Formation and Propagation of Love Waves in a Surface Layer with a P-Wave Source

A. L. Florence
S. A. Miller

SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025

April 1990

Scientific Report No. 2

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AIR FORCE BASE, MASSACHUSETTS 01731-5000

90 08 22 057
The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the U.S. Government.

This technical report has been reviewed and is approved for publication.

JAMES F. LEWKOWICZ
Contract Manager
Solid Earth Geophysics Branch
Earth Sciences Division

JAMES F. LEWKOWICZ
Branch Chief
Solid Earth Geophysics Branch
Earth Sciences Division

FOR THE COMMANDER

DONALD H. ECKHARDT, Director
Earth Sciences Division

This report has been reviewed by the ESD Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS).

Qualified requestors may obtain additional copies from the Defense Technical Information Center. All others should apply to the National Technical Information Service.

If your address has changed, or if you wish to be removed from the mailing list, or if the addressee is no longer employed by your organization, please notify GL/IMA, Hanscom AFB, MA 01731-5000. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document requires that it be returned.
**Report Title:** Formation and Propagation of Love Waves in a Surface Layer With a P-Wave Source

**Authors:**
A. L. Florence  
S. A. Miller

**Performing Organization Name(s) and Address(es):**
SRI International  
333 Ravenswood Avenue  
Menlo Park, CA  94025

**Sponsoring/Monitoring Agency Name(s) and Address(es):**
Geophysics Laboratory  
Hanscom AFB  
Massachusetts 01731-5000

**Contract Manager:** James Lewkowicz/LWH

**Abstract:**
The objective of this research is to investigate experimentally, and support with theoretical calculations, the formation and propagation of Love waves from a P-wave source due to scattering at material heterogeneities. The P-wave source is a spherical piezoelectric crystal cast in a surface layer of rock simulant overlaying a higher impedance granite substrate. Excitation of the piezoelectric crystal with a known voltage applies a spherical compressional pulse of known amplitude to the surrounding medium. Lateral heterogeneities cast in the surface layer convert incident P-wave energy into shear waves. The horizontally polarized shear waves (SH waves) trapped in the surface layer waveguide are the Love waves we will measure at the surface.

This report summarizes an investigation of the source by deriving an approximate analytic solution of a spherical crystal in an elastic medium. The analytic solution shows good agreement with experimental results of pressure histories measured in water at three locations from the source, and is then extended to an elastic medium. The elastic medium calculation is used to predict expected signal levels in a sensor evaluation experiment and determine the boundary conditions.

**Subject Terms:**
Love waves  
P-wave scattering  
Piezoelectric crystal  
Explosion discrimination

**Security Classification:** Unclassified
pressure history applied to the medium. The boundary pressure history will be used as input to finite element code calculations of the surface wave experiment to assist in the instrumentation design and analysis of the experimental results.
CONTENTS

FIGURES ........................................................................ iv

OBJECTIVE AND APPROACH ........................................... 1

PROGRESS .................................................................... 3

Solution of a Spherical Piezoelectric Source in an Elastic Medium .......... 3

Piezoelectric Spherical Shell .............................................. 3

Spherical Cavity in an Elastic Medium .................................. 7

Fluid Medium .................................................................. 11

Numerical Values (Solid Medium) ........................................ 12

Numerical Values (Water) ................................................... 14

Application of Solution in a Water Medium ............................. 14

Application of Solution to an Elastic Medium .......................... 17

Evaluation Experiment in Pourstone .................................... 17
### FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Schematic of scale-model laboratory experiment</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Configuration for measuring stress pulse amplitudes in water at different radii from the source and sphericity of piezoelectric source</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>Input voltage history to the piezoelectric source in the water pressure experiment</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>Comparison of measured and calculated pressure histories in water at a range of 0.91-cm from the center of the source</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>Comparison of measured and calculated pressure histories in water at a range of 1.51-cm from the center of the source</td>
<td>19</td>
</tr>
<tr>
<td>6</td>
<td>Comparison of measured and calculated pressure histories in water at a range of 3.38-cm from the center of the source</td>
<td>20</td>
</tr>
<tr>
<td>7</td>
<td>Calculated velocity histories at 3 ranges in pourstone from a spherical piezoelectric crystal excited by 316 volts</td>
<td>21</td>
</tr>
<tr>
<td>8</td>
<td>Calculated displacement histories at three ranges in pourstone from a spherical piezoelectric crystal excited by 316 volts</td>
<td>22</td>
</tr>
<tr>
<td>9</td>
<td>Calculated radial stress histories at three ranges in pourstone from a spherical piezoelectric crystal excited by 316 volts</td>
<td>23</td>
</tr>
<tr>
<td>10</td>
<td>Calculated circumferential stress histories at three ranges in pourstone from a spherical piezoelectric crystal excited by 316 volts</td>
<td>24</td>
</tr>
<tr>
<td>11</td>
<td>Configuration for source/sensor evaluation experiment</td>
<td>25</td>
</tr>
</tbody>
</table>
OBJECTIVE AND APPROACH

Detection of underground nuclear explosions includes the spectral analysis of seismograms, an important portion of which is the contribution of Love waves. Field evidence suggests that it may be possible to discriminate between nuclear events and earthquakes by examining the Love wave records. The spectra for these events are different because an earthquake generates shear waves directly, whereas an underground explosion generates P-waves, from which Love waves are produced by scattering from material heterogeneities.

The objective of this research is to investigate experimentally, and support by theoretical calculations, the formation and propagation of Love waves from a P-wave source due to scattering at material heterogeneities. The approach is shown schematically in Figure 1. In these experiments, a spherical piezoelectric crystal (P-wave generator) is cast in a surface layer of rock simulant overlying a higher impedance granite substrate. Excitation of the piezoelectric crystal with a known voltage applies a pressure pulse of known amplitude to the cavity boundary, propagating compressional waves into the surrounding medium. Lateral heterogeneities of simple geometries (cylindrical and planar scattering surfaces) are cast into the surface layer, converting incident P-wave energy into shear waves. The horizontally polarized shear waves (SH-waves) trapped in the surface layer wave-guide are the Love Waves we will measure at the free-surface. The sensors at the surface will be distributed so both the undisturbed signal and the signals modified by scattering can be monitored at the surface.
Figure 1. Schematic of scale-model laboratory experiment.
PROGRESS

An analytic solution of a spherical piezoelectric crystal was derived to predict expected signal levels for a sensor evaluation experiment, and to provide a boundary pressure history as input for finite element code calculation.

SOLUTION OF A SPHERICAL PIEZOELECTRIC SOURCE IN AN ELASTIC MEDIUM

The source is a spherical shell of lead zirconate titanate ceramic, designated PZT-4, of outside radius \( a = 0.6350 \) cm, inside radius \( b = 0.4826 \) cm, and thickness \( h = 0.1524 \) cm. The electrical polarization is radial and the electrical and mechanical properties are spherically symmetric and transversely isotropic. In the usual spherical coordinate system \((r, \theta, \phi)\), the properties are isotropic with respect to the circumferential coordinates \((\theta, \phi)\).

