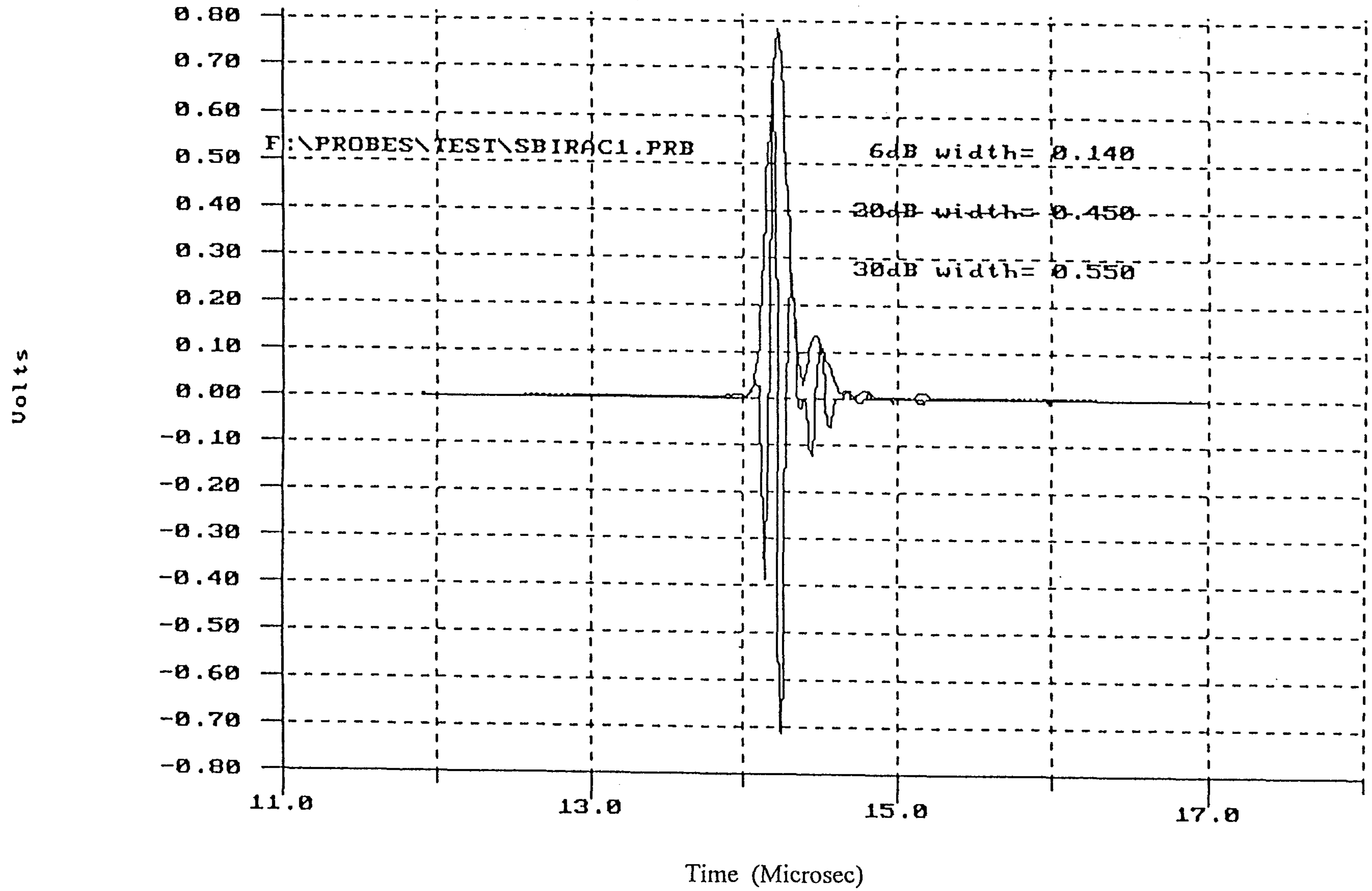

Figure 4. Experimental time-domain response of single array element with 50 ohm MUX in series with the array element. Abscissa from 11 to 18 microseconds, ordinate from -.6 to +.6 volts.

