192
823-73
U.S. 1973
UK, Germany + Japan

10. 312

HEDL TME 73-61
UC-79p

PRESSURE WAVE TRANSMISSION
IN A FLUID CONTAINED IN A
PLASTICALLY DEFORMING PIPE

HANFORD ENGINEERING DEVELOPMENT LABORATORY
Operated by Westinghouse Hanford Company
Subsidiary of Westinghouse Electric Corporation

P.O. Box 1970 Richland, WA 99352

Prepared for the U.S. Atomic Energy Commission
Division of Reactor Development and Technology
under Contract No. AT(45-1)-2170

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

PRELIMINARY REPORT

This report contains information of a preliminary nature prepared in the course of work under Atomic Energy Commission Contract AT(45-1)2170. This information is subject to correction or modification upon the collection and evaluation of additional data.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$ 4.00 ; Microfiche \$0.95

PRESSURE WAVE TRANSMISSION
IN A FLUID CONTAINED IN A
PLASTICALLY DEFORMING PIPE

G. L. Fox and K. R. Merckx

June 1973

—NOTICE—

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Hanford Engineering Development Laboratory

Operated by the
Westinghouse
Hanford Company

A Subsidiary of
Westinghouse Electric
Corporation

for the United States
Atomic Energy Commission
Contract No. AT(45-1)-2170

MASTER

ABSTRACT

Pressure wave propagation in a fluid filled pipe has been investigated when the wall undergoes plastic deformation. Results show that any pressure pulse sufficient to cause plastic deformation will travel at substantially reduced velocities. This allows unloading waves that normally occur with transient pulses to overtake and dissipate pressures above yielding. Thus, only pressures which cause elastic deformation will propagate long distances along a pipe.

TABLE OF CONTENTS

INTRODUCTION	1
SUMMARY AND CONCLUSIONS	2
Discussion of Analysis	3
Use of Analysis	5
REFERENCES	6
APPENDIX A - BASIC EQUATIONS OF WAVE MOTION	A-1
APPENDIX B - CURVE SMOOTHING AND TANGENT MODULUS CALCULATIONS	B-1
APPENDIX C - LISTING OF COMPUTER PROGRAM	C-1

PRESSURE WAVE TRANSMISSION IN A FLUID CONTAINED IN A PLASTICALLY DEFORMING PIPE

By

G. L. Fox and K. R. Merckx

INTRODUCTION

Pressure wave transmission down pipes is a significant phenomenon in evaluating the effects of an energetic reactor power excursion on the primary system components. A hypothetical accident of this type creates high pressure pulses at the reactor piping nozzles. The transmission of such pressure pulses through pipe, valves, pumps, and heat exchangers is usually studied with the techniques used in water hammer analyses.^(1,2) These analyses do not consider plastic deformation of the piping. Plastic deformation is the major factor in reducing the magnitude of transmitted pressure waves if the pressure is of sufficient magnitude to cause plastic yielding. This report describes a method of analysis and a computer program which estimates effect of plastic pipe deformation on the reduction of the magnitude of the transmitted pressure pulse.

The method of analysis described in this report is a one-dimensional dynamic analysis. The method of approach is similar to that used in standard treatments on water hammer in that the change in fluid column length is related to both the fluid compressibility and the pipe deformation. The difference in this analysis from the standard water hammer analyses is that plastic deformation of the pipe is taken into account. Also, the method of numerical evaluation is based on the identity in structure of the partial differential equation for the deformational waves down the fluid column and for longitudinal plastic waves down a bar.⁽³⁾ The similarity of these solutions is used to take the standard particular solution of plastic waves down a bar and interpret it in terms of the pressure wave and the resultant deformations in

the piping system. The evaluation procedure has been formulated to use the data from experimental stress-strain curves for the piping material. The particular solution used in the analysis applies for constant boundary pressure pulses or inlet fluid velocities, and does not apply for varying pressure pulses.

SUMMARY AND CONCLUSIONS

A one-dimensional computer code named BHAM has been developed to analyze the effects of a pressure pulse traveling down a piping system which is plastically deforming. Using the pipe radius and wall thickness, the program predicts wave pressure, wave velocity, fluid strain, fluid velocity, and wave arrival time at a prescribed location for each strain value read into the program. The density and compressibility of sodium are prescribed with a data statement.

