AN ACOUSTICAL EXPLORATION TECHNIQUE FOR DETECTING OIL TRAPPED UNDER SEA ICE

H.W. Kwan and H.W. Jones
Technical University of Nova Scotia
P.O. Box 1000
Halifax, Nova Scotia B3J 2X4

ABSTRACT

This paper reviews in outline the theoretical and practical aspects of an acoustical method of detecting oil trapped under sea ice. Following discussion of the theoretical problems, information relating to acoustical mode conversion in the ultrasound reflected from the lower side of the ice is presented. An experiment in a large salt water tank, with about 80 cm of ice, is described and the results are related to theory which is presented. A commentary on the lessons learned from this experiment is given. An outline of the design for a prototype field apparatus is presented.

SOMMAIRE

On présente un bref aperçu des aspects pratique et théorique d'une méthode acoustique pour détecter l'huile emprisonnée sous les glaces océaniques. On discute entre autre des modes de propagation acoustique de l'onde ultrasonique refléchie du dessous de la glace. Des mesures effectuées dans un réservoir d'eau salée avec 80 cm de glace sont comparées avec la théorie et les conséquences de cette expérience discutées. Finalement les grandes lines d'un appareil prototype sont présentées.

INTRODUCTION

In earlier papers (1,2,3) introductory considerations relating to an acoustical method of detecting oil under ice were presented. These considerations included a study of the physical properties of sea ice and oil, and a summary of acoustical methods which had been attempted (unsuccessfully) on earlier occasions. A new method of using ultrasound was explored in outline. The principle of this method is shown in Figure 1. A short pulse of ultrasound is transmitted into the ice, this pulse is reflected and mode converted at the interface between the ice and the oil or water. The two returning pulses, one, a compressional wave and the other a shear wave, are received and recorded. The received signals carry two pieces of information, i.e., that relating to the thickness of the ice, and that which indicates the presence of oil or water in contact with the ice. The incident wave can be either compressional or shear; we have argued on earlier occasions that compressional waves appear to be a better choice for practical and theoretical reasons (3). The relative amplitudes of the returning waves indicate the presence, or otherwise, of oil. The thickness of oil which can be detected appears to be quite small. It is estimated that this thickness can be less than half the sound wavelength, and it may be possible to detect oil layers of 0.5 cm or less in practical circumstances.

Many practical problems exist in the design of a pice of apparatus for economical and regular use in the field. We base the following commentary on the limited amount of field experience which has been obtained to date. In field experiments oil was detected under 80 cm of salt water ice; the oil thickness varied from about 2 cm to less than 1 cm. There are difficulties due to unwanted artifacts in experimental data. It becomes important to recognize such artifacts and reduce their influence in data interpretation, particularly if automatic data assessment is used.

Interfacial Effects

The method we are describing depends on the interfacial effects at the bottom of the ice. It is necessary to be able to evaluate the results to be expected, consequently the required theory is outlined in the following paragraphs.

The reflection and refraction of compressional or shear waves at an interface between two materials is a complicated phenomenon. When a wave is incident on an interface, reflection, transmission and mode conversion can occur. The special circumstances of this case relating to transmission from solid to liquid and solid to visco-elastic liquid have been studied in general terms (4,5,6,7). If we suppose a general case in which we are dealing with transmission from visco-elastic to visco-elastic media, then limiting conditions allow us to evaluate all the cases of practical interest in these circumstances.

Figure 2 shows the geometry relating to the boundary and the sound waves incident upon it. The reflection and refraction coefficients are determined by solution of a set of linear equations which arise from the need to conserve displacement and force at the boundary. The coefficients are obtained from:

$$A_\ell R_\ell = B_\ell \tag{1}$$

where $\ell = 1,2$ for incident compressional or shear waves, respectively and

where,

$$A_\ell = \begin{bmatrix} \sin\zeta_{\ell 11} & \cos\zeta_{\ell 12} & -\sin\zeta_{\ell 21} & \cos\zeta_{\ell 22} \\ \cos\zeta_{\ell 11} & -\sin\zeta_{\ell 12} & \cos\zeta_{\ell 21} & \sin\zeta_{\ell 22} \\ -\rho_1 S_{11}\cos 2\zeta_{\ell 12} & \rho_1 S_{12}\sin 2\zeta_{\ell 12} & \rho_2 S_{21}\cos 2\zeta_{\ell 22} & \rho_2 S_{22}\sin 2\zeta_{\ell 22} \\ (\rho_1 S_{12}^2/S_{11})\sin 2\zeta_{\ell 11} & \rho_1 S_{12}\cos 2\zeta_{\ell 12} & (\rho_2 S_{22}^2/S_{21})\sin 2\zeta_{\ell 21} & -\rho_2 S_{22}\cos 2\zeta_{\ell 22} \end{bmatrix}$$