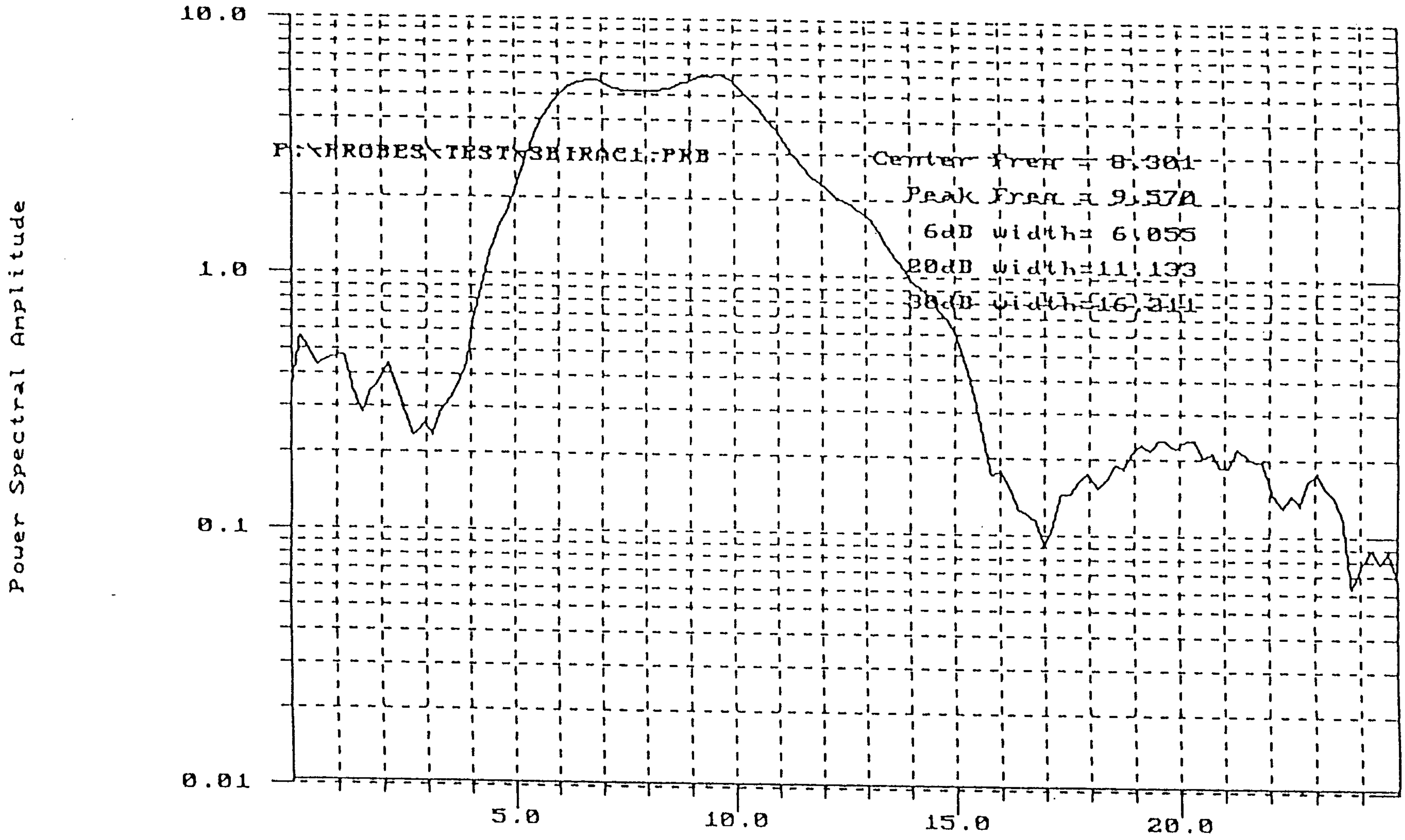

Figure 5. Experimental spectrum of the signal from Figure 4. Abscissa is Frequency from 0 to 24 MHZ, ordinate is Power Spectral Amplitude from -20 to -90 dB.

simulated the electrical properties of the MUX. The cable lengths used for the experimental tests were 0.33m of 46 AWG micro coax cable in series with approximately 0.8m of RG174 coax. For this specific electrical loading, the KLM theoretical model indicates that the MUX should have essentially no effect on acoustic performance. The loss of receiving performance is almost exactly offset by the gain in transmitting performance.

The acoustic response of all elements was evaluated using pulse echo measurements from a perfect reflector (large, flat stainless steel plate). Figures 2 and 3 show the time and frequency domain responses of a typical element with no simulated MUX attached. These results indicate that a very broad band, clean response was achieved. Figure 4 and 5 show the time and frequency domain responses of one of the elements which was connected with a series MUX. The primary difference in response is the secondary peak in the time-domain plot and the resultant dip in the frequency spectrum. These signal characteristics are attributable to a poorly bonded lens and are not the sort of signal changes that would be expected by adding the MUX. In terms of overall amplitude of the response, the MUX does not appear to have degraded the signal strength.