Examples of output from BHAM are shown in Tables I and II. Table I contains the results from fitting and smoothing stress-strain data for Type 316 annealed stainless steel tested at a strain rate of 0.1 sec^{-1} at 1000°F . The tangent modulus, which is required for wave speed calculations, is obtained by differentiating the smoothed stress-strain data.

Table II contains the results from the plastic wave analysis. These results show that any pressure pulse sufficient to cause yielding, (i.e., above 400 psi) will travel at substantially reduced velocity and the wave velocity decreases as the pressure level increases. This allows unloading waves, which travel at elastic velocities of 4385 ft/sec, to overtake and dissipate pressure waves above yielding. The last column in Table II shows the wave arrival time at a prescribed location or the time to reach a specific value of strain. Using Table II, the following conclusions may be drawn:

- Pressure waves which cause plastic deformation travel much slower than elastic waves, resulting in wave dispersion.

- Permanent deformation is maximized near the initial portion of the pipe and thereafter decreases.
- Subsequent pressure drops in the reactor vessel result in unloading waves, traveling at elastic velocities which quickly overtake the slower plastic waves, reducing them to pressure levels corresponding to nominal pipe yield pressures.
- Only pressures which cause elastic deformation will propagate long distances from the reactor vessel; large vessel pressures will never reach the primary loop piping components due to the short pressure duration resulting from hypothetical accidents.

Thus, these analyses provide good physical insight to the effects of a pipe's behavior through all the ranges of pressures which will cause plastic deformations of the piping.

Discussion of Analysis

The theoretical bases for describing the effects of plastic yielding on pressure wave transmission down a pipe are described in Appendix A. The type of assumptions used in water hammer theory^(1,2) or flow through flexible tubes⁽⁴⁾ are used in this development; that is the longitudinal deformations of the water column are governed by fluid compressibility and the radial deformation of the pipe. Plastic yielding is determined using the Tresca yield criteria which permits evaluation without requiring the axial pipe stress. This assumption may slightly underpredict the pressure causing yield. Experimental results for pressurized cylinders, where the axial stress is one-half the circumferential stress, have shown the Tresca criteria underpredicts the yield point by about 8%, although the discrepancy diminishes as the stress ratio, axial stress/circumferential stress, is reduced. For pressure wave propagation down a pipe, the stress ratio should be 1/2 or less, depending on location of elbows and pipe lengths, so the expected error would be about 8% or less. Radial inertia effects of the pipe wall deformations are neglected.

This assumes the pipe wall is always in equilibrium with the moving pressure wave. Neglecting radial pressure waves and time for the wall to achieve equilibrium tends to overpredict the rate of attenuation. These assumptions have been experimentally verified for piping systems many diameters long. The conclusions of these analyses should be similarly valid, although the pressure decay will probably occur over a more extended region of pipe than predicted.

The above assumptions permit the pressure wave problem to be treated as a 1-dimensional system and the resulting wave equation takes the same form as that for plastic waves in a bar. The particular analytic solution⁽³⁾ was selected for a step pressure wave boundary condition to provide insight to the fluid wave problem. This solution was used because general closed form solutions are not available and this solution for the step pressure wave clearly demonstrates the phenomena of wave dispersion applicable to the problem.

The analyses are performed so that plastic wave velocities, strains in the fluid, strains in the pipe, velocity in the fluid, and pressure in the fluid are analyzed for each data point given in the input up until the pipe becomes plastically unstable. Data points should be selected relatively close together because the velocity in the fluid is obtained by a numerical integration procedure.

The computer program, which is listed in Appendix C is a relatively short program that is based on the particular solution given in Appendix A. Since this solution requires no iterations or matrix inversions, etc., the running time of the program for a particular set of data can be measured in seconds. The analyses uses a very small portion of core storage and the calculational scheme is stable for all inputs. The program could be used on any computer system because of its small core storage requirements. The initial portion of the listing in Appendix C describes the data input required by the program. The only feature of this data input which may not be standard is the use of a

control card at the end of the material data with a -1 to end the reading of the material input and a control card of -999 at the end of the piping description cards to start the reading of another case.

Tables I and II are respectively the material smoothing analysis output and wave analysis output from the program. Since the results of analyses performed by this program are directly related to the material input values, care must be taken to assure oneself that there is not a significant strain rate dependence over the ranges of strain rate predicted by the program. Strain rates may be estimated by taking the times of arrival at the location of interest and dividing the strain increments within the tube by these times of arrival.

