Project Title: Prediction of Layered Properties Using an Inverse N-Layered Program.

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Sponsor: Federal Highway Administration

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CA—4 (1/79)
USER'S MANUAL FOR

VESYS G WITH INVERSE SOLUTION

by

James S. Lai
Francis C. Cheung

Prepared for

Federal Highway Administration
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August, 1979
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<td>44</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

A goal of the Federal Highway Administration's (FHWA) pavement research is a rational design procedure that can be used to establish optimum pavement design for a variety of materials and local service conditions. Figure 1 shows the concepted basis for the VESYS structural and Management System [1]. The current development of the VESYS System has been in Phase I, known as the VESYS Structural Subsystem. The VESYS computerized Structural Subsystem will predict pavement responses, pavement distresses and its life expectancy as a function of the properties of pavement materials, traffic and environment. Figure 2 shows schematically the VESYS Structural Subsystem. The Subsystem consists of four models: primary response, general response, damage and performance. From Fig. 2 it can be seen that the pavement responses, as well as the damage and performance of a given pavement structure, depend on geometry of the pavement structure, the loading condition, the physical properties of the layer materials comprising the pavement structure, and the effect of the environment (temperature, moisture, etc.) on the physical properties of the materials.

In the current VESYS IIM System [2], the layered pavement structure consists of three-layers and the material property of each layer can be characterized as linear elastic and/or linear viscoelastic. The influences of load amplitude and duration are considered in the computation of the general response due to a haversine load. The damage laws (cracking, rutting and roughness) are formulated from observations of the behavior of the distress properties of materials and from the primary and general responses of the pavement system. The serviceability of the pave-
GENERATE A DESIGN CONFIGURATION (A SET OF MATERIALS PROPERTIES AND GEOMETRY)

DEFINE OPERATIONAL ENVIRONMENT (TRAFFIC AND REGIONAL CLIMATIC PATTERNS)

PREDICT DAMAGE WITH TIME (RUTTING, ROUGHNESS, CRACKING)

DETERMINE: SERVICEABILITY, LIFE EXPECTANCY, AND RELIABILITY

GENERATE MAINTENANCE POLICIES

UPDATE SERVICEABILITY, LIFE, EXPECTANCY, AND RELIABILITY VS. TIME

DETERMINE ASSOCIATED COSTS: MAINTENANCE, VEHICLE OPERATING, AND CONSTRUCTION

CHECK CONSTRAINTS ON DESIGN AND COST

CHECK OPTIMALITY

OPTIMAL DESIGN

Figure 1. Graphical representation of a pavement design process (Ref. 1).
Figure 2. Flow Chart of VESYS IIM and VESYS G Computer Program.
ment is hypothesized to be represented by the AASHTO definition of serviceability index.

The three-layer pavement model used in VESYS IIM may restrict the applicability of the VESYS System due to the fact that many pavements consist of more than three layers of different materials. In addition, subdivision of any of these layers, where moisture and/or temperature gradients exist, is necessary to be able to realistically model the pavement structures under different environmental conditions. To overcome this restriction of limiting a pavement structure to consist of only three layers, a primary response model which is capable of handling N layers has since then been developed and incorporated into the VESYS System, and is known as VESYS G [3,4].

Parallel to the development of the N-layered viscoelastic probabilistic solution for VESYS G at the University of Utah, the solution of the inverse problem for the N-layer solution was developed [5]. The development of this inverse solution along with a computer program make it possible to determine in-situ properties of the layered materials using measured surface deflections as input. This inverse solution in conjunction with the VESYS System can be utilized in pavement overlay design. Wherein the layer properties of the existing pavement, to be overlaid, can be estimated from measuring the surface deflection basin in conjunction with the inverse solution. With this information available the VESYS System can be used to design an optimized overlay on the existing pavement structure. Therefore, incorporating the inverse solution into the VESYS System is an logical extension of the VESYS System.