These acoustic results indicate that a high performance, high frequency, small acoustic array can be built. The array does not suffer from the overall size constraints of a 5mm package, excellent performance can be achieved with a very short acoustic stack, and minimal losses result from the addition of the MUX.

Mechanical Packaging Issues:

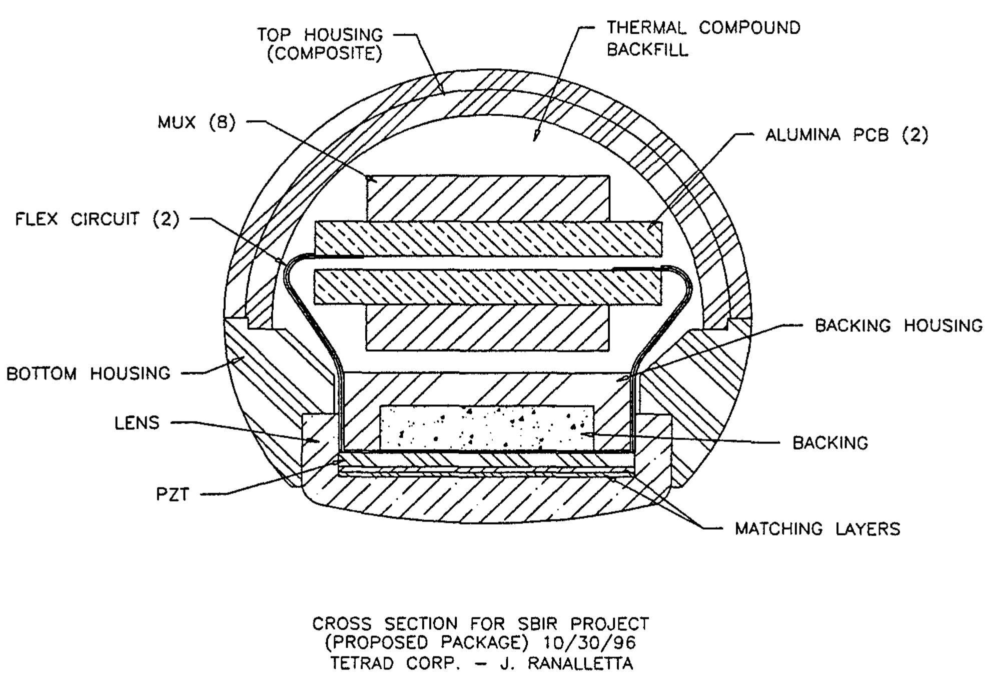

Figure 6. Axial cross-section of the final, 5mm probe package design.

The mechanical packaging of all the necessary components within a 5mm OD package has always been one of the most challenging aspects of this project. A number of design iterations were performed and the most promising choice for the final package is presented in the following two figures. Figure 6 illustrates a cross-section view through the 5 mm acoustic module showing the size relationships of the acoustic components and the electronic components. The design

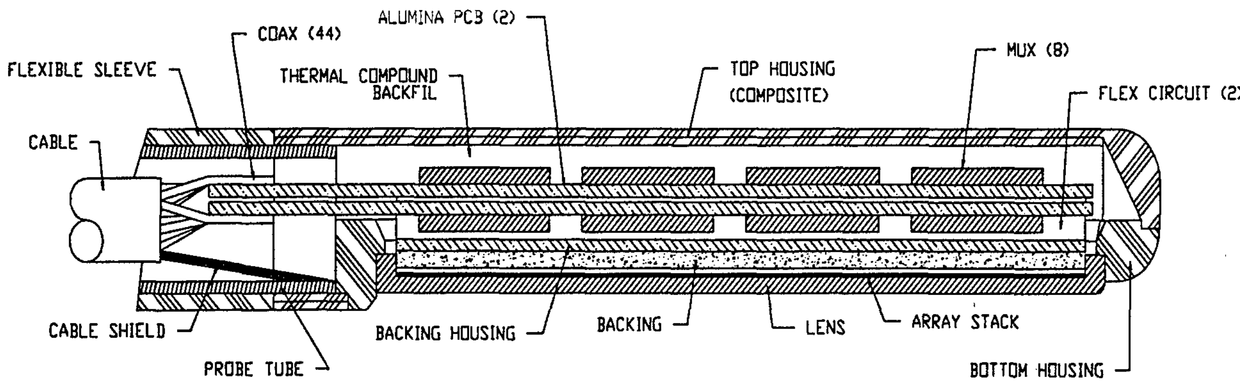

Figure 7. Longitudinal cross-section of the final, 5mm probe package design.

calls for a very "short" acoustic stack (approximately 1.5 mm tall) which is possible because of the high-frequency of this array (i.e., thin PZT and Matching Layers), high loss backing material, and rigid internal backing member. The MUXes are attached to proposed ceramic substrate (probably using "chip scale package" methods) and the ceramic substrate is attached to the acoustic module using flex circuits. The "over-and-under" relationship of MUX to PCB is done so that the two flex circuits can be approximately the same length and can therefore use the same layout. It is anticipated that the final PCB layout will require 5 layers to accommodate the number of lines required for attachment of the array flex circuit and the coax cables (not shown on this drawing). A composite housing is shown which is made of an inner metal layer (for heat dissipation and electrical shielding) and an outer plastic layer (electrical isolation and biocompatibility).