Use of Analysis

The program described in this report is for a constant pressure pulse or initial velocity input applied to a semi-infinite pipe containing a fluid. The simple numerics result from the particular solution that exists for these boundary conditions for this particular non-linear partial differential equation. Thus, this analysis provides a good description for the physical phenomena, but the particular solution used in this analysis does not apply for problems where a time varying pressure history is applied on the pipe boundary ($x = 0$) nor where changes in pipe cross-sectional areas are encountered. General techniques⁽⁴⁾ of analyzing flow through flexible tubes or more advanced dynamic codes should be applied for such cases.

Even if complicated time-pressure histories and changes in cross-sectional areas are encountered in a particular application, this relatively simple analysis can be used to provide physical insight and provide test cases for checking the more complicated general analyses. The two solutions provided by this analysis are encountered in many applications; thus, this analysis provides both descriptive and applicatory justification for its use on fluid wave transmission problems.

REFERENCES

1. J. Parmakian, Water Hammer Analysis, Prentice Hall, 1955.
2. C. Jaeger, Engineering Fluid Mechanics, Blackie & Sons, London, 1956 (p 278).
3. H. Kolsky, Stress Waves in Solids, Dover, New York, 1963.
4. V. L. Streeter, E. B. Wylie, Hydraulic Transients, McGraw-Hill, New York, 1967 (Chpt. 14).

MATERIAL PROPERTY FIT

TYPE 316 SS ANNEALED WITH STRAIN RATE OF .1 IN/IN-SEC, TEMP = 1000 DEG F

THE PIPE WALL MATERIAL HAS BEEN FIT TO THE FOLLOWING FUNCTION

$$\text{STRESS} = \text{CK1} * \text{STRAIN} ** \text{CN1} + \text{CK2} * \text{EXP}(\text{CN2} * \text{STRAIN}) + \text{CK3} * \text{EXP}(\text{CN3} * \text{STRAIN})$$

CK1	CN1	CK2	CN2	CK3	CN3
.17025+06	.49685-00	.10037+05	-.80203+02	-.37060+06	-.11424+05

TRUE STRAIN IN/IN	INPUT STRESS PSI	FITTED STRESS PSI	TANGENT MODULUS PSI
.00062	14700.00	14700.00	.23709677+08
.00200	16600.00	16312.29	.12429304+07
.00400	18000.00	18237.01	.77670453+06
.00600	19300.00	19602.75	.61214277+06
.00800	20500.00	20742.44	.53634000+06
.01000	21600.00	21771.95	.49717906+06
.01600	24600.00	24595.98	.45433162+06
.02000	26500.00	26330.37	.44361280+06
.03000	30700.00	30716.69	.42115530+06
.04000	34500.00	34798.28	.39465465+06
.06000	41700.00	42149.92	.34181922+06
.08000	46200.00	48548.78	.30010288+06
.10000	54200.00	54226.06	.26914339+06
.12000	59700.00	59364.66	.24574050+06
.14000	64700.00	64089.49	.22743973+06
.16000	69300.00	68485.66	.21266888+06
.20000	76800.00	76515.53	.19008519+06
.24000	82300.00	83770.50	.17342382+06

TABLE 1. Pipe Wall Material Properties

TYPE 316 SS ANNEALED WITH STRAIN RATE OF .1 IN/IN-SEC, TEMP = 1000 DEG F

PIPE RADIUS = 13.812IN. WALL THICKNESS = .375IN.

WAVE PRESSURE PSI	PIPE STRAIN IN/IN	WAVE VELOCITY FT/SEC	FLUID STRAIN IN/IN	FLUID VELOCITY FT/SEC	WAVE ARRIVAL TIME AT 30.00 FEET SEC
398.61	.00062	4385.49	-.0019	4.14	.00684
441.12	.00200	1205.34	-.0047	12.05	.02489
491.19	.00400	945.55	-.0088	16.44	.03173
525.87	.00600	831.72	-.0129	20.04	.03607
554.22	.00800	772.09	-.0169	23.29	.03886
579.41	.01000	738.10	-.0209	26.34	.04064
646.76	.01600	693.76	-.0331	35.01	.04324
668.41	.02000	678.80	-.0411	40.54	.04420
765.49	.03000	645.01	-.0613	53.89	.04651
872.15	.04000	607.30	-.0814	66.50	.04940
1014.96	.06000	530.25	-.1216	89.38	.05658
1123.22	.08000	461.75	-.1618	109.31	.06497
1205.36	.10000	402.87	-.2020	126.66	.07447
1257.86	.12000	351.20	-.2421	141.78	.08542
1315.10	.14000	304.41	-.2821	154.91	.09855
1350.21	.16000	260.62	-.3222	166.23	.11511
1392.54	.20000	175.25	-.4023	183.68	.17118
1457.36	.24000	67.11	-.4823	193.38	.44705