Thus, the main objective of this research effort is to integrate
the VESYS System with the Inverse Solution. VESYS G instead of VESYS IIM was chosen for this work. The reasons for making this decision were; (1) for overlay applications, it is most likely that the total number of layers, including overlay, will be more than three, and (2) the VESYS G and the Inverse Solution are highly compatible. The integrated system is tentatively named "VESYS G-with Inverse Solution". Description of this integrated system is presented in Chapter 2.

Chapter 3 presents the operating instruction for using the system. This chapter has been written in such a way that it can be used independently by the computer analyst. Chapter 4 presents design examples to illustrate the application of the systems. The inputs for the design examples are presented in Appendix 1. The users should have no problem in implementing the system after reading through Chapters 3, 4 and Appendix 1. It is strongly recommended however that the VESYS IIM [2] should be reviewed by the users.

Appendix 2 presents the program documentation for the integrated system. The presentation is brief, although it should be useful for modifying the program. The analytical solution of the Inverse problem is presented briefly in Appendix 3.

Appendix 4 presents the evaluation of the layer properties of a FHWA prototype flexible pavement [6] using the integrated system. The results presented herein including the comparison of the experimentally measured layer properties with the predicted properties should provide useful information with regard to the applicability of the Inverse Solution.
2. DESCRIPTION OF VESYS G - INVERSE

The logic of the VESYS G-Inverse is shown in Fig. 3. In the original VESYS G [3] as well as VESYS IIM [2] as illustrated in Fig. 3, there are four types of runs available to the user of the systems for different analyses. These four types of analyses are:

TYPE 1: Primary response, damage and performance analyses
TYPE 2: Primary response analysis only
TYPE 3: Damage and performance analyses only
TYPE 4: Curve-fitting only

In the VESYS G-INVERSE, an additional run TYPE 5 was incorporated into the system as depicted in Fig. 3. Modifications on the VESYS G and the INVERSE have been made and the integration of these two modified programs has been streamlined in terms of eliminating the duplications, reducing the overall program size, and optimizing the operation procedures. For example, in sample problem 2 of Chapter 4 where TYPE 5 run was executed to obtain the in-situ properties of the pavement structure from the measured surface deflection, the material properties obtained in TYPE 5 run were stored in the program and could be used directly, without exit and reenter, for TYPE 1, or TYPE 2 run. Thus, from a single "JOB" entry, the predicted material properties and the responses and damage/performance of the pavement structure can be obtained.

In the following the primary response model and the Inverse Solution scheme for the integrated VESYS G-INVERSE are discussed. The other models including general response, damage and performance are identical to that of the VESYS IIM [2]. The reader is referred to the manual for the detail discussions of those models.
Figure 3. Macro Flow Chart of VESYS G-INVERSE Including TYPE 5 Run.
2.1 VESYS G Primary Response Model

The primary response model PRIME for the VESYS G is a viscoelastic closed from probabilistic solution for N-layered pavement systems.

The geometrical model is a multi-layered, semi-infinite half-space, see Fig. 4. Each layer has distinct material properties characterized as linear elastic or linear viscoelastic. The material properties can be random (mean and deviation) or deterministic (mean value only). The loading is considered to be uniform, normal to the surface and acting over a circular area. The responses of the pavement system are the stresses (normal stress, tangential stress, radial stress and shear stress), strains (normal, tangential and radial) and vertical deflection at any specified radial position and vertical position. As pointed out in [3,4], the viscoelastic solution for the primary responses (stresses, strains, and deflections) was obtained using the "quasi-elastic" solution. This method involves replacing elastic moduli in a N-layered elastic solution by instantaneous values of the relaxation moduli (or creep compliances). Thus, the viscoelastic solution consists of a series of elastic solutions, with each elastic solution corresponding to the value of the viscoelastic solution at that specific time.

The quasi elastic solution consists of two parts, determining the expected values for the primary responses, and the deviations for the primary responses. CHEV5L [7] program was used in the first part to determine the expected values for the primary responses. Modifications were made on CHEV5L such that the program can handle any number of layers instead of a maximum of five layers.