Figure 7 shows a longitudinal cross-section view through the 5 mm acoustic module. The drawing shows that we anticipate using 8 MUXes in all and that the MUXes are small enough to be totally packaged behind the acoustic stack. The length of the module is increased somewhat to accommodate the attachment of the coax cable bundle. The coax cable assembly will consist of a bundle of 47 micro coaxial cables each with a center conductor of 46 AWG. The bundle size of this cable without the outer sheath is 2.51 mm (0.99") which is anticipated to be sufficiently small to fit through a 5 mm OD articulated section.

Heat Control and Dissipation:

Because of the small size of the package and the increased "ON-resistance" of the proposed MUX, there was concern about the heat generation and dissipation within the array module. A program for mathematically modeling the thermal properties of the array module was undertaken. A software package known as PC3D from Harvard Thermal[4] was acquired and tested. This package is a finite difference, 3D modeling package which allows the user to generate models consisting of many thousands of thermal nodes, multiple heat sources, and a variety of heat dissipation mechanisms (convection, conduction, radiation, flow, etc.).

Model Validation

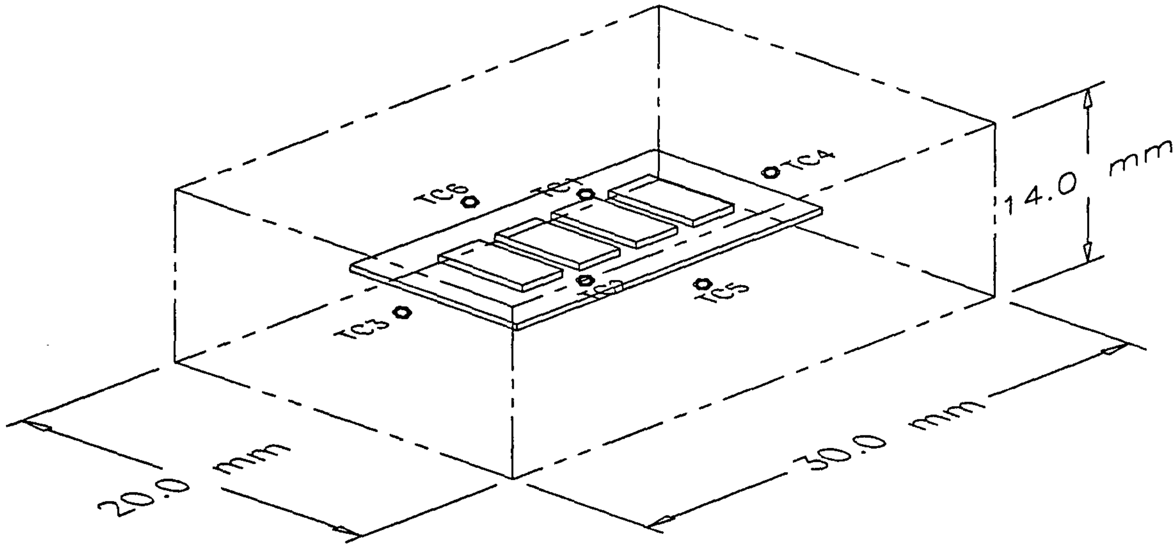

Figure 8. Perspective view of the model used to validate the thermal computer model.

The model was installed and validated by comparing the software predictions to observations made on a simple physical model. The physical model consisted of a box with resistors, substrate, and thermocouples potted in place. Figure 8 is a drawing of the physical model which was constructed. It consisted of materials and heat sources which were all well characterized and could therefore be modeled completely. The heat sources consisted of 4, 1/2 watt, 200 ohm surface mount resistors mounted on a 92% Alumina substrate. The entire assembly was potted inside a copper box using Epo-Tek H77 thermal potting compound and thermocouples were placed at the 6 locations indicated. The device was immersed in a constant temperature water bath and 10 volts (2 Watts) was applied to the resistors for 2 hours until thermal equilibrium was established. The final observed temperature values and the results of running the computer model for these same conditions are shown below:

Table 2. Results of Thermal Validation Experiment:

	Twater	T1	T2	T3	T4	T5	T6
Observed	21.4	26.4	27.7	27.1	27.0	28.0	27.8
Predicted	21.4	31.8	30.35	27.4	27.4	28.2	28.8

The only constraints for the model were that the case temperature be 21.4°C and that the total power dissipated by the resistors be 2 Watts. Observation made on thermocouples T3 through T6 are nearly identical to those predicted by the computer model. These four sensors were potted directly in the model during its construction and we are quite confident of their placement. Observations made with thermocouples T1 and T2 are substantially lower than the predicted temperatures. These two sensors were placed in the model by drilling holes to a specified depth, inserting the junction, and then refilling the holes with potting material. We are less confident of their placement. Overall, the results of this experiment are positive and provide confidence that the computer model can be used to predict the internal temperatures of the final packages devices.

Cable Characterization

In order to perform thermal analysis of the 5 mm probe module, the heat loss associated with conduction down the coaxial cable was quantified. The experimental method used was to attach all cables of a micro-coax cable assembled to a thin copper foil. By placing this foil in a hot calorimeter and observing the rate of temperature decrease compared to an identical calorimeter with no cable present, we were able to infer the thermal resistance of available coax cable assemblies. Measurements were made on 42 and 44 gauge cable assemblies and an extrapolation to 46 gauge coax was made. The results are presented in the following table:

Table 3. Characterization of Thermal Resistance of Micro coax Cable Assemblies.

Cable description	**Thermal resistance**
42 AWG, 136 conductors	78.6 °C/Watt (measured)
44 AWG, 155 conductors	163 °C/Watt (measured)
46 AWG, 40 conductors	500 °C/Watt (extrapolated)

Modeling of Thermal Performance

As described in the above material, the KLM transducer model was extended to provide further information about power dissipation in each component of the model. Results are presented in Figure 9 showing the power dissipated in each of the model components as a function of frequency assuming that 1 watt of total acoustic power is available. These results are presented in numerical form in Table 4.