TABLE II. Results of BHAM Calculations

APPENDICES

APPENDIX A

BASIC EQUATIONS OF WAVE MOTION

The equations describing a one-dimensional solution for the dynamic behavior in a fluid contained in a pipe that undergoes plastic deformation are presented in this appendix. Some of the pertinent assumptions used in this derivation are that the radial inertia of the pipe is neglected, that the radial variations in fluid motions are neglected, that the gravitational forces are neglected, that the original dimension of the pipe are uniform, and that the fluid column remains continuous.

The position of a fluid particle is described by Lagrangian coordinates $x(t)$, and the displacement function $u(t) = x(t) - x(0)$. The axial equilibrium of the fluid column including inertial effects is described by the expression

$$\rho \ddot{x} + \frac{\partial P}{\partial x} = 0 \quad (A-1)$$

where P = fluid pressure
 ρ = fluid density

A unique relation between the pressure and the fluid column strain is assumed to exist; thus,

$$\frac{\partial P}{\partial x} = \frac{dP}{d\epsilon} = \frac{\partial \epsilon}{\partial x} = \frac{dP}{d\epsilon} \frac{\partial^2 u}{\partial x^2} \quad (A-2)$$

where $\epsilon = \frac{\partial u}{\partial x}$ is the true strain of the fluid column.

An increment of fluid volume Δv is decreased dv by an increment in pressure

$$dv = \left(\frac{-dP}{K} \right) \Delta v = \left(\frac{-dP}{K} \right) \pi R^2 \Delta x, \quad (A-3)$$

where R = inner radius of pipe
 K = compressibility of fluid

The increment in pressure also causes an incremental change in the pipe radius dR . For a material obeying a Tresca yield criteria (or a free ended pipe obeying a von Mises yield criteria), the radial increment is given by

$$dR/R = d\left(\frac{RP}{H}\right) / E_p \quad (A-4)$$

where H = tube thickness

E_p = tangent modulus to tensile true stress-strain curve

$\bar{\sigma} = RP/H$ = instantaneous circumferential membrane stress in pipe

Material volume remains constant during plastic deformation and for a Tresca yield condition the circumferential strain is the negative of the radial strain ($dR/R = -dH/H$). Equation (A-4) is solved for the relation between the increment in circumferential strain and pressure increment.

$$\frac{dR}{R} = \frac{R}{H} \left[\frac{dP}{(E_p - 2\sigma)} \right] \quad (A-5)$$

Instantaneous values of the pipe radius and pipe thickness are related to the circumferential strain in the pipe, $\bar{\epsilon}$, and the initial dimensions R_0 and H_0 by the relations

$$R = R_0 \exp(\bar{\epsilon}),$$

$$H = H_0 \exp(-\bar{\epsilon}) \quad (A-6)$$

The fluid is assumed to remain in contact with the pipe, thus both the change of the fluid column length, dx , and the increase of the pipe dimension, dR , can be related to the change of fluid volume to yield the mass conservation relation

$$dv = \pi \Delta x \ 2RdR + \pi R^2 dx = \left(\frac{-dP}{K}\right) \pi R^2 \Delta x \quad (A-7)$$

Since $(dx/\Delta x) = d\epsilon$, Equations (A-3), (A-5), and (A-7) can be solved to yield

$$\frac{dP}{d\epsilon} = - \left(\frac{1}{K} + \frac{2R}{H(E_p - 2\sigma)} \right)^{-1} \quad (A-8)$$

Substitution of Equations (A-8) and (A-2) yields the resultant wave equation

$$\frac{\partial^2 u}{\partial t^2} = C_p^2 \frac{\partial^2 u}{\partial x^2}, \quad (A-9)$$

where the wave velocity C_p is

$$C_p^2 = (1/\rho) \left(\frac{1}{K} + \frac{2R}{H(E_p - 2\sigma)} \right)^{-1} \quad (A-10)$$