The source is cast in a rock simulant, designated Pourstone, which is homogeneous and isotropic. Our analysis treats the source subjected to a voltage pulse and an interface reaction from the surrounding medium. This reaction is determined by an analysis of the spherical wave propagation in the surrounding medium caused by the reaction while ensuring equal radial displacements at the interface. Approximations are introduced to simplify the analysis without changing the basic dynamic response.

PIEZOELECTRIC SPHERICAL SHELL

The standard notations\(^1\) for the physical quantities involved are

\[
\begin{align*}
S_i & \quad \text{strain} \\
T_i & \quad \text{stress} \\
E_m & \quad \text{electric field} \\
E_{ij}^{E} & \quad \text{elastic compliance coefficients} \\
E_{ij}^{E} & \quad \text{elastic stiffness coefficients} \\
d_{mi} & \quad \text{piezoelectric constants} \\
e_{mj} & \quad \text{piezoelectric constants}
\end{align*}
\]

\(^{1}\) For the physical quantities involved are

\[
\begin{align*}
S_i & \quad \text{strain} \\
T_i & \quad \text{stress} \\
E_m & \quad \text{electric field} \\
E_{ij}^{E} & \quad \text{elastic compliance coefficients} \\
E_{ij}^{E} & \quad \text{elastic stiffness coefficients} \\
d_{mi} & \quad \text{piezoelectric constants} \\
e_{mj} & \quad \text{piezoelectric constants}
\end{align*}
\]
The general relationships among the strain, stress, and electric field are

\[ S_i = s_{ij}^E T_j + d_{mi} E_m \tag{1} \]

or

\[ T_j = c_{ij}^E S_i - e_{mj} E_m \tag{2} \]

with

\[ i,j = 1,2,...,6 \quad m = 1,2,3 \]

Considerable simplification of equations (1) and (2) results when we make use of the general properties, \( s_{ij} = s_{ji} \) and \( c_{ij} = c_{ji} \), transverse isotropy (rotational symmetry about the \( x_3 \) axis), and spherically symmetric electrical excitation with \( E_1 = E_2 = 0 \). Then, equations (1) and (2) become

\[ S_2 = S_1 = (s_{11} + s_{12}) T_1 + s_{13} T_3 + d_{31} E_3 \tag{3a} \]

\[ S_3 = 2s_{13} T_1 + s_{33} T_3 + d_{33} E_3 \tag{3b} \]

\[ T_2 = T_1 = (c_{11} + c_{12}) S_1 + c_{13} S_3 - e_{31} E_3 \tag{4a} \]

\[ T_3 = 2c_{13} S_1 + c_{33} S_3 - e_{33} E_3 \tag{4b} \]

The local \((x_1, x_2, x_3)\) triad is the spherical coordinate system \((\theta, \phi, r)\). Thus, stress components \( T_1 \) and \( T_3 \) are \( T_0 \) and \( T_r \), strain components \( S_1 \) and \( S_3 \) are \( S_0 \) and \( S_r \), and the electric field component \( E_3 \) is \( E_r \).

The equation of motion of a shell element is

\[ \frac{\partial T_3}{\partial r} + \frac{2}{r} (T_3 - T_1) = \rho \frac{\partial^2 \xi}{\partial t^2} \tag{5} \]

in which \( \xi(r,t) \) is the outward radial displacement and \( \rho \) is the density of the PZT-4. The strains are

\[ S_1 = \frac{\xi}{r} \quad S_3 = \frac{\partial \xi}{\partial r} \tag{6} \]

Substitution in (5) of the stresses from (4) followed by substitution of the strains from (6) leads to the governing equation

4
\[
\frac{c_{33} \partial^2 \xi}{\partial r^2} + 2c_{33} \frac{1}{r} \frac{\partial \xi}{\partial r} - 2(c_{11} + c_{12} - c_{13}) \frac{\xi}{r^2} - \rho \frac{\partial^2 \xi}{\partial t^2} = e_{33} \frac{\partial E}{\partial r} + 2(e_{33} - e_{31}) \frac{E}{r}
\]  

(7)

where we have replaced the symbol \(E_3\) by \(E\). If the potential at the inner radius \(r = b\) is higher than the potential at the outer radius \(r = a\) by the voltage \(V\), the field is

\[
E(r,t) = \frac{ab}{a - b} \cdot \frac{V(t)}{r^2}
\]

(8)

Then equation (7) becomes

\[
\frac{c_{33} \partial^2 \xi}{\partial r^2} + 2c_{33} \frac{1}{r} \frac{\partial \xi}{\partial r} - 2(c_{11} + c_{12} - c_{13}) \frac{\xi}{r^2} - \rho \frac{\partial^2 \xi}{\partial t^2} = - \frac{2ab}{a - b} e_{31} V(t) \frac{1}{r^3}
\]

(9)

At the free inner boundary, \(r = b\), the radial stress component is \(T_3 = 0\) so by equations (4b), (6), and (8) this condition is

\[
\frac{\partial \xi}{\partial r} + 2 \frac{\xi}{r} = \frac{e_{33}}{c_{33}} \frac{ab}{a - b} \cdot \frac{V}{r^2} \quad \text{at} \quad r = b
\]

(10)

The condition at the outer boundary depends on the problem being solved. For a traction free outer boundary, the condition is \(T_3 = 0\) at \(r = a\), that is,

\[
\frac{\partial \xi}{\partial r} + 2 \frac{\xi}{r} = \frac{e_{33}}{c_{33}} \frac{ab}{a - b} \cdot \frac{V}{r^2} \quad \text{at} \quad r = a
\]

(11)

To obtain an upper bound on the interface pressure at \(r = a\), we have \(S_1 = S_2 = 0\) at \(r = a\), that is,

\[
\frac{\xi}{r} = 0 \quad \text{at} \quad r = a
\]

(12)

This condition corresponds to a spherical source in a rigid material. For our case of an elastic material, the condition at \(r = a\) is \(T_3 = -p(t)\), the interaction pressure. The solution is a relationship between the radial displacement at \(r = a\) and the interaction pressure. By analyzing the problem of a pressure \(p(t)\) acting in a spherical cavity of radius \(r = a\) in an
elastic medium, we obtain a second relationship between cavity wall radial displacement and the pressure \( p(t) \). Equating the displacements gives an equation for the required interface pressure.

The governing equation (9) and the various boundary conditions can be solved explicitly but the results are extremely cumbersome. Therefore, for aiding the interpretation of experimental results, the source analysis is simplified by using thin shell theory. In this theory, the radial component of stress, \( T_3 \), is neglected.