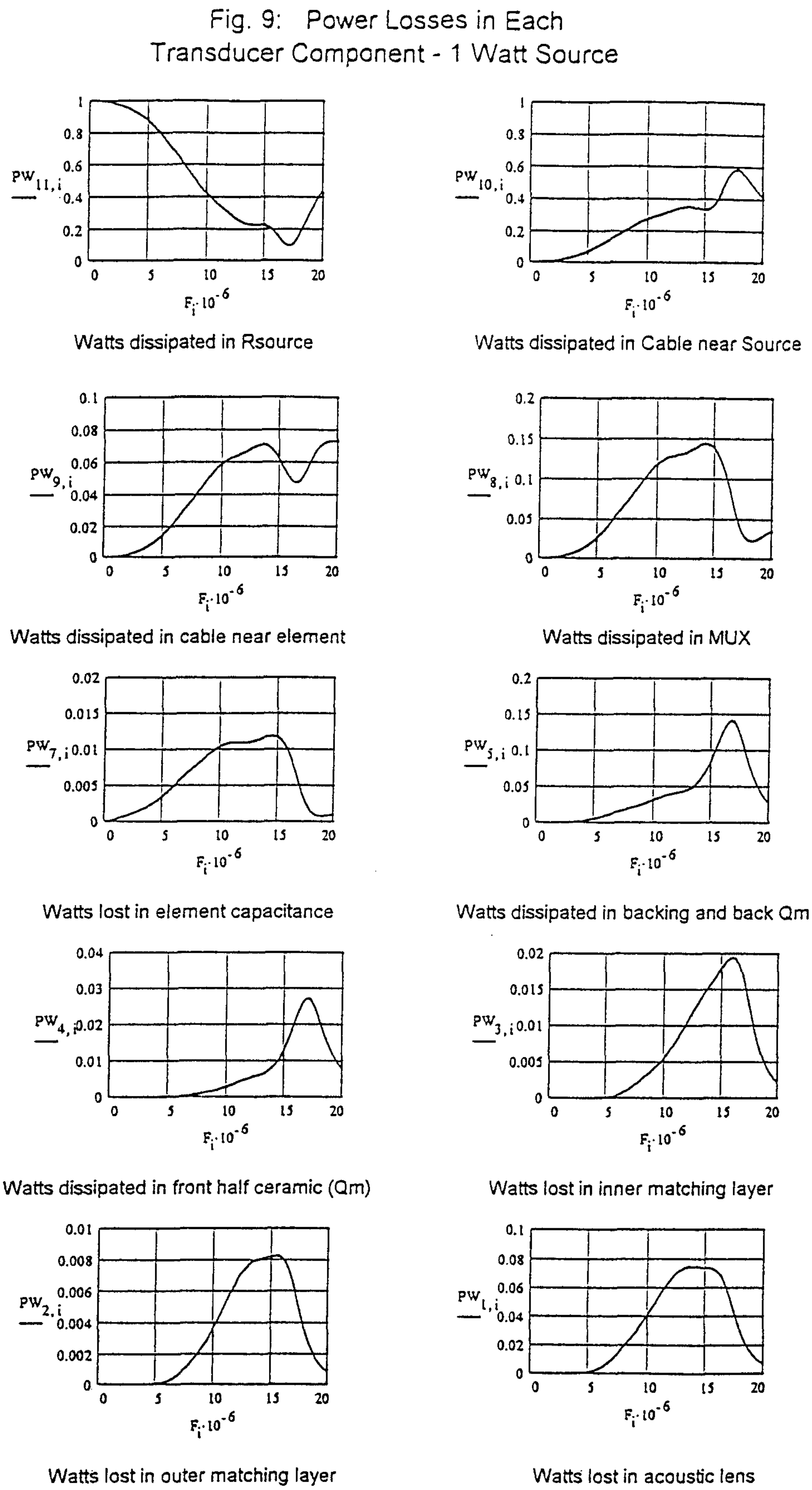

Figure 9. Results of theoretical modeling of losses within the transducer signal path.

Table 4: Power dissipated in each Model Component

Component	Broadband Losses	Losses at 7.5 MHz
Front Acoustic Load	0.025	0.022
Lens	0.025	0.015
Outer Match Layer	0.002	0.001
Inner Match Layer	0.004	0.002
Ceramic Front	0.002	0.001
Backing and Ceramic Back	0.023	0.018
Capacitors	0.007	0.007
MUX	0.078	0.074
Distal Cable	0.041	0.039
Proximal Cable	0.191	0.180
Rsource	0.602	0.640

This table illustrates how 1 Watt of total power is partitioned over each component of the array. Broad band losses refer to losses integrated over the useful transducer bandwidth and the Losses at 7.5 MHz refer to the predicted losses expected for a Doppler operating mode.

A thermal computer model of the 5 mm laparoscopic probe was generated. Independent heat sources representing electrical dissipation in the MUXes and acoustic dissipation in the backing, ceramic, and lens were provided. Figure 10 shows the longitudinal cross section of the computer model and the relative placement of the heat sources within the package. Based upon the focal properties of the array and the desire to limit the thermal index (TIS) for the array to approximately 1, we calculated that the acoustic power output of the array (32 active elements) would be approximately 21 milliwatts. This translates to 0.656 milliwatts/element when operating the array in a 7.5 MHz Doppler Mode. This number was used to scale the data presented in Table 2 and under these conditions, the total power dissipation in the lens, matching layers, ceramic, backing, and MUXes was found to be 108 milliwatts. The input parameters of the Model were adjusted so that the ratio of heat dissipated in each source matched the ratios presented in Table 2 and so that the total heat loss was 108 milliwatts. Figure 11 shows the results of running this Modeling work assuming that the three primary heat loss mechanisms are convection through the case to 37°C air, conduction through the lens to 37°C water, and conduction through the cable to 25°C air. These conditions are believed to realistically simulate the operation of a laparoscopic probe in a pneumoperitoneum. Under these conditions, the maximum case temperature is expected not to exceed 40.5°C and the maximum internal temperature is expected not to exceed 41°C. In other words, the maximum internal temperature is not expected to rise more than 4°C above the ambient conditions.