A particular solution is obtained for Equation (A-9) if $x(t) = tC_p$. The C_p is assumed to be a unique function of ϵ in the fluid which can be inverted to yield

$$\epsilon = f(C_p) = f(x/t) \quad (A-11)$$

This relation can be used to solve for the fluid displacements u

$$u(x) = \int_{-\infty}^x \frac{\partial u}{\partial x} dx = t \int_{-\infty}^{(x/t)} f(C) dC \quad (A-12)$$

The $u(x)$ from Equation (A-12) identically satisfies Equation (A-9). The fluid velocity is given by

$$\frac{\partial u}{\partial t} = \int_{-\infty}^{(x/t)} f(C) dC - \left(\frac{x}{t} \right) f(x/t)$$

which for $x = 0$

$$V = \left. \frac{\partial u}{\partial t} \right|_{x=0} = \int_{-\infty}^0 \epsilon(c) dC = \int_0^{(-\epsilon)_{\max}} C_p d(-\epsilon) \quad (A-13)$$

The prescribed solution applies for either a constant pressure or constant velocity imposed at $x(t) = 0$. A constant maximum strain or constant maximum pressure would correspond to a $(C_p)_{\max}$ and the resultant conditions in the fluid column are

$$\begin{aligned} (-\epsilon)_{\max} & \quad 0 \leq x \leq C_{p \max} t \\ \epsilon = f(C_p) & \quad C_{p \max} t \leq x \leq C_{\epsilon} t \\ \epsilon = 0 & \quad x \geq C_{\epsilon} t \end{aligned} \quad (A-14)$$

where C_{ϵ} corresponds to elastic pipe and fluid behavior. The mass conservation relationship (A-7), expressed in terms of total strains is

$$\begin{aligned} \log (v/v_0) &= - \int_0^P \frac{dP}{K} = \frac{-P}{K} = \ln \frac{x}{x_0} + 2 \ln \frac{R}{R_0} \\ &= \epsilon + 2 \bar{\epsilon}, \end{aligned} \quad (A-15)$$

where $\bar{\epsilon}$ = circumferential strain in the pipe. Equation (A-15) defines the relation between the pressure in the fluid, strain of the fluid column and strain in the pipe. For a given strain on the pipe, the instantaneous pipe thickness and radius can be determined with Equation (A-6), fluid pressure with (A-4), and fluid strain with Equation (A-15).

NOMENCLATURE

x	=	fluid column length in Lagrangian coordinates
u	=	displacement of fluid particle [$X(t) - X(0)$]
R	=	instantaneous inner pipe radius
H	=	instantaneous inner pipe thickness
ϵ	=	true strain in fluid column
$(\cdot)$	=	material derivative with respect to time
$\underline{P}$	=	pressure in fluid
C_p	=	wave velocity in fluid
K	=	fluid compressibility
E_p	=	tangent modulus of true stress strain curve
V	=	fluid particle velocity
ρ	=	fluid density
ΔV	=	incremental volume in the fluid column
$\bar{\epsilon}$	=	true circumferential strain in the pipe
$\bar{\sigma}$	=	true circumferential stress in the pipe

APPENDIX B

DATA SMOOTHING AND TANGENT MODULUS CALCULATIONS

Reference: J. M. Steichen, "A Functional Description of the True Stress-Strain Behavior of Type 304 Stainless Steel at High Strain Rates," HEDL-TME 72-127, November 1972.

The equations in Appendix A can be evaluated for any value of true strain $\bar{\epsilon}$ in a pipe if the corresponding true stress $\bar{\sigma}$ and tangent modulus E_p are known. If experimental data of true stress versus true strain are available, the estimation of the tangent moduli might give erroneous results if numerical differencing techniques are used. A smooth continuous tangent modulus can be obtained by fitting the stress-strain data with a functional equation and then differentiating to obtain the tangent modulus.

The reference describes two mathematical forms used to functionalize type 304 stainless steel properties. The classical Ludwik relation, $\sigma = K\epsilon^n$, was modified according to Ludwigson to obtain:

$$\sigma = K_1 \epsilon^{n_1} + K_2 e^{n_2 \epsilon} \quad (1)$$

σ = stress

ϵ = plastic strain

K_1, K_2, n_1, n_2 are material constants

This provided an excellent fit of the data and was used for functionalization of existing strain rate data. A disadvantage of this method is the plastic strain should be utilized for stress evaluation while conventional calculations require the total strain.