$$B_1 = \begin{bmatrix} -\sin\theta_1 \\ \cos\theta_1 \\ \rho_1 S_{11}\cos 2\zeta_{112} \\ (\rho_1 S_{12}^2/S_{11})\sin 2\theta_1 \end{bmatrix}, \quad B_2 = \begin{bmatrix} \cos\theta_2 \\ \sin\theta_2 \\ -\rho_1 S_{12}\sin 2\theta_2 \\ -\rho_1 S_{12}\cos 2\theta_2 \end{bmatrix}, \quad R_\ell = \begin{bmatrix} R_{\ell 11} \\ R_{\ell 12} \\ R_{\ell 21} \\ R_{\ell 22} \end{bmatrix}$$

and $R_{\ell mn}$, are the displacement reflection and refraction coefficients. The suffix m refers to the medium through which the wave is passing and suffix n refers to compressional or shear waves when its value is 1 or 2 respectively. The angle θ_ℓ is the angle between the incident wave and the Y axis. The various angles $\zeta_{\ell mn}$ (which are the complex angles) are related through their sines to the velocity of propagation ratios as the complex Snell's law:

$$\sin\zeta_{\ell mn} = S_{mn}\sin\theta_\ell / S_{1\ell}, \text{ for } \ell,m,n = 1,2 \tag{2}$$

where $S^2_{m1} = (\lambda_m + 2\mu_m)/\rho_m$, $S^2_{m2} = \mu_m/\rho_m$

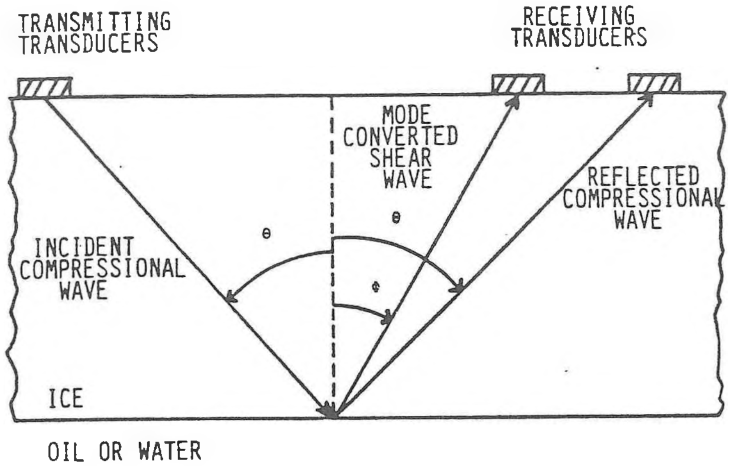


Figure 1
Schematic of Experimental set up.

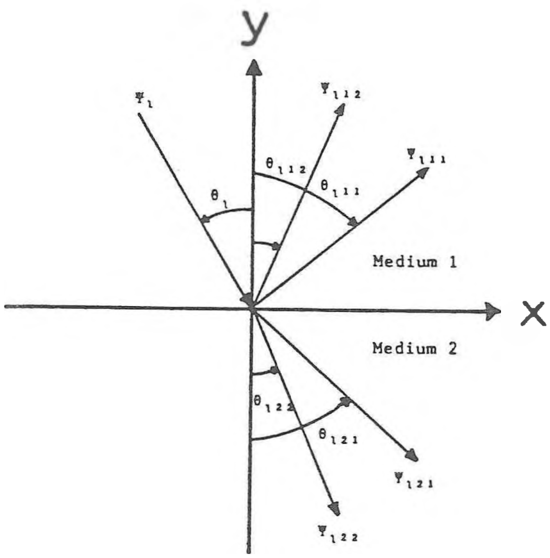


Figure 2
Reflection and Refraction Phenomena at the interface Y = 0.