Let the mean radius of the shell be \( r = a \) and introduce the interface pressure \( p(t) \) to be determined. The shell outward radial displacement is \( \xi(t) \) and the thickness is \( h \). The equation of motion is

\[
\rho \ddot{\xi} = -\frac{2}{a} T_1 \cdot \frac{p(t)}{h}
\]  

and if in equation (3a) we set \( T_3 = 0 \) and \( S_1 = \xi/a \) to provide the average circumferential stress \( T_1 \) in equation (13), we obtain

\[
\ddot{\xi} + \omega^2 \xi = -\frac{p(t)}{\rho h} + \omega^2 a d_{31} E
\]  

where

\[
\omega^2 = 2/\rho a^2 (s_{11} + s_{12})
\]

The initial conditions of interest are

\[
\xi(0) = 0 \quad \dot{\xi}(0) = 0
\]

The solution of equation (14) satisfying the initial conditions (16) is

\[
\xi(t) = \frac{1}{\omega} \int_0^t \left( \omega^2 a d_{31} E(\tau) - \frac{1}{\rho h} p(\tau) \right) \sin \omega(t - \tau) d\tau
\]

If the driving electric field is

\[
E(t) = E_0(1 - e^{-\alpha t})
\]
the shell velocity, according to the displacement (17), is given by

$$ \frac{\ddot{x}(t)}{v} = \frac{\alpha}{\omega + (\omega/\alpha)^2} \left( \alpha_0 \cos\omega t - \cos\omega t + e^{-\alpha t} \right) - \frac{1}{\rho h} \int_0^t p(\tau) \cos\omega(t - \tau) d\tau $$

(19)

where

$$ v = \omega a d_0 E_0 $$

(20)

The velocity, $v$, is the maximum velocity achieved by the shell in a vacuum when subjected to a step voltage, $E_0$. Formula (19) gives the relationship between the shell radial velocity and the interaction pressure from the surrounding elastic medium.

**SPHERICAL CAVITY IN AN ELASTIC MEDIUM**

When the stress-strain relationships

$$ \sigma_r = (\lambda + 2\mu) \frac{\partial \xi}{\partial r} + 2\lambda \frac{\xi}{r} $$

(21)

$$ \sigma_\theta = \lambda \frac{\partial \xi}{\partial r} + 2(\lambda + \mu) \frac{\xi}{r} $$

(22)

are substituted in the equation of motion

$$ \frac{\partial \sigma_r}{\partial r} + \frac{2}{r} (\sigma_r - \sigma_\theta) = \rho_m \frac{\partial^2 \xi}{\partial t^2} $$

(23)

we obtain the displacement equation

$$ \frac{\partial^2 \xi}{\partial r^2} + \frac{2}{r} \frac{\partial \xi}{\partial r} - \frac{2\xi}{r} = \frac{1}{c^2} \frac{\partial^2 \xi}{\partial t^2} $$

(24)
In (21) and (22), the $\sigma_r$ and $\sigma_\theta$ are the radial and circumferential stress components, and $\lambda$ and $\mu$ are the Lamé constants for the isotropic elastic medium. In (23), $\rho_m$ is the medium density. In (24), $c^2 = (\lambda + 2\mu)/\rho_m$ where $c$ is the elastic wave velocity.

Introduction of the displacer ent potential $\Psi$ defined by

$$\xi = \frac{\partial \phi}{\partial r}$$  \hspace{1cm} (25)

reduces (24) to

$$\frac{\partial^2 (r \phi)}{\partial r^2} = \frac{1}{c^2} \frac{\partial^2 (r \phi)}{\partial t^2}$$  \hspace{1cm} (26)

The solution of (26) describing outgoing waves is

$$\phi(r,t) = \frac{1}{r} f(s) \quad s = t - (r - a)/c$$  \hspace{1cm} (27)

In terms of the function $f(s)$, the displacement, velocity, and stresses are

$$\xi = - \frac{f'}{cr} \frac{f}{r^2}$$  \hspace{1cm} (28)

$$\frac{\partial \xi}{\partial t} = - \frac{f''}{cr} \frac{f'}{r^2}$$  \hspace{1cm} (29)

$$\sigma_r = \rho c^2 \left( \frac{f''}{cr^2} + \frac{2(1 - 2\theta)}{1 - \theta} \left( \frac{f'}{cr^2} + \frac{f}{r^3} \right) \right)$$  \hspace{1cm} (30)

$$\sigma_\theta = \frac{\rho c^2}{1 - \theta} \left( \frac{\partial f}{c^2 r} - (1 - 2\theta) \left( \frac{f'}{cr^2} + \frac{f}{r^3} \right) \right)$$  \hspace{1cm} (31)

in which $\theta$ is Poisson's ratio.

For a given cavity wall velocity, $\dot{\xi}(t)$, we have, from (29), the equation

$$f''(s) + \frac{c}{a} f(s) = ca\dot{\xi}'(s)$$  \hspace{1cm} (32)
and \( f(0) = f'(0) = 0 \) at the wave front \( s = 0 \). The solution is

\[
f(s) = - c \tau \int_{0}^{s} e^{c \tau / a} \xi(\tau) d\tau
\]

with

\[
f(s) = - \frac{c}{a} f(s) - c a \xi(s)
\]

\[
f''(s) = \frac{c^2}{a^2} f(s) - c a \xi'(s) + c^2 \xi(s)
\]

The cavity pressure required to maintain the cavity wall velocity is found by substituting (33), (34), and (35) in the radial stress formula (30) and setting \( r = a \) (\( s = t \)) and \( \sigma_r(a,t) = -p(t) \). These steps give

\[
p(t) = \rho c \dot{\xi}(t) - \frac{\rho c^2}{a} \left\{ \frac{f(t)}{a^2} + \xi - \frac{2(1 - 2\vartheta)}{1 - \vartheta} \xi \right\}
\]

with \( f(t) \) given by (33) with \( s = t \).

Formally, the velocity of the interface between the source and the medium is obtained by solving the equation that results from substituting the interface pressure (36) in the shell velocity equation (19). This equation is inconvenient so we introduce an approximation for the interface pressure (36). By integrating \( f(t) \) from (33) by parts, we obtain

\[
\frac{f(t)}{a^2} = - \xi + e^{(c/a)\tau} \int_{0}^{t} e^{(c/a)\tau} \dot{\xi}(\tau) d\tau
\]

For an electric field excitation (18) on the sphere in a vacuum, the second term on the right hand side of (37) is much smaller than the first term if \( \alpha \ll \omega \), which it is in our case. Assuming a similar relative magnitude when the source is embedded in a solid allows us to approximate \( f(t) \) by

\[
\frac{f(t)}{a^2} = - \xi
\]
so that (36) simplifies to

\[ p(t) = \rho c \ddot{\xi}(t) + \frac{\rho c^2}{a} \frac{2(1 - 2\theta)}{1 - \theta} \dot{\xi}(t) \]  

(38)

Substitution of (38) in the shell equation (14) gives

\[ \ddot{\xi} + 2\gamma \dot{\xi} + \Omega^2 \xi = \omega v(1 - e^{-\alpha t}) \]  

(39)

where

\[ \gamma = \rho_m c/2\rho \]  

(40)

\[ \Omega^2 = \omega^2 + (\rho_m c^2/\rho a)[2(1 - 2\theta)(1 - \theta)] \]  

(41)

and \( \rho_m \) is the density of the medium. The wave speed in the medium is defined by \( c^2 = (\lambda + 2\mu)/\rho_m \). In terms of the stiffness coefficients, the angular frequency of the piezoelectric shell in a vacuum is given by

\[ \omega^2 = 2(c_{11} + c_{12} - 2c_{33}/c_{33})/\rho a^2 \]  

(42)

In (39), the velocity, \( v \), is given by (20).