The mathematical formulation for the solution of expected values and the deviations for the primary responses has been presented in the previous
reports [3,4]. The program documentation for the primary response model is presented in Appendix 2.

2.2 INVERSE Layered Solution

The solution of the inverse problem developed by Hou [5] is described briefly in this section. For detailed information the reader is referred to the original report.

The geometry of a pavement system and the load condition for the solution of the inverse problem is shown in Fig. 4. The pavement system consists of N-layers of different thicknesses and different material properties. Each layer is assumed to be linearly elastic or linearly viscoelastic. The loading is axisymmetric.

The solution for the stresses, strains and deflections of this N-layer system with prescribed layer moduli and Poisson's ratios is identical to that described in Section 2.1 for VESYS G primary response model. The calculated surface deflection $Y_j$ at any radial position $r_j$ can be expressed by the following equation:

$$Y_j = f(r_j; E_1, \ldots, E_n; \nu_1, \ldots, \nu_n; h_1, \ldots, h_{n-1}; a, q)$$ (1)

where $E$'s, $\nu$'s, and $h$'s are the elastic moduli, Poisson's ratios and the thicknesses of the layers, and $a$ and $q$ are the radius and the uniform pressure of the circular loading.

The problem for the inverse solution is to determine the in-situ layer moduli, $E_1, \ldots, E_n$, from a set of prescribed Poisson's ratios $(\nu_1, \ldots, \nu_n)$, layered thickness $h_1, \ldots, h_{n-1}$, and $a$ and $q$ for the circular load for the pavement system and the surface deflection basin of the pavement. The essence of this inverse solution is to estimate the layer moduli by matching the predicted surface deflections $Y_j$ with the prescribed surface deflections $W_j$ at all positions. In solving this problem, initial trial values of moduli $E_i$ (or $X_i$ in Fig. 5), along with
Figure 4. Schematic of N-Layered Viscoelastic System
Figure 5. INVERSE Program Solution Scheme.
the other properties $v_i$, $h_i$, $a$ and $q$ are input to the elastic layered system to calculate the corresponding surface deflections $Y_i$. The difference between $Y_i$ and $W_i$ are minimized using a least-squares method in an iterative fashion. The moduli are adjusted from the initial trial values at each successive iterations. The iteration terminates when the total error between the calculated and the prescribed surface deflections at all radial positions is less than some prescribed value. The corresponding material properties are then taken to be the in-situ moduli of the layered system. A flow chart illustrates this numerical procedure as shown in Fig. 5. It has been shown in [5] that the minimization method used in this inverse solution leads to a unique solution for $E_1$, $\ldots$, $E_n$, under the constraints of given $h_i$, $v_i$ and loading conditions.

A limited sensitivity analysis of the inverse solution has been conducted in [5] concerning the convergence of the solution and the effect of Poisson's ratio on the prediction. It has been found from the study that the rate of convergence of the solution depends on the closeness of the initial trial values of layer moduli, the number of deflection points, and the allowable error for each iteration; that the optimum number of deflection points is about twice the number of layers in the system; and that the effect of varying Poisson's ratio within the practical limit on the surface deflections is small.
3. OPERATING INSTRUCTIONS

The operating instructions for VESYS G-INVERSE are similar to the current versions of VESYS IIM and VESYS G [2,3]. It is recommended that anyone planning to use this program should first familiarize himself with the VESYS IIM User's Manual [2].