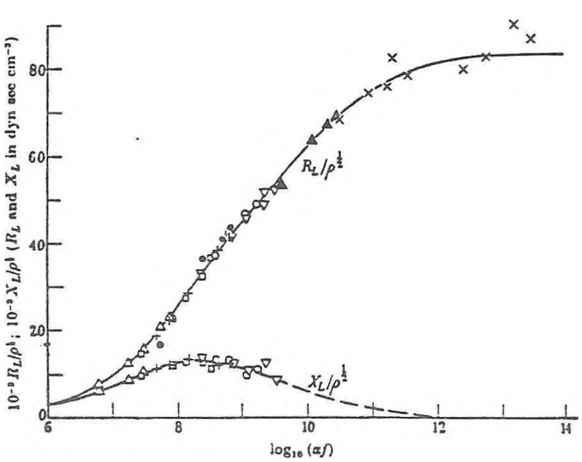


Figure 3
Resistive and reactive components of a high viscousity oil, for various temperatures, as a function of frequency. ($\alpha = \eta_T/\eta_{300}$. η is viscosity at indicated temperature. After Barlow and Lamb, 1959)

λ_m and μ_m are the complex Lame's elastic constants of material, and ρ_m is the density of material. It is to be noted that the matrices associated with equation (1) have been corrected to remove errors contained in the original publication.

The complex properties of visco-elastic substances are dependent on several factors, among them the temperature and frequency of the ultrasound. Figure 3 shows typical data for various oils. As a consequence of these factors, the solutions of equation (1) will also depend on the conditions which are related to a particular experimental problem.

Curves 1 and 2 in figure 7 are an estimate of the limits of the relative ratio of the compressional to shear waves returned from the lower surface for an oil in contact with the ice by comparison to water next to the ice. Curve 1 is the high frequency limit; curve 2 is the low frequency limit obtained from the use of equations (1) and (2). In practice, experimental results can be expected to lie between these boundaries.

Experimental Work

The experiments on salt water ice at lower frequencies require a large sheet of thick ice and Esso Resources Canada Ltd allows us to use their large outdoor brine tank at Calgary. Figure 4a and b show part of the ice sheet on the tank and a block of ice taken from the site of our experiments. The ice on the tank was about 80 cm thick and made from brine, frozen from the top surface by winter temperatures assisted by refrigeration pipes laid on the surface. There was a relatively large volume of unfrozen water in the tank; probably less than 20% of the original brine was frozen. Consequently, the ice is a fair approximation to the sea ice, except that its lower surface is flat (see Figure 4b) because of the lack of wave action and ridging during freezing.

The transducers which were used operated at a basic frequency of 144 kHz. The transducers were driven by a large amplitude tone-burst provided by a broadband power amplifier. The receiving transducer was similar to the transmitter. The received signals were transmitted via a head amplifier and a coaxial line to a variable bandwidth filter and other receiving electronics. Figure 5 shows a typical trace of a received signal. Measurements were made for angle θ (see Figure 1) in the range of 5° to 30°, with water in contact with the ice. Next a depression 2.5 cm deep was melted in the underside of the ice, using the method illustrated in Figures 6. This depression was filled with oil, and a set of measurements with oil in contact with the ice was made. Two points should be stressed; first the dimensions of the melted area containing the oil were sufficiently large to "contain" the main lobe of incident beam of the transmitting transducer. This means that the received signal came primarily from the oil-filled region. The second point concerns the displacement of the water by the oil from the ice surface. Much thought was given to this point and a variety of methods for placing the oil were discussed. Finally the oil was just released from a can into the cavity. Immediately after oil was in place, repeated readings were obtained. During the course of these readings, the oscilloscope traces changed, showing that the water was displaced from the surface as the oil insinuated itself into the cracks of the ice. Later borings showed that the oil had penetrated about 30 cm into the ice over a period of 24 hours. An estimate of the oil transport suggests that about

Figure 4(a)
General view of Basin.

Figure 4(b)
A block of ice from the Basin.

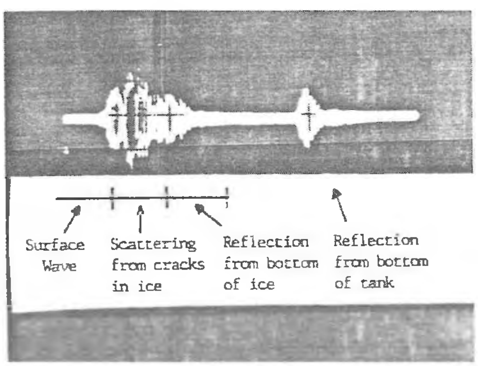


Figure 5
Typical trace of a signal.
Vertical = 50 mV/div.
Horizontal = 0.2 msec/div.