The solution of equation (39) satisfying the initial conditions (16) is

\[ \frac{\Omega^2}{\omega^2} \xi(t) = 1 - \frac{1}{\Omega^2 + (\gamma - \alpha)^2} \left\{ \Omega^2 e^{-\alpha t} - \alpha e^{-\gamma t} \left( \begin{array}{c} \Omega(2\gamma - \alpha) - \alpha \Omega \sin \Omega t \\ \Omega \sin \Omega t \end{array} \right) \right\} \]  

(43)

where

\[ \bar{\Omega}^2 = \Omega^2 - \gamma^2 \]  

(44)

For excitations with rise times that are long compared to the natural quarter period, we have \( \alpha^2 \ll \bar{\Omega}^2 \) and the radial displacement (43) becomes
\[
\frac{\Omega^2}{\alpha \omega} \cdot \xi(t) = 1 - e^{-\alpha t} - \frac{\alpha}{\Omega} e^{\gamma t} \sin \Omega t
\]  

(45)

The shell radial velocity obtained by differentiating (45) is,

\[
\frac{\Omega^2}{\alpha \omega} \cdot \dot{\xi}(t) = e^{-\alpha t} - e^{\gamma t} \left( \cos \Omega t - \frac{\gamma}{\Omega} \sin \Omega t \right)
\]  

(46)

Substitution of \( \dot{\xi}(t) \) from (45) into (33) and performing the integration gives

\[
- \frac{\Omega^2}{a^2 \omega} f(s) = 1 - \frac{1}{(c/a) - \alpha} \left( e^{-\alpha s} - \alpha e^{-(c/a)s} \right) - \frac{\alpha(c/a)}{\Omega^2} \times \\
\left\{ e^{-(c/a)s} - e^{\gamma s} \left( \cos \Omega s - \frac{(c/a) - \gamma}{\Omega} \sin \Omega s \right) \right\}
\]  

(47)

Formulas (34) and (35) determine \( f' \) and \( f'' \) because \( \xi(s), \xi'(s), \) and \( f(s) \) are given by (45), (46), and (47). Consequently, we can determine \( \xi, \xi', \sigma_r, \) and \( \sigma_\theta \) by (28)-(31).

**FLUID MEDIUM**

If we set \( \phi = 1/2 \) in the frequency formula (41),

\[
\Omega^2 = \omega^2
\]  

(48)

and, by (44)

\[
\overline{\Omega}^2 = \omega^2 - \gamma^2
\]  

(49)

where the fluid wave velocity is \( c = (K/\rho_m) \), \( K \) being the fluid bulk modulus. In our case, \( \gamma < \omega \) so (45), (46), and (47) become

\[
\xi(s) = \frac{\nu}{\omega} \left( 1 - e^{-\alpha s} - \frac{\alpha}{\omega} e^{\gamma s} \sin \omega s \right)
\]  

(50)

\[
\xi'(s) = \frac{\nu \alpha}{\omega} \left( e^{-\alpha s} - e^{\gamma s} \left( \cos \omega s - \frac{\gamma}{\omega} \sin \omega s \right) \right)
\]  

(51)
\[- \frac{\omega}{a^2} f(s) = 1 - \frac{1}{(c/a) - \alpha} \left\{ e^{-\alpha s} - \alpha e^{-(c/a)s} \right\} \]
\[- \frac{\alpha(c/a)}{\omega^2} \left[ e^{-(c/a)s} - \alpha \left( \cos \omega s - \frac{(c/a) - \gamma}{\omega} \sin \omega s \right) \right] \]

(52)

Stress formulas (30) and (31) are replaced by the pressure formula

\[ p = - \rho mf''(s)/r \]

(53)

where \( f''(s) \) is determined by (35), (50), (51), and (52).

**NUMERICAL VALUES (SOLID MEDIUM)**

The properties we require of the PZT-4 ceramic are

**Elastic compliance coefficients (m\(^2\)/N)**

\[
\begin{align*}
S_{11}^E & = 12.30 \times 10^{-12} \\
S_{12}^E & = -4.05 \times 10^{-12} \\
S_{13}^E & = -5.31 \times 10^{-12} \\
S_{33}^E & = 15.50 \times 10^{-12}
\end{align*}
\]

**Elastic stiffness coefficients (N/m\(^2\))**

\[
\begin{align*}
c_{11}^E & = 13.90 \times 10^{10} \\
c_{12}^E & = 7.78 \times 10^{10} \\
c_{13}^E & = 7.43 \times 10^{10} \\
c_{33}^E & = 11.50 \times 10^{10}
\end{align*}
\]

**Piezoelectric constants (m/V, c/N)**

\[
\begin{align*}
d_{31} & = -123 \times 10^{-12} \\
d_{33} & = 289 \times 10^{-12}
\end{align*}
\]

**Piezoelectric constants (Nm/V, c/m\(^2\))**

\[
\begin{align*}
e_{31} & = -5.20 \\
e_{33} & = 15.10
\end{align*}
\]

**Density** \( \rho = 7.5 \times 10^3 \text{ kg/m}^3 \)

The properties of the 'Pourstone' medium are

**Young's modulus** \( E = 16.4 \text{ GPa} \)

**Shear modulus** \( \mu = 6.3 \text{ GPa} \)
Bulk modulus \( K \) & 13.8 GPa
Poisson's ratio \( \nu \) & 0.3
Lame constant \( \lambda \) & 9.6 GPa
Density \( \rho_m \) & \( 1.79 \times 10^3 \) kg/m\(^3\)
P-wave velocity \( c_p \) & 3.52 mm/\( \mu \)s (km/s)
S-wave velocity \( c_s \) & 1.88 mm/\( \mu \)s (km/s)

The dimensions of the spherical source are

Outer radius \( a \) & 6.350 mm
Inner radius \( b \) & 4.826 mm
Thickness \( h \) & 1.524 mm

The driving voltage, \( V(t) \), is taken in the form

\[
V(t) = V_0 (1 - e^{-\alpha t})
\]  

(54)

applied to the outside of the spherical shell. If the value at the midradius, \( (a + b)/2 \), is chosen to represent the field strength, then according to (8) and (54),

\[
E(t) = -644 V_0 (1 - e^{-\alpha t}) \text{ volts/m}
\]

By letting the voltage reach 90% of \( V_0 \) in 20 \( \mu \)s, the value of \( \alpha \) is determined as \( \alpha = 0.115 \) \( \mu \)s\(^{-1}\). Also, if \( V_0 = 300 \) volts, we have \( E_0 = -0.1932 \times 10^6 \) volts/m. Hence,

\[
E(t) = -0.1932 \times 10^6 (1 - e^{-0.115 t})
\]

where \( t \) has \( \mu \)s units.