The present approach is similar to the reference except that total strains are used for the correlation and an additional term is added to improve the fit near the yield point.

$$\sigma = K_1 \epsilon^{n_1} + K_2 e^{n_2 \epsilon} + K_3 e^{n_3 \epsilon} \quad (2)$$

First, the data for strains greater than 5% are fit to the function $\sigma = K_1 \epsilon^{n_1}$. This is done by applying the log function which produces the first order polynomial.

$$\ln \sigma = \ln K_1 + n_1 \ln \epsilon \quad (3)$$

The coefficients K_1 and n_1 are then evaluated using a "least squares" procedure. The deviation of the data beyond the yield point from this fit is calculated by:

$$\Delta_1 = \sigma_i - K_1 \epsilon^{n_1} = K_2 e^{n_2 \epsilon}$$

where σ_i are experimental stresses

Again using the log function

$$\ln \Delta_1 = \ln K_2 + n_2 \epsilon \quad (4)$$

The coefficients K_2 and n_2 are evaluated as before. A second deviation is calculated to improve the fit about the yield point:

$$\Delta_2 = \sigma - K_1 \epsilon^{n_1} - K_2 e^{n_2 \epsilon} = K_3 e^{n_3 \epsilon} \quad (5)$$

This procedure for treating experimental stress-strain data provides a good method for obtaining curve fits and tangent moduli. A listing of the computer program incorporating this technique is included in Appendix C.

BHAM. PLANAR WAVE IN FLUID IN A PIPE

USES A WATER HAMMER APPROACH ALONG WITH THE THEORY FOR PLASTIC WAVES IN A BAR.- REF. H.KOLSKY -STRESS WAVES IN SOLIDS-P164
J.PARMAKIAN -WATERHAMMER ANALYSIS-P9
PLASTIC DEFORMATION OF PIPE TAKEN INTO ACCOUNT TO OBTAIN THE WAVE EQUATION FORM. TRESCA YIELD CONDITION OR AXIALLY FREE PIPE ARE ASSUMED TO DETERMINE EFFECT OF AXIAL STRESSES ON YIELDING. THE STRESS-STRAIN CURVE IS FITTED USING A LUDWIGSON RELATION WITH AN EXTRA TERM FOR FITTING NEAR YIELD POINT. THE CONTINUOUS ANALYTIC CURVE IS DIFFERENTIATED TO OBTAIN TANGENT MODULI. FIRST VALUE SHOULD BE YIELD STRESS AND STRAIN. AT LEAST FIVE DATA CARDS SHOULD BE BETWEEN YIELD AND ONE PERCENT, ONE AND FIVE PERCENT, AND FIVE PERCENT AND END OF DATA.

NOMENCLATURE

EK = COMPRESSIBILITY OF FLUID (PSFT)
R = INITIAL INNER RADIUS OF PIPE
H = PIPE THICKNESS
RHO = FLUID DENSITY (SLUG/FT**3)
ET = TANGENT MODULUS (PSI)
EPSB = EFFECTIVE STRAIN
SIG = EFFECTIVE STRESS
SIGD = INPUT STRESS FROM TEST CURVE (PSI)
P = PRESSURE IN PIPE (PSI)
EPS = STRAIN OF FLUID COLUMN
CP = WAVE VELOCITY IN FLUID (FT/SEC)
VT = VELOCITY OF FLUID INTO PIPE (FT/SEC)
XC = LENGTH OF WATER COLUMN TO GET TIME OF ARRIVAL
TIM = TIME OF ARRIVAL OF WAVE AT STATED STRAIN, ETC.

```

C      ***INPUT***
C
C      CARD  0--IDENT  (13A6)
C      CARD  1--EPSB,SIGD  (9F10.0)
C      --USE -1. TO END READING MATERIAL INPUT
C      CARD  2--R,H,XC  (9F10.0)
C      --USE -999. TO READ ANOTHER CASE
C      ---USE -1. TO HALT PROGRAM
C
C
C      PARAMETER KS=100
C      DIMENSION P(KS), EPS(KS), CP(KS),EPSB(KS)
C      1 ,ET(KS), SIG(KS), SIGD(KS), VT(KS) ,TIM(KS)
C      DIMENSION IDENT(13)
C
C      DATA RHO/ 1.58 / EK /88.6E+6 /
C
C      ***INPUT OF STRESS-STRAIN RELATION***
C      999 CONTINUE
C      READ(5,123) (IDENT(K),K=1,13)
C      123 FORMAT(13A6)
C      KKS = 5
C      JKS = 4
C      CK2 = 0.
C      CN2 = 0.
C      CK3 = 0.
C      CN3 = 0.
C      2 CONTINUE
C      READ(5,101) EPSB(KKS),SIGD(KKS)
C      IF(EPSB(KKS).LT.0.0) GO TO 3
C      IF (EPSB(KKS).LE. .05) JKS=JKS+1
C      KKS = KKS + 1
C      GO TO 2
C      3 CONTINUE
C      KKS = KKS - 1