Array Module Showing Placement of Heat Sources

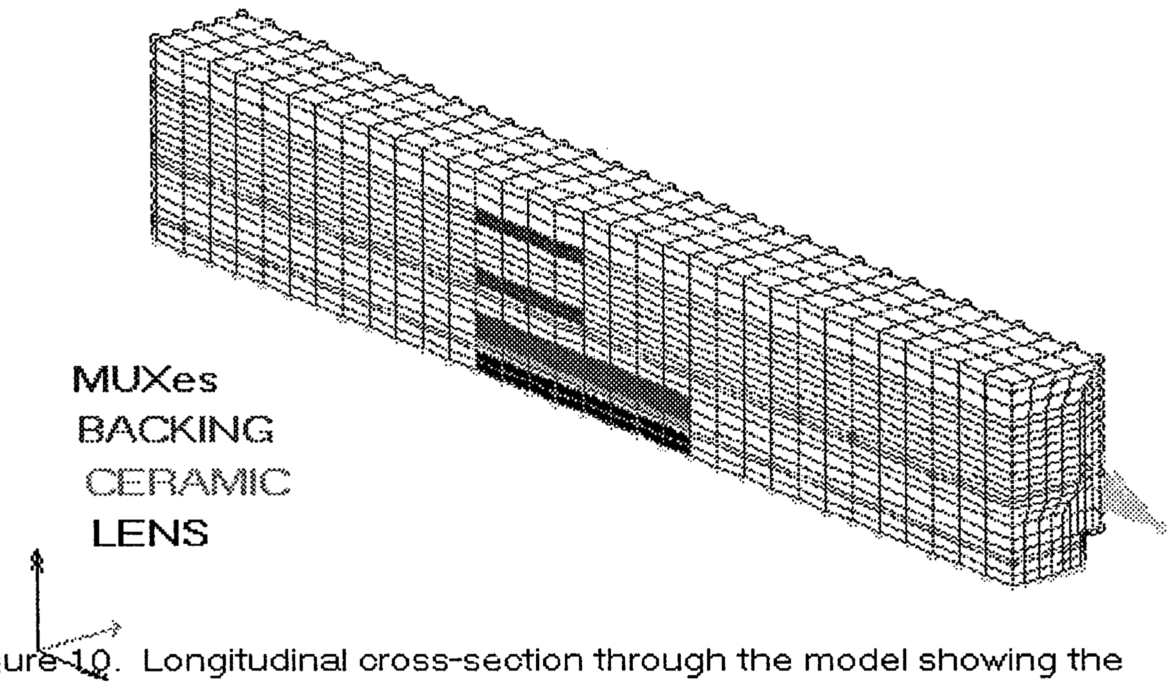

Figure 10. Longitudinal cross-section through the model showing the relative placement of heat sources.