The natural angular frequency of the spherical source (in a vacuum), according to (15), is \( \omega = 0.895 \times 10^6 \) rad/s and the natural frequency is \( f = \omega/2\pi = 142 \) kHz.

If the voltage is applied slowly to the free shell, the maximum radial displacement is

\[
\xi_s = ad_3 E_0 = 0.15 \times 10^{-3} \text{ mm} = 0.15 \mu \text{m}
\]

If the same voltage (300 volts) is applied instantaneous, the maximum displacement is \( 2\xi_s \), and the maximum velocity is

\[
\max \dot{\xi} = v = \omega ad_3 E_0 = \omega \xi_s = 13.4 \text{ cm/s}
\]
If the voltage is applied slowly to the shell confined by a rigid medium, the interface pressure is \( p = - (2h/a)T_1 \) where the circumferential stress is \( T_1 = - d_{31}E_\sigma/(s_{11} + s_{12}) \). The magnitude of this pressure is \( p = 14.05 \) bars (206 psi).

In Equation (39) governing the shell motion in an elastic medium, the numerical values of \( \gamma \) and \( \Omega \), and consequently \( \dot{\Omega} \) are

\[
\gamma = 0.276 \times 10^6 \text{ rad/s} \quad \Omega = 1.073 \times 10^6 \text{ rad/s} \quad \dot{\Omega} = 1.037 \times 10^6 \text{ rad/s}
\]

For comparison, we note that \( \dot{\alpha} = 0.115 \times 10^6 \text{ s}^{-1} \). Because \( \alpha^2 \ll \dot{\Omega}^2 \) formulas (45), (46), and (47) for the shell radial displacement and velocity and the potential function \( f(s) \) are applicable. The value of \( c/a \) occurring in \( f(s) \) is \( c/a = 0.554 \times 10^6 \text{ s}^{-1} \).

The oscillatory part of the solution has a frequency of \( \ddot{\Gamma} = \Omega/2\pi = 165 \text{ kHz} \) with a period of \( T = 1/\ddot{\Gamma} = 6 \mu\text{s} \).

**NUMERICAL VALUES (WATER)**

Using a density of \( \rho_m = 1 \text{ gram/cm}^3 \) and a bulk modulus of \( K = 2.245 \text{ GPa (22.45 kbar)} \), we obtain

- Wave velocity \( c = (K/\rho_m)^{1/2} = 1.50 \text{ mm/\mu s} \)
- Damping parameter \( \gamma = 0.066 \times 10^6 \text{ rad/s} \)
- Spring parameter \( \Omega = \omega = 0.895 \times 10^6 \text{ rad/s} \)
- Angular frequency \( \dot{\Omega} = 0.893 \times 10^6 \text{ rad/s} = \Omega \)
- Velocity parameter \( c/a = 0.236 \times 10^6 \text{ s}^{-1} \)
- Excitation parameter \( \alpha = 0.115 \times 10^6 \text{ s}^{-1} \)

**APPLICATION OF SOLUTION IN A WATER MEDIUM**

We applied the solution just derived for the case of a spherical piezoelectric source in a water medium, and compared the calculated and measured pressure histories at three radii from the source. The experimental configuration is shown in Figure 2. In the experiments, the crystal was excited with a known voltage history, and free-field water pressure histories were measured at radii of 0.91, 1.51, and 3.38-cm measured from the center of the source. The input voltage history to the crystal is shown in Figure 3. The voltage reaches 90 % of the peak value of 316 volts at 10 \mu\text{s}, so in the formulation
Figure 2. Configuration for measuring stress pulse amplitudes in water at different radii from the source and sphericity of piezoelectric source.
Figure 3. Input voltage history to the piezoelectric source in the water pressure experiment.
described previously, the value of $\alpha$ is $0.230 \times 10^6 \mu s^{-1}$, and the field strength as a function of time is described by:

$$E(t) = -0.2075 \times 10^6 (1 - e^{-0.23 \times t})$$

where the field strength, $E(t)$, has units Volts/m and $t$ has units $\mu$s.

The calculated and measured pressure histories are shown superposed for the three gage locations in Figure 4, 5, and 6. At the first gage location, the measured and calculated histories show very good agreement in oscillation frequency and peak amplitude. At the further out locations, the measurements show larger damping than predicted by the calculation, but satisfactory agreement is observed in peak pressure and the oscillation frequency.

APPLICATION OF SOLUTION TO AN ELASTIC MEDIUM

The agreement between calculation and experiment in a water medium is sufficient to extend the solution to an elastic medium and estimate the expected amplitudes of velocity and displacement at different ranges in the medium. In addition, the calculated pressure history at the source/medium interface can be used as an input boundary condition for finite element calculations of the experiment shown in Figure 1. The results of the finite element calculations will be useful for estimating expected signal levels on the surface and assist in instrumentation selection for that experiment. The elastic medium is a rock simulant called pourstone, with the elastic properties listed on page (16). Using the same voltage history shown in Figure 3 as the input, the calculated velocity histories at radii of 0.635 cm (source/medium interface), 1.5- and 2.5-cm are shown superposed in Figure 7. The corresponding displacements for the three locations are shown in Figure 8, and the radial and circumferential stress histories are shown in Figures 9 and 10, respectively.

EVALUATION EXPERIMENT IN POURSTONE

We performed experiments to compare the calculated and measured velocity and displacement histories in a sphere of pourstone. The experimental configuration is shown in Figure 11. In this experiment, copper loops were cast in the midplane of a 12-cm diameter sphere of pourstone to measure radial particle velocity histories at different radii from the source. The specimen is placed in an external magnetic field, and we measure the induced voltage as the conductor cuts flux lines during passage of the stress wave. The particle velocity is proportional to the induced voltage, the magnetic field strength, and the
Figure 4. Comparison of measured and calculated pressure histories in water at a range of 0.91-cm from the center of the source.
Figure 5. Comparison of measured and calculated pressure histories in water at a range of 1.51-cm from the center of the source.
Figure 6. Comparison of measured and calculated pressure histories in water at a range of 3.38-cm from the center of the source.
Figure 7. Calculated velocity histories at 3 ranges in pourstone from a spherical piezoelectric crystal excited by 316 volts.
Figure 8. Calculated displacement histories at three ranges in pourstone from a spherical piezoelectric crystal excited by 316 volts.
Figure 9. Calculated radial stress histories at three ranges in pourstone from a spherical piezoelectric crystal excited by 316 volts.
Figure 10. Calculated circumferential stress histories at three ranges in pourstone from a spherical piezoelectric crystal excited by 316 volts.
Figure 11. Configuration for source/sensor evaluation experiment.
length of the conductor. To increase the expected signal, we increased the gage length by constructing gages consisting of 10 windings of copper wire. Accelerometers and PVDF foils were mounted on the surface of the sphere to measure free-surface acceleration and strain, respectively.