```

```

C      SET UP INITIAL VALUES OF ELASTIC STRESS-STRAIN IN ARRAY
      ET(5) = SIGD(5)/EPSB(5)
      EPSB(1) = EPSB(5)*0.6
      DELESB = 0.1*EPSB(5)
      DO 8 J=2,4
8     EPSB(J) = EPSB(J-1)+DELESB
      DO 6 K=1,4
6     SIGD(K) = ET(5)*EPSB(K)
      SX1 = 0.
      SX2 = 0.
      SX2X2 = 0.
      SX1X2 = 0.
C      SET UP ARRAY FOR FITTING FOR GREATER THAN 5 PERCENT STRAIN
      DO 7 KB=JKS,KKS
      X1 = ALOG(SIGD(KB))
      X2 = ALOG(EPSB(KB))
      SX1 = X1+SX1
      SX2 = X2+SX2
      SX2X2 = X2*X2+SX2X2
      SX1X2 = X1*X2+SX1X2
7     CONTINUE
      ENN = KKS-JKS+1
      CALL CFIT(SX1,SX2,SX2X2,SX1X2,ENN,CK1,CN1)
C      CALCULATE FIRST DEVIATION OF DATA AND FIRST FIT AND SET UP ARRAY
C
      SX3 = 0.
      SX4 = 0.
      SX3X4 = 0.
      SX4X4 = 0.

      DO 11 LM= 5,KKS
      DEL1 = SIGD(LM)-CK1*EPSB(LM)**CN1
      IF(LM.EQ.5) DEL1B = DEL1
      IF(DEL1/DEL1B .LT. .1) GO TO 13
      X3 = ALOG(DEL1)
      X4 = EPSB(LM)

```

C-4

```

      SX3 = X3 + SX3
      SX4 = EPSB(LM) + SX4
      SX4X4 = X4*X4 + SX4X4
      SX3X4 = X3*EPSB(LM) + SX3X4
11  CONTINUE
13  ENN1 = LM-5
      IF(ENN1 .LT. 1.9) GO TO 18
      CALL CFIT(SX3,SX4,SX4X4,SX3X4,ENN1,CK2,CN2)
C   CALCULATE SECOND DEVIATION OF DATA AND SECOND FIT AND SET UP ARRAY
18  SX5 = 0.
      SX6 = 0.
      SX6X6 = 0.
      SX5X6 = 0.
C
      DO 20 KSN = 1,KKS
      DEL2 = SIGD(KSN)-CK1*EPSB(KSN)**CN1-CK2*EXP(EPSB(KSN)*CN2)
      IF(KSN .EQ. 1.) DEL2B=DEL2
      IF(DEL2/DEL2B .LT..01) GO TO 23
      X5 = ALOG(ABS(DEL2))
      X6 = EPSB(KSN)
      SX5 = X5+SX5
      SX6 = EPSB(KSN)+SX6
      SX6X6 = X6*X6+SX6X6
      SX5X6 = X5*EPSB(KSN) + SX5X6
20  CONTINUE
23  ENN2 = KSN-1
      IF(ENN2 .LT. 1.9) GO TO 28
      CALL CFIT(SX5,SX6,SX6X6,SX5X6,ENN2,CK3,CN3)
      IF(DEL2B.LT. 0.) CK3=-CK3
C   CALCULATE TANGENT MODULI AT EACH VALUE OF STR. IN
C
28  CONTINUE
      DO 30 J=1,4
      ET(J) = ET(5)
30  SIG(J) = SIGD(J)
      SIG(5) = SIGD(5)

```

C

```

DO 40 K=6,KKS
TERM2 = CK2*EXP(CN2*EPSB(K))
TERM3 = CK3*EXP(CN3*EPSB(K))
ET(K) = CK1*CN1*EPSB(K)**(CN1-1.)+CN2*TERM2+CN3*TERM3