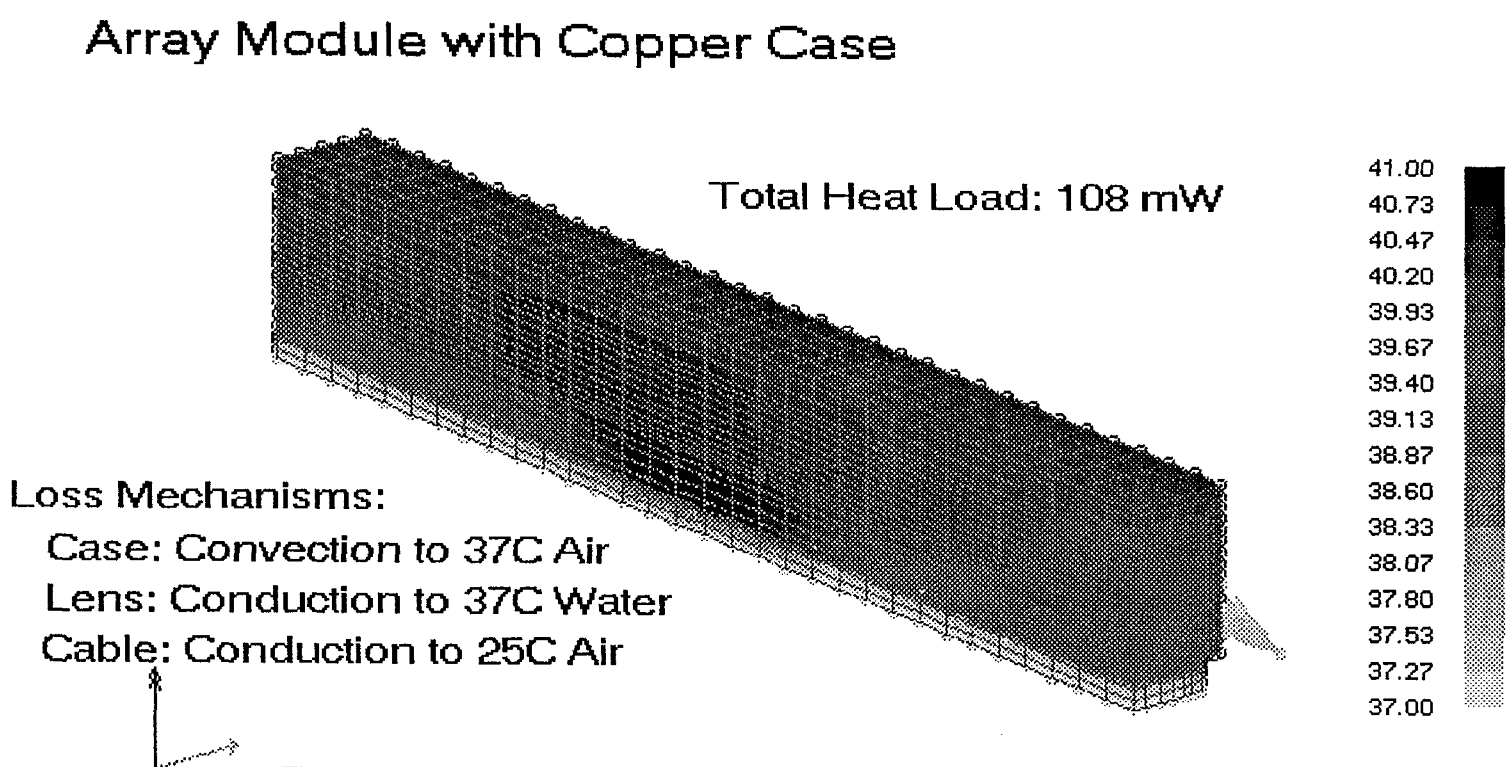

Figure 11. Longitudinal cross-section through the model showing the steady state temperature distribution.

To test this theoretical Modeling result, a thermal model of the acoustic model was constructed. Figure 12 shows the longitudinal cross-section of this model, which used chip resistors mounted to ceramic substrate to simulate the electrical dissipation of the MUX, and used Nichrome wire embedded in the PZT to simulate the acoustic dissipation. With this module totally submerged

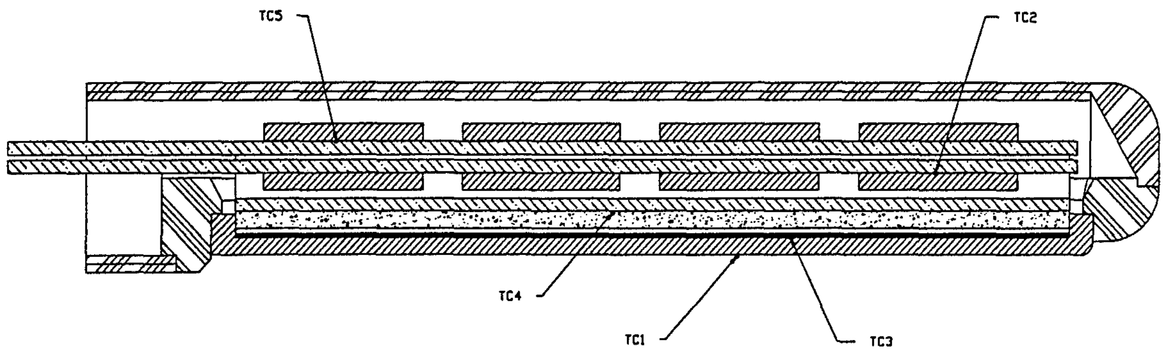

Figure 12. Longitudinal cross-section through the experimental thermal model

in water, and applying 108 milliwatts total power for approximately 4 hours, we observed a maximum internal temperature rise of 3.7°C (TC3) over the ambient water bath conditions.

CONCLUSIONS:

This project has been very successful in that it has allowed Tetrad to demonstrate the feasibility of building a 5mm, 128 element linear array with integrated electronics. Tasks undertaken and completed during the course of the project were:

1. Evaluation of technologies which can be used for multilayer circuit boards.
2. Evaluation of factors effecting MUX size and their effect on acoustic array performance.
3. Evaluation of technologies which can be used for array and cable interconnect.
4. Testing and evaluation of the heat generation and dissipation mechanisms for this small package.
5. Design and procurement of array interconnect flex-circuits.
6. Construction and testing of actual size thermal models.
7. Construction and testing of actual size acoustic models.

Our Phase I findings can be summarized as follows:

- Excellent acoustic performance can be achieved with a small acoustic stack
- MUX dimensions can be reduced sufficiently by selecting proper trade-off among ON-resistance, voltage, and capacitance and by developing the proper IC packaging technology.
- Packaging of 8, 16-channel MUXes and the acoustic stack with 128 elements within the 5mm package is possible.

- Increased MUX ON-resistance does not degrade acoustic performance.
- Even with higher MUX ON-resistance, sufficient heat sinking can be obtained for TIS = 1.
- Acoustic and thermal prototypes of the final 5 mm package were built and tested. Results indicate that the experimentally observed heat rises are equal to or less than theoretically predicted and that the acoustic performance is excellent.

Based upon these very positive results, it appears that a Phase II portion of this project in which the technology is further developed and used to build fully functional prototypes is feasible and has a high likelihood for success.

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BIBLIOGRAPHY:

No papers or meeting talks have yet been given.

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