We are currently analyzing the data obtained from the particle velocity gages. The accelerometers and PVDF foils did not produce satisfactory signals because the range of the measurement was too large. Consequently, we plan to fabricate a smaller specimen to evaluate these gages at locations closer to the source.
Contractors (United States)

Prof. Thomas Ahrens
Seismological Lab, 252-21
Division of Geological & Planetary Sciences
California Institute of Technology
Pasadena, CA 91125

Prof. Charles B. Archambeau
CIRES
University of Colorado
Boulder, CO 80309

Prof. Muawia Barazangi
Institute for the Study of the Continent
Cornell University
Ithaca, NY 14853

Dr. Douglas R. Baumgardt
ENSCO, Inc
5400 Port Royal Road
Springfield, VA 22151-2388

Prof. Jonathan Berger
IGPP, A-025
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, CA 92093

Dr. Lawrence J. Burdick
Woodward-Clyde Consultants
566 El Dorado Street
Pasadena, CA 91109-3245

Dr. Karl Coyner
New England Research, Inc.
76 Olcott Drive
White River Junction, VT 05001

Prof. Vernon F. Cormier
Department of Geology & Geophysics
U-45, Room 207
The University of Connecticut
Storrs, CT 06268

Professor Anton W. Dainty
Earth Resources Laboratory
Massachusetts Institute of Technology
42 Carleton Street
Cambridge, MA 02142

Prof. Steven Day
Department of Geological Sciences
San Diego State University
San Diego, CA 92182

Dr. Zoltan A. Der
ENSCO, Inc.
5400 Port Royal Road
Springfield, VA 22151-2388

Prof. John Ferguson
Center for Lithospheric Studies
The University of Texas at Dallas
P.O. Box 830688
Richardson, TX 75083-0688

Prof. Stanley Flatte
Applied Sciences Building
University of California
Santa Cruz, CA 95064

Dr. Alexander Florence
SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025-3493

Prof. Henry L. Gray
Vice Provost and Dean
Department of Statistical Sciences
Southern Methodist University
Dallas, TX 75275

Dr. Indra Gupta
Teledyne Geotech
314 Montgomery Street
Alexandria, VA 22314

Prof. David G. Harkrider
Seismological Laboratory
Division of Geological & Planetary Sciences
California Institute of Technology
Pasadena, CA 91125

Prof. Donald V. Helmberger
Seismological Laboratory
Division of Geological & Planetary Sciences
California Institute of Technology
Pasadena, CA 91125

Prof. Eugene Herrin
Institute for the Study of Earth and Man
Geophysical Laboratory
Southern Methodist University
Dallas, TX 75275

Prof. Robert B. Herrmann
Department of Earth & Atmospheric Sciences
St. Louis University
St. Louis, MO 63156
Prof. Bryan Isacks  
Cornell University  
Department of Geological Sciences  
SNEE Hall  
Ithaca, NY 14850

Dr. Rong-Song Jih  
Teledyne Geotech  
314 Montgomery Street  
Alexandria, VA 22314

Prof. Lane R. Johnson  
Seismographic Station  
University of California  
Berkeley, CA 94720

Prof. Alan Kafka  
Department of Geology & Geophysics  
Boston College  
Chestnut Hill, MA 02167

Dr. Richard LaCoss  
MIT-Lincoln Laboratory  
M-200B  
P. O. Box 73  
Lexington, MA 02173-0073 (3 copies)

Prof. Fred K. Lamb  
University of Illinois at Urbana-Champaign  
Department of Physics  
1110 West Green Street  
Urbana, IL 61801

Prof. Charles A. Langston  
Geosciences Department  
403 Deike Building  
The Pennsylvania State University  
University Park, PA 16802

Prof. Thorne Lay  
Institute of Tectonics  
Earth Science Board  
University of California, Santa Cruz  
Santa Cruz, CA 95064

Prof. Arthur Lerner-Lam  
Lamont-Doherty Geological Observatory  
of Columbia University  
Palisades, NY 10964

Dr. Christopher Lynnes  
Teledyne Geotech  
314 Montgomery Street  
Alexandria, VA 22314

---

Prof. Peter Malin  
University of California at Santa Barbara  
Institute for Crustal Studies  
Santa Barbara, CA 93106

Dr. Randolph Martin, III  
New England Research, Inc.  
76 Olcott Drive  
White River Junction, VT 05001

Dr. Gary McCartor  
Mission Research Corporation  
735 State Street  
P.O. Drawer 719  
Santa Barbara, CA 93102 (2 copies)

Prof. Thomas V. McEvilly  
Seismographic Station  
University of California  
Berkeley, CA 94720

Dr. Keith L. McLaughlin  
S-CUBED  
A Division of Maxwell Laboratory  
P.O. Box 1620  
La Jolla, CA 92038-1620

Prof. William Menke  
Lamont-Doherty Geological Observatory  
of Columbia University  
Palisades, NY 10964

Stephen Miller  
SRI International  
333 Ravenswood Avenue  
Box AF 116  
Menlo Park, CA 94025-3493

Prof. Bernard Minster  
IGPP, A-025  
Scripps Institute of Oceanography  
University of California, San Diego  
La Jolla, CA 92093

Prof. Brian J. Mitchell  
Department of Earth & Atmospheric Sciences  
St. Louis University  
St. Louis, MO 63156

Mr. Jack Murphy  
S-CUBED, A Division of Maxwell Laboratory  
11800 Sunrise Valley Drive  
Suite 1212  
Reston, VA 22091 (2 copies)
Dr. Bao Nguyen  
GL/LWH  
Hanscom AFB, MA 01731-5000

Prof. Jeremiah Sullivan  
University of Illinois at Urbana-Champaign  
Department of Physics  
1110 West Green Street  
Urbana, IL 61801

Prof. John A. Orcutt  
IGPP, A-025  
Scripps Institute of Oceanography  
University of California, San Diego  
La Jolla, CA 92093

Prof. Clifford Thurber  
University of Wisconsin-Madison  
Department of Geology & Geophysics  
1215 West Dayton Street  
Madison, WI 53706

Prof. Keith Priestley  
University of Cambridge  
Bullard Labs, Dept. of Earth Sciences  
Madingly Rise, Madingly Rd.  
Cambridge CB3 OEZ, ENGLAND