```

C

```

SIG(K) = CK1*EPSB(K)**CN1 + TERM2 + TERM3

```

```

40 CONTINUE

```

C

```

WRITE(6,205) (IDENT(K),K=1,13)
205 FORMAT( //22H MATERIAL PROPERTY FIT ///1H 13A6 //)
WRITE(6,210) CK1,CN1,CK2,CN2,CK3,CN3
210 FORMAT(63H THE PIPE WALL MATERIAL HAS BEEN FIT TO THE FOLLOWING FU
1NCTION //70H STRESS = CK1*STRAIN**CN1 + CK2*EXP(CN2*STRAIN) + CK3
2*EXP(CN3*STRAIN) // 3X3HCK1 14X 3HCN1 12X 3HCK2 13X 3HCN2 12X
3 3HCK3 12X 3HCN3/ 6(E10.5,5X))
WRITE(6,215)
215 FORMAT( /// 2X11HTRUE STRAIN 9X 12HINPUT STRESS 7X 13HFITTED STRE
1SS 6X15HTANGENT MODULUS / 5X 5HIN/IN 16X 3HPSI 17X 3HPSI 17X
23HPSI /)
WRITE(6,220) (EPSB(K),SIGD(K),SIG(K),ET(K), K=5,KKS)
220 FORMAT(3X F7.5, 14X F9.2, 12X F9.2, 8X E15.8 )

```

C

C

C

C

```

***PIPE INPUT***

```

```

1 CONTINUE

```

```

READ(5,101) R,H,XC

```

```

101 FORMAT(3F10.0)

```

```

IF(R.LT.-9.) GO TO 999

```

```

IF(R.LT.0.0) GO TO 901

```

```

C   ***STRESS-STRAIN AND VELOCITIES***
136 DO 5 K=5,KKS
    RC = R*EXP(EPSB(K))
    HC = H*EXP(-EPSB(K))
    P(K) = SIG(K)*HC/RC
    EPS(K) = -144.*P(K)/EK - 2.*EPSB(K)
    ETADJ = 144.*( ET(K) - 2.*SIG(K) )
    IF( ETADJ.LE. 1.0E-12 ) GO TO 55
    CP(K) = SQRT( (EK/RHO) / ( 1. + 2.*RC*EK/(HC*ETADJ) ) )
    KEND = K
    5 CONTINUE
55 CONTINUE
    VT(1) = -EPS(1)*CP(1)
    DO 10 K=2,KEND
    VT(K) = - .5*(CP(K-1)+CP(K))*(EPS(K)-EPS(K-1)) + VT(K-1)
    10 CONTINUE
    WRITE(6,201) IDENT,R,H,XC
201 FORMAT(1H1//13A6//15H PIPE RADIUS = F6.3, 3HIN. 5X 17HWALL THICKNE
    1SS = F6.3, 3HIN./ 100X 17HWAVE ARRIVAL TIME / 14H WAVE PRESSURE
    28X 11HPIPE STRAIN 8X 13HAVE VELOCITY 8X 12HFLUID STRAIN 7X
    31HFLUID VELOCITY 5X 3HAT F5.2, 5H FEET /5X 3HPSI 17X 5HIN/IN
    415X 6HFT/SEC 14X 5HIN/IN 15X 6HFT/SEC 14X 3HSEC / )
    DO 15 K=5,KEND
    TIM(K) = XC/CP(K)
    WRITE(6,202) P(K),EPSB(K),CP(K),EPS(K) ,VT(K),TIM(K)

202 FORMAT(4X F7.2 , 13X F7.5 , 14X F7.2 , 15X F6.4 ,11X F6.2,
    112X F7.5 )
    15 CONTINUE
    KPLUS = KEND + 1
    IF( KEND .LT. KKS ) WRITE(6,203) P(KPLUS)
203 FORMAT(1H0, 26HPIPE BECAME UNSTABLE AT P= , E11.4 )
    GO TO 1
901 CONTINUE
    STOP
    END

```

```
SUBROUTINE CFIT(SX1,SX2,SX2X2,SX1X2,ENN,CK,CN)
  DETER = ENN*SX2X2-SX2*SX2
  IF(DETER .EQ. 0.) GO TO 20
  AA = (SX1*SX2X2-SX1X2*SX2)/DETER
  CN = (ENN*SX1X2-SX1*SX2)/DETER
  CK=EXP(AA)
  GO TO 40
20 WRITE(6,30) SX1,SX2,SX2X2,SX1X2,ENN
30 FORMAT(33H ERROR IN SOLUTION FOR CURVE FIT / 5E15.8 )
  STOP
40 CONTINUE
  RETURN
  END
```