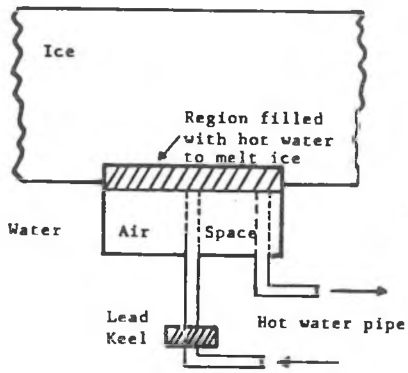


Figure 6
Experimental arrangement for melting ice.

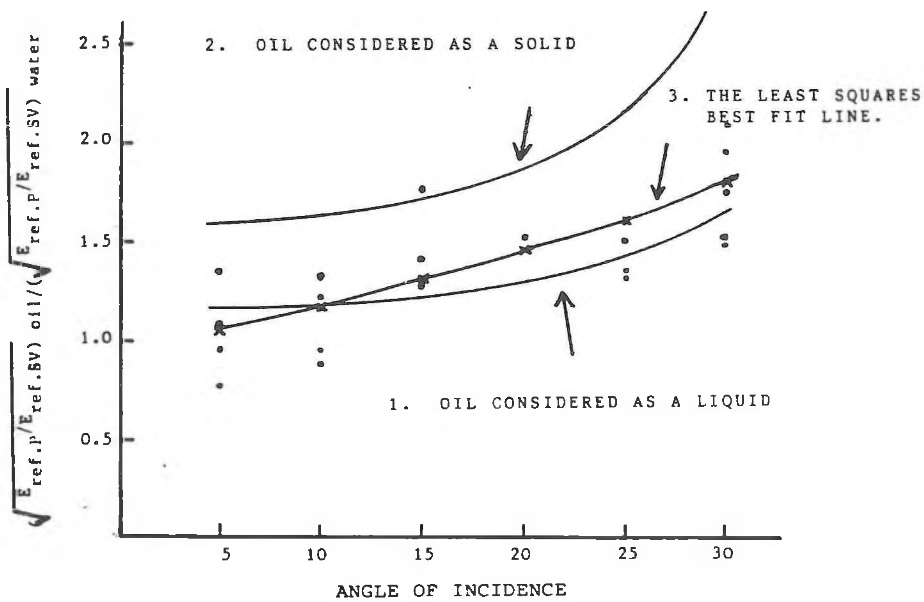


Figure 7
P wave incident in the sea ice against oil or water. The ratio of the square root of the energy ratio of the reflected P wave to the reflected sv wave of ice/oil interface to ice/water interface vs. incident angle. •: Experimental Data.

half of the oil "soaked" into the ice, leaving about 1 cm or less in contact with the ice surface at the end of the experiments. It was essential, of course, that air should not be trapped under the ice, and to this end the divers who assisted the experiments used closed circulation breathing apparatus and took every care to avoid such problems. A final detail concerns the pulse broadening of the shear wave. The broadening arises for reasons of geometry and the difference in the velocity of propagation between the compressional and shear waves. The principle effect it produces, in practice, is to reduce the signal amplitude. As the effect is the same for oil or water in contact with the ice, it would not appear at first sight to affect the ratios presented in the results.

When the oil measurements were completed, a piece of ice was removed from an area close to the site of the experiments (see Figure 4b). This piece was used for making measurements of the compressional and shear velocities of sound. The shear waves were produced by mode conversion at a prismatic face inclined at an angle of incidence; this face can be seen in the photograph with transducers mounted for shear velocity measurements.

Finally, several holes were bored at the test site to confirm the presence of the oil and its positioning (which had been placed originally by reference to markers pushed through the ice).

The data which had been collected was used to plot the graph shown in Figure 7. Clearly, at angles of θ greater than 10^{o}, there is little difficulty in saying that the experimental results indicate the presence of oil. It is interesting to note that the least squares best fit line gives an approximate fit to the visco-elastic properties which would be expected for the oil which was used. At angles of incidence of 10^{o} and less, the indication of the presence of oil is uncertain. It is possible that the difficulty arises primarily from the path length of the shear wave. When the path length is shorter, the arrival of the slower wave is coincidental with the arrival of components of the compressional wave which have been scattered from relatively distant points in the ice sheet. As the time of flight of shear wave increases, this overlap decreases until it becomes relatively insignificant. The masking effect of these scattered signals causes the indicated amplitude of the shear wave to decrease because the compressional component is absent. If this is the case, the ratio plotted in Figure 7 will increase (i.e. when the compressional component is absent).