Prof. M. Nafi Toksoz  
Earth Resources Lab  
Massachusetts Institute of Technology  
42 Carleton Street  
Cambridge, MA 02142

Prof. Paul G. Richards  
L-210  
Lawrence Livermore National Laboratory  
Livermore, CA 94550

Prof. John E. Vidale  
University of California at Santa Cruz  
Seismological Laboratory  
Santa Cruz, CA 95064

Dr. Wilmer Rivers  
Teledyne Geotech  
314 Montgomery Street  
Alexandria, VA 22314

Prof. Terry C. Wallace  
Department of Geosciences  
Building #77  
University of Arizona  
Tucson, AZ 85721

Dr. Wilmer Rivers  
Teledyne Geotech  
314 Montgomery Street  
Alexandria, VA 22314

Prof. Charles G. Sammis  
Center for Earth Sciences  
University of Southern California  
University Park  
Los Angeles, CA 90089-0741

Dr. Raymond Willeman  
GL/LWH  
Hanscom AFB, MA 01731-5000

Prof. Christopher H. Scholz  
Lamont-Doherty Geological Observatory  
of Columbia University  
Palisades, NY 10964

Dr. Lorraine Wolf  
GL/LWH  
Hanscom AFB, MA 01731-5000

Prof. David G. Simpson  
Lamont-Doherty Geological Observatory  
of Columbia University  
Palisades, NY 10964

Prof. Francis T. Wu  
Department of Geological Sciences  
State University of New York  
at Binghamton  
Vestal, NY 13901

Dr. Jeffrey Stevens  
S-CUBED  
A Division of Maxwell Laboratory  
P.O. Box 1620  
La Jolla, CA 92038-1620

Prof. Brian Stump  
Institute for the Study of Earth & Man  
Geophysical Laboratory  
Southern Methodist University  
Dallas, TX 75275

-3-
OTHERS (United States)

Dr. Monem Abdel-Gawad  
Rockwell International Science Center  
1049 Camino Dos Rios  
Thousand Oaks, CA 91360

Dr. G.A. Bollinger  
Department of Geological Sciences  
Virginia Polytechnical Institute  
21044 Derring Hall  
Blacksburg, VA 24061

Prof. Keiiti Aki  
Center for Earth Sciences  
University of Southern California  
University Park  
Los Angeles, CA 90089-0741

Dr. Stephen Bratt  
Science Applications Int'l Corp.  
10210 Campus Point Drive  
San Diego, CA 92121

Prof. Shelton S. Alexander  
Geosciences Department  
403 Deike Building  
The Pennsylvania State University  
University Park, PA 16802

Michael Browne  
Teledyne Geotech  
3401 Shiloh Road  
Garland, TX 75041

Dr. Kenneth Anderson  
BBNSTC  
Mail Stop 14/1B  
Cambridge, MA 02238

Mr. Roy Burger  
1221 Serry Road  
Schenectady, NY 12309

Dr. Ralph Archuleta  
Department of Geological Sciences  
University of California at Santa Barbara  
Santa Barbara, CA 93102

Dr. Robert Burridge  
Schlumberger-Doll Research Center  
Old Quarry Road  
Ridgefield, CT 06877

Dr. Thomas C. Bache, Jr.  
Science Applications Int'l Corp.  
10210 Campus Point Drive  
San Diego, CA 92121 (2 copies)

Dr. Jerry Carter  
Rondout Associates  
P.O. Box 224  
Stone Ridge, NY 12484

J. Barker  
Department of Geological Sciences  
State University of New York at Binghamton  
Vestal, NY 13901

Dr. W. Winston Chan  
Teledyne Geotech  
314 Montgomery Street  
Alexandria, VA 22314-1581

Dr. T.J. Bennett  
S-CUBED  
A Division of Maxwell Laboratory  
11800 Sunrise Valley Drive, Suite 1212  
Reston, VA 20191

Dr. Theodore Cherry  
Science Horizons, Inc.  
710 Encinitas Blvd., Suite 200  
Encinitas, CA 92024 (2 copies)

Mr. William J. Best  
907 Westwood Drive  
Vienna, VA 22180

Prof. Jon F. Claerbout  
Department of Geophysics  
Stanford University  
Stanford, CA 94305

Dr. N. Biswas  
Geophysical Institute  
University of Alaska  
Fairbanks, AK 99701

Prof. Robert W. Clayton  
Seismological Laboratory  
Division of Geological & Planetary Sciences  
California Institute of Technology  
Pasadena, CA 91125
Prof. Ta-liang Teng
Center for Earth Sciences
University of Southern California
University Park
Los Angeles, CA 90089-0741

Dr. R.B. Tittmann
Rockwell International Science Center
1049 Camino Dos Rios
P.O. Box 1085
Thousand Oaks, CA 91360

Dr. Gregory van der Vink
IRIS, Inc.
1616 North Fort Myer Drive
Suite 1440
Arlington, VA 22209

Professor Daniel Walker
University of Hawaii
Institute of Geophysics
Honolulu, HI 96822

William R. Walter
Seismological Laboratory
University of Nevada
Reno, NV 89557

Dr. Gregory Wojcik
Weidlinger Associates
4410 El Camino Real
Suite 110
Los Altos, CA 94022

Prof. John H. Woodhouse
Hoffman Laboratory
Harvard University
20 Oxford St.
Cambridge, MA 02138

Dr. Gregory B. Young
ENSCO, Inc.
5400 Port Royal Road
Springfield, VA 22151-2388
Dr. Ralph Alewine III  
DARPA/NMRO  
1400 Wilson Boulevard  
Arlington, VA 22209-2308  

Paul Johnson  
ESS-4, Mail Stop 1979  
Los Alamos National Laboratory  
Los Alamos, NM 87545

Mr. James C. Battis  
GL/LWH  
Hanscom AFB, MA 01731-5000

Mr. James C. Battis  
GL/LWH  
Hanscom AFB, MA 01731-5000

Janet Johnston  
GL/LWH  
Hanscom AFB, MA 01731-5000

Dr. Robert Blandford  
DARPA/NMRO  
1400 Wilson Boulevard  
Arlington, VA 22209-2308

Dr. Katharine Kadinsky-Cade  
GL/LWH  
Hanscom AFB, MA 01731-5000

Eric Chael  
Division 9241  
Sandia Laboratory  
Albuquerque, NM 87185

Ms. Ann Kerr  
IGPP, A-025  
Scripps Institute of Oceanography  
University of California, San Diego  
La Jolla, CA 92093

Dr. John J. Cipar  
GL/LWH  
Hanscom AFB, MA 01731-5000

Dr. Max Koontz  
US Dept of Energy/DP 5  
Forrestal Building  
1000 Independence Avenue  
Washington, DC 20585

Mr. Jeff Duncan  
Office of Congressman Markey  
2133 Rayburn House Bldg.  
Washington, DC 20515