3.1 VESYS G-INVERSE Source Code

Developed on: CDC Cyber 7C

Transfered to: IBM 360/65 under OS

Compiler: IBM FORTRAN G level

Typical Statistics:

<table>
<thead>
<tr>
<th>Step</th>
<th>CPU Second</th>
<th>Core (Bytes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compile</td>
<td>81.96 sec.</td>
<td>148 k</td>
</tr>
<tr>
<td>LKED</td>
<td>4.19</td>
<td>132 k</td>
</tr>
<tr>
<td>Go (Execute)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TYPE 2 (5 layer)</td>
<td></td>
<td>296 k</td>
</tr>
<tr>
<td>TYPE 2 (3 layer)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TYPE 5 (5 layer)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Machine-Dependant Consideration

<table>
<thead>
<tr>
<th>word size = single precision</th>
<th>32 bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>double precision</td>
<td>64 bits</td>
</tr>
</tbody>
</table>

Input/output Files:

Input is via logical unit 5 (card reader)

Output is via logical unit 6 (line printer)

3.2 INPUT DATA

3.2.1 Commands

Input data values for VESYS are read from cards. Each input variable is associated with a "command" word, which is punched before the value of the variable on the data card. The program reads the command first, and then uses it as a keyword for matching the subsequent data value to the proper variable. This allows some flexibility in the order to input data.
After the value of a variable is read, it is checked against a predefined "reasonable" range of values. If the value of any variable lies outside this range, an error message is printed and the program is terminated.

Because many of the input variables have predefined "default" values stored within the program, it is not necessary to input a value for every variable. VESYS automatically assumes the default value for any of these variables which are not input.

VESYS is designed to cycle back to its own starting point so that multiple sets of data may be run with one execution of the program. The data for each separate problem is terminated in the input deck by an ENDOFRUN command. This command signals the program to begin executing with the data that has been read thus far. When the problem is complete, VESYS begins reading data for the next "run" with the first card after the previously read ENDOFRUN command. The last ENDOFRUN command in a data deck is followed immediately by an ENDOFJOB command, which causes the program to cease processing.

When a "job" is submitted with multiple "runs", the first run uses the default values, supplanted where indicated by the input data. Each subsequent run begins with the data values left over from the previous run and supplants where necessary with its own input data. It may be useful to think of each run of a job as having the values used in the previous run by default. Any variables to be changed can be explicitly input. Others will remain the same. This feature allows the user to see the effect of changing a few variables without having to reread all of the data deck.

The input commands recognized by VESYS are of 3 basic types:

1. LOGICAL - No data value is needed. The presence or absence of the command indicates which way a decision is to be made in the program.
2. **SCALAR** - One data value is read in the field immediately following the command. Absence of the command causes the default value, if any, to be assumed. Absence of a **data value** following the command will cause "zero" to be assumed, since blanks are read as zeros.

3. **ARRAY** (or "Vector") - An array of several data values are read on the card(s) following this command. (No defaults exist for array values). No other commands or values can be on the same cards as an **ARRAY COMMAND**. The number of data values stored in the array is determined by an associated **SCALAR COMMAND**.

### 3.2.2 Formats

There are only two input formats; one for reading commands and the values associated with scalar commands, and another for reading the array values following an array command.

All commands, and the values with scalar commands, are read with

**FORMAT (4(A8,E12.4),**

<table>
<thead>
<tr>
<th>1</th>
<th>9</th>
<th>21</th>
<th>29</th>
<th>41</th>
<th>49</th>
<th>61</th>
<th>69</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMMAND</td>
<td>VALUE</td>
<td>COMMAND</td>
<td>VALUE</td>
<td>COMMAND</td>
<td>VALUE</td>
<td>COMMAND</td>
<td>VALUE</td>
<td>COMMAND</td>
</tr>
</tbody>
</table>

After an array command, the subsequent card(s) contain the array values in this format: **FORMAT (6E12.4)**, that is

<table>
<thead>
<tr>
<th>1</th>
<th>13</th>
<th>25</th>
<th>39</th>
<th>49</th>
<th>61</th>
<th>72</th>
</tr>
</thead>
<tbody>
<tr>
<td>VALUE</td>
<td>VALUE</td>
<td>VALUE</td>
<td>VALUE</td>
<td>VALUE</td>
<td>VALUE</td>
<td>VALUE</td>
</tr>
</tbody>
</table>

### 3.2.3 General Instructions and Suggestions for Command Use

1. All commands must begin in the first column of the command field. All commands consist of eight (8) characters, including trailing blanks. All 8 characters, including blanks, must
correct for a command to be recognized.