Design of Prototype Apparatus

Figure 8 shows the layout of the arrangement of the data acquisition and data processing for a prototype apparatus. The electronic part consists of a LeCroy instrument package in a Camac mini crate and an IBM-PC. The LeCroy instrument package consists of the following components housed in a Camac (IEEE-588) crate: (i) amplifier, (ii) digitizer, (iii) Camac to GPIB Interface, which allows the computer access to the Camac bus to program and receive data from the digitizer. Conventional techniques will be used in the probability assessment for the recognition of scattering from a rough lower surface of the ice.

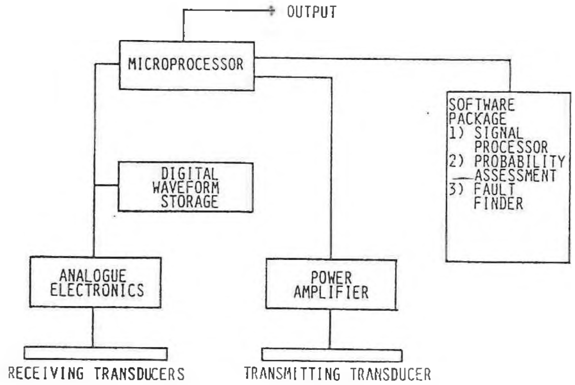


Figure 8
Schematic for
Prototype Apparatus

CONCLUSION

The principles and experimental work of an acoustical method for detecting oil spill under salt ice are described. It is shown that initial field data support the method which is proposed and that quite thin layers of oil can be detected. Experimental results are supported by a fairly detailed statement of the theory involved. An outline design of a prototype apparatus is presented and future field trials on arctic sea ice will undoubtedly lead to modification of the ideas which are outlined here.

ACKNOWLEDGEMENTS

This work is supported by funding from Esso Resources Canada Limited and the Environmental Protection Service.

REFERENCES

1. Jones, H.W. and Kwan, H.W., "The Detection of Oil Spills Under Arctic Ice by Ultrasound", Proc. Fifth AMOP Technical Seminar, pp. 391-411, (1982).

2. Jones, H.W. and Kwan, H.W., "The Detection of Crude Oil Under Seawater in the Arctic Ocean", Proc. Sixth AMOP Technical Seminar, pp. 241-252, (1983).

3. Jones, H.W. and Kwan, H.W., "An Ultrasonic Exploration Technique for Finding Oil Under Arctic Sea Ice", Ultrasonics International 83 Conference Proceedings, pp. 182-187, (1983).

4. Mott, G., "Reflection and Refraction Coefficients at a Fluid/Solid Interface", J. Acoust. Soc. Amer., 50, (3), pp. 819-829, (1970).

5. Cooper, H.F., "Reflection and Transmission of Oblique Plane Waves at a Plane Interface Between Visco-elastic Media", J. Acoust. Soc. Amer., 42, (5), pp. 1064-1069, (1967).

6. Barlow, A.J. and Lamb, B.J., "The Visco-elastic Behaviour of Lubricating Oils under Cyclic Shearing Stress", Proc. Roy. Soc. A., 253, pp. 52-69, (1959).

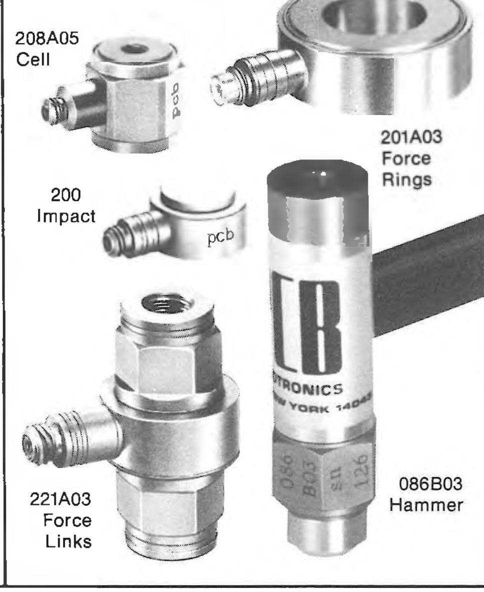
7. Brekhovskikh, L.M., Waves in Layered Media, 2nd Ed. Academic Press, (1980).