Dr. W.H.K. Lee  
Office of Earthquakes, Volcanoes,  
& Engineering  
345 Middlefield Road  
Menlo Park, CA 94025

Dr. Jack Evemden  
USGS - Earthquake Studies  
345 Middlefield Road  
Menlo Park, CA 94025

Dr. William Leith  
U.S. Geological Survey  
Mail Stop 928  
Reston, VA 22092

Art Frankel  
USGS  
922 National Center  
Reston, VA 22092

Dr. Richard Lewis  
Director, Earthquake Engineering & Geophysics  
U.S. Army Corps of Engineers  
Box 631  
Vicksburg, MS 39180

Dr. T. Hanks  
USGS  
Nat'l Earthquake Research Center  
345 Middlefield Road  
Menlo Park, CA 94025

James F. Lewkowicz  
GL/LWH  
Hanscom AFB, MA 01731-5000

Dr. James Hannon  
Lawrence Livermore Nat'l Laboratory  
P.O. Box 808  
Livermore, CA 94550

Mr. Alfred Lieberman  
ACDA/VI-OA'State Department Bldg  
Room 5726  
320 - 21st Street, NW  
Washington, DC 20451
Stephen Mangino
GL/LWH
Hanscom AFB, MA 01731-5000

Dr. Frank F. Pilotte
HQ AFTAC/TT
Patrick AFB, FL 32925-6001

Dr. Robert Masse
Box 25046, Mail Stop 967
Denver Federal Center
Denver, CO 80225

Katie Poley
CIA-OSWR/NED
Washington, DC 20505

Art McGarr
U.S. Geological Survey, MS-977
345 Middlefield Road
Menlo Park, CA 94025

Mr. Jack Rachlin
U.S. Geological Survey
Geology, Rm 3 C136
Mail Stop 928 National Center
Reston, VA 22092

Richard Morrow
ACDA/VI, Room 5741
320 21st Street N.W
Washington, DC 20451

Dr. Robert Reinke
WL/NTESG
Kirtland AFB, NM 87117-6008

Dr. Keith K. Nakanishi
Lawrence Livermore National Laboratory
P.O. Box 808, L-205
Livermore, CA 94550

Dr. Byron Ristvet
HQ DNA, Nevada Operations Office
Attn: NVCG
P.O. Box 98539
Las Vegas, NV 89193

Dr. Carl Newton
Los Alamos National Laboratory
P.O. Box 1663
Mail Stop C335, Group ESS-3
Los Alamos, NM 87545

Dr. George Rothe
HQ AFTAC/TGR
Patrick AFB, FL 32925-6001

Dr. Kenneth H. Olsen
Los Alamos Scientific Laboratory
P.O. Box 1663
Mail Stop C335, Group ESS-3
Los Alamos, NM 87545

Dr. Alan S. Ryall, Jr.
DARPA/NMRO
1400 Wilson Boulevard
Arlington, VA 22209-2308

Howard J. Patton
Lawrence Livermore National Laboratory
P.O. Box 808, L-205
Livermore, CA 94550

Dr. Michael Shore
Defense Nuclear Agency/SPSS
6801 Telegraph Road
Alexandria, VA 22310

Mr. Chris Paine
Office of Senator Kennedy
SR 315
United States Senate
Washington, DC 20510

Donald L. Springer
Lawrence Livermore National Laboratory
P.O. Box 808, L-205
Livermore, CA 94550

Colonel Jerry J. Perrizo
AFOSR/NP, Building 410
Bolling AFB
Washington, DC 20332-6448

Mr. Charles L. Taylor
GL/LWG
Hanscom AFB, MA 01731-5000
CONTRACTORS (Foreign)

Dr. Ramon Cabre, S.J.
Observatorio San Calixto
Casilla 5939
La Paz, Bolivia

Prof. Hans-Peter Harjes
Institute for Geophysik
Ruhr University/Bochum
P.O. Box 102148
4630 Bochum 1, FRG

Prof. Eystein Husebye
NTNF/NORSAR
P.O. Box 51
N-2007 Kjeller, NORWAY

Prof. Brian L.N. Kennett
Research School of Earth Sciences
Institute of Advanced Studies
G.P.O. Box 4
Canberra 2601, AUSTRALIA

Dr. Bernard Massinon
Societe Radiomana
27 rue Claude Bernard
75005 Paris, FRANCE (2 Copies)

Dr. Pierre Mecheler
Societe Radiomana
27 rue Claude Bernard
75005 Paris, FRANCE

Dr. Svein Mykkeltveit
NTNF/NORSAR
P.O. Box 51
N-2007 Kjeller, NORWAY
FOREIGN (Others)

Dr. Peter Basham  
Earth Physics Branch  
Geological Survey of Canada  
1 Observatory Crescent  
Ottawa, Ontario, CANADA K1A 0Y3

Dr. Fekadu Kebede  
Seismological Section  
Box 12019  
S-750 Uppsala, SWEDEN

Dr. Edouard Berg  
Institute of Geophysics  
University of Hawaii  
Honolulu, HI 96822

Dr. Tormod Kvaerna  
NTNF/NORSAR  
P.O. Box 51  
N-2007 Kjeller, NORWAY

Dr. Michel Bouchon  
I.R.I.G.M.-B.P. 68  
38402 St. Martin D’Heres  
Cedex, FRANCE

Dr. Peter Marshall  
Procurement Executive  
Ministry of Defense  
Blacknest, Brimpton  
Reading FG7-4RS, UNITED KINGDOM

Dr. Hilmar Bungum  
NTNF/NORSAR  
P.O. Box 51  
N-2007 Kjeller, NORWAY

Prof. Ari Ben-Menahem  
Department of Applied Mathematics  
Weizman Institute of Science  
Rehovot, ISRAEL 951729

Dr. Michel Campillo  
Observatoire de Grenoble  
I.R.I.G.M.-B.P. 53  
38041 Grenoble, FRANCE

Dr. Robert North  
Geophysics Division  
Geological Survey of Canada  
1 Observatory Crescent  
Ottawa, Ontario, CANADA K1A 0Y3

Dr. Kin Yip Chun  
Geophysics Division  
Physics Department  
University of Toronto  
Ontario, CANADA M5S 1A7

Dr. Frode Ringdal  
NTNF/NORSAR  
P.O. Box 51  
N-2007 Kjeller, NORWAY

Dr. Alan Douglas  
Ministry of Defense  
Blacknest, Brimpton  
Reading RG7-4RS, UNITED KINGDOM

Dr. Jorg Schlittenhardt  
Postfach 510153  
D-3000 Hannover 51, FEDERAL REPUBLIC OF GERMANY

Dr. Roger Hansen  
NTNF/NORSAR  
P.O. Box 51  
N-2007 Kjeller, NORWAY

Ms. Eva Johannisson  
Senior Research Officer  
National Defense Research Inst.  
P.O. Box 27322  
S-102 54 Stockholm, SWEDEN