2. All data values must have a decimal point punched in the field. This includes integers.

3. Blank command fields are ignored. Blanks in data fields are read as zeros.

4. When an array (or vector) command is read, the data value field is ignored. Data values for the array are read from subsequent cards.

5. Each array command must appear on a card by itself. No other commands may appear on this card.

6. There are no default values for arrays.

3.2.4 Deck Structure

Figure 6. Example of a VESYS "job" with three "runs".
3.3 TYPES OF RUNS AVAILABLE

There are five types of runs available to the user of VESYS. The particular analysis desired is selected by specifying the appropriate value for the TYPE command:

<table>
<thead>
<tr>
<th>Value of TYPE</th>
<th>Analysis Performed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>Primary Response and Damage/Performance</td>
</tr>
<tr>
<td>2.0</td>
<td>Primary Response Only</td>
</tr>
<tr>
<td>3.0</td>
<td>Damage/Performance Only</td>
</tr>
<tr>
<td>4.0</td>
<td>Curve-Fitting Only</td>
</tr>
<tr>
<td>5.0</td>
<td>Moduli Determination Only</td>
</tr>
</tbody>
</table>

3.3.1 Type 1 Analysis:

This calls for a full run which produces predictions of pavement response and expected lifetime on the basis of system geometry, materials characteristics, and environment. The primary response model passes primary response information to the damage model. Serviceability predictions are then made, based on the primary response information and the various environmental parameters. The following variables will ordinarily be supplied by the user for a TYPE 1 run:

```
TITLE
TYPE 1.0  Control Variables
INDEX
NUMIT*
NLAYER*  
THICK*  
LOADING  
RADIUS  
```

* Variables not in VESYS IIM. The meaning of these variables will be discussed in Section 3.4.
<table>
<thead>
<tr>
<th>NZPOINTS*</th>
<th>NRPOINTS*</th>
<th>ZPOINTS*</th>
<th>RPOINTS*</th>
<th>ZCRACK*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Output Positions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NTSTATIC</th>
<th>TSTATIC</th>
<th>LAYER1*</th>
<th>LAYER2*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Creep Compliances</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LAYER 7*</th>
<th>LAYER 8*</th>
<th>POISSON*</th>
<th>CURVEFIT*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material Properties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STRNCOEF</th>
<th>STRNEXP</th>
<th>COEFK1</th>
<th>COEFK2</th>
<th>K1K2CORL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fatigue and Damage Variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GNU</th>
<th>ALPHA</th>
<th>CORLOEF</th>
<th>CORLEXP</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>TOLERANCE</th>
<th>QUALITYP</th>
<th>STDEVO</th>
<th>PSIFAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Serviceability Bounds</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NTRANDOM</th>
<th>TUNITS</th>
<th>TRANDOM</th>
<th>LAMBDA</th>
<th>AMPLITUd</th>
<th>VCATMP</th>
<th>DURATION</th>
<th>VCDUR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Traffic Variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NTEMTS</th>
<th>TEMPS</th>
<th>REFTEMP</th>
<th>BETA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature Variables</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NDEFLECT*</th>
<th>RDEFLECT*</th>
<th>DEFLECT*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inverse Solution</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ENDORFRUN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signals end of inputs, begins execution of run.</strong></td>
</tr>
</tbody>
</table>
Subsequent TYPE 3 runs (damage/performance only) may use the values which are generated for these variables. The advantage of this is that it permits analysis of the same pavement under several different traffic, temperature and serviceability conditions without recomputing the primary response information. A considerable amount of computer time can be saved in this way, because the static load analysis requires a significant computational effort.

A sample input for Type 1 analysis is shown in Appendix 1.