ICP QUARTZ SENSORS

(integrated circuit - piezoelectric)

PRESSURE Series 100

FORCE Series 200



MOTION Series 300
(Shock and Vibration)

MEASURAND	PRESSURE			FORCE			MOTION		
Model No.	102A05 112A21	101A02 111A22	108A 109A	200B Impact	201A03 221A03	208A05	302A	303A02	308B
Range psi, lb, g	100	15 000	80 000	10	50	500	500	500	50
Resolution psi, lb, g	0.004	0.2	2	0.0004	0.02	0.2	0.02	0.02	0.002
Sensitivity mV/unit	50	1	0.1	500	10	1	10	10	100
Resonant Frequency Hz	250 000	400 000	300 000	70 000	70 000	70 000	45 000	70 000	25 000
Output Voltage V	5	5	8	5	5	5	5	5	5
Temperature Range °F	−100 to +275	−100 to +275	−100 to +275	−100 to +250	−100 to +250	−100 to +250	−100 to +250	−40 to +200	−100 to +250
Vibration (max.) g	2000	2000	2000	2000	2000	2000	2000	1000	500
Size (dia. x length) in	.248 x 1.38	.248 x 1.38	.320 x 1.70	.650 x 1.15	.650 x 1.15	.625 x 1.025	.484 x 1.30	.275 x .58	.75 x 1.32
Weight gram	6	6	12	14	14	25	25	3	87
Connector (coaxial)	10-32	10-32	10-32	10-32	10-32	10-32	10-32	5-44	10-32
Other Models (includes numerous other ranges, sizes and sensitivities)	Blast Cryogenic Helium Bleed Water Cooled	Spark Plug Sound Conformai Hi-Frequency		Other Ranges Other Sizes Miniature Impact	Press Monitor Industrial Ring & Link Sledge Hammers		Seismic Hi-Sensitivity Ring Industrial	Hermetic Gnd. Isolated	

ICP QUARTZ SENSORS with built-in microelectronic amplifiers simplify the task of dynamic measurements. You can operate them over long coaxial or two wire cables, couple directly to your scope or analyzer and cover extremely wide ranges with just one sensor. You'll also appreciate their value, economy, ruggedness, reliability and stability. They are structured with crystalline quartz, stress-gage elements and function to transfer dynamic phenomena into electrical signals, more convenient for recording or analyzing.

OTHER PRODUCTS include a complete line of conventional charge-mode transducers and associated charge amplifiers. Piezoelectronic products include power units, voltage amplifiers, filters, integrators, vibration meters, and digital peak meters. Instrumented impulse hammers help test the behavior of structures. Dynamic calibrators build confidence in quartz sensors. These precision, space-age products are all made in the U.S.A. by the No. 1 American quartz company. For more information, just call or write.

PCB PIEZOTRONICS, INC.
3425 Walden Avenue, Depew, New York 14043-2495
Telephone: 716-684-0001, TWX: 710-263-1371

PCB PIEZOTRONICS *"Leader in Quartz Dynamic Instrumentation"*

Manager
Electro Acoustic
Design/Development

Northern Telecom is a world leader in the advanced technology of telecommunications. Our leadership in virtually every aspect of design, manufacture and marketing is a direct result of a special environment that we have created that encourages both people and technological innovation to flourish.

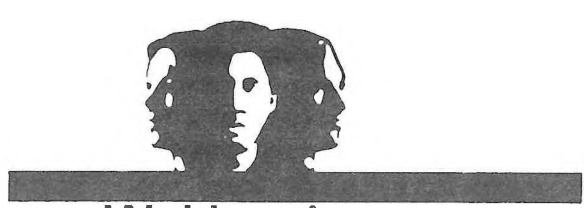
Based in our Station Apparatus Division in London, you will provide guidance to a technical staff of engineers and technologists involved in the development and support of telephony products. In addition you will be responsible for electro acoustic device (loudspeakers, microphones, earphones) design and system evaluation including measurements.

You will have at least 5 years industry experience and a familiarity with acoustic standards i.e., IEEE, IEC and CCITT. Background in analog electronics and telephony would be strong assets. A Bachelors degree in electrical or electronic engineering is mandatory.

As well as receiving first-class remuneration, you will be provided with outstanding scope for both personal and professional growth.

Please send your detailed resume, in confidence, to:

Larry Zalmers
Senior Specialist, Human Resources
Station Apparatus Division
Northern Telecom Canada Ltd.
Sise Road, P.O. Box 5155
London, Ontario N6A 4N3



We hire talent

nt northern telecom