3.3.2 **TYPE 2 Analysis**

This calls for primary response calculations only. It produces values for stresses, strains, and deflections in a N-layered linear viscoelastic system.

3.3.3 **TYPE 3 Analysis**

It is recommended that TYPE 3 runs be made only after the primary response variables have been calculated in a TYPE 1 run. For a user to input all the required information requires a good understanding of the program. Primary response values can be passed directly from a TYPE 1 run to subsequent TYPE 3 runs of the same job. This is explained above for the TYPE 1 analysis.

3.3.4 **TYPE 4 Analysis**

This runs the curve-fitting routines on a set of data. The coefficients and DELTAS for a Dirichlet series which approximates the input curve are printed out. The approximation used is based on a least-squares fit. This type of analysis may be used in order to find the user input DELTA values which result in accurate curve fits for the creep compliance data from layer materials. Although VESYS will compute values for DELTAS when they are not specifically input, a better set of curve
fits may be obtained by a carefully chosen set of DELTAS.

3.3.5 TYPE 5 Analysis

This runs the INVERSE program for moduli determination from field measured surface deflection data. Geometry of the deflection basin and the corresponding measured deflections of a pavement system are used as input. Commands NLAYER and LAYER1, ... LAYER8 are used to input first estimates of moduli for the layers. Results of the predicted moduli from the TYPE5 runs will be returned in the internal variables associated with these commands, so a TYPE1 or TYPE2 run can be made immediately after a TYPE 5 run.

3.4 DIRECTORY OF NEW COMMANDS

The meaning of the new commands used in VESYS G-INVERSE that are not found in VESYS IIM will be explained in this section. The meaning of the other commands that are common for VESYS G and VESYS IIM will be explained in the next section.

NUMIT  (Default 20)
The number of Sub-Intervals

NLAYER  (Default 1.0)
The number of layers in a pavement system including subgrade

THICK  (Array-no default)
The array of layer thicknesses, excluding subgrade

NZPOINTS( Default 1.0)
The number of vertical positions for output

NRPOINTS( Default 1.0)
The number of radial positions for output

ZPOINTS (Array - no default)
The array of radial positions from the center of the load at which the primary response information is desired.

LAYER1  (Array - no default)
LAYER2
  
  
  
  
  

The array of the master creep compliance curves, mean and coeff. of variation, for layer 1 to layer X where X equals to NLAYER.

Mean value and the coeff. of variation of the creep compliance are read in as a pair. Thus, the first two numbers in the array of LAYER1 represent the mean of coeff. of variation of the creep compliance for layer 1 material at time corresponding to the first point in TSTATIC. Similarly the third and fourth numbers represent the mean and coeff. of variation at time corresponding to the second point in TSTATIC.

The array for each layer should consist of exactly two times NTSTATIC elements (maximum 2 x 25), and NTSTATIC must be input before any of these arrays. The format for the array is 6E12.4. See Appendix 1 for Sample Input/Output for the Input of LAYER1 to LAYERX.

ZCRACK (Default to depth of layer 1)
Depth at which strain is obtained to determine cracking index.

POISSON (Array-No Default)
Poisson's Ratio for each layer, including subgrade.

CURVEFIT (Default - No Curvefit)
Flag indicating whether layer moduli are to be curvefitted.

NDEFLECT (Default 1.0)
Number of points of deflection basin

REDEFLECT (Array - No Default)
Radial locations of points of deflection basin

DEFLECT (Array - No Default)
Corresponding measured deflections of deflection basin

Commands in VESYS IIM that are not used in VESYS G are:

ITYPES
THICK1
THICK2
LAYER1
LAYER2
LAYER3
VARCOEF1
VARCOEF2
VARCOEF3
3.5 DIRECTORY OF OTHER COMMANDS

The meaning of the other commands used in VESYS G that are essentially the same as that in VESYS IIM will be explained briefly in this section.

For more detailed information concerning each command, the user is referred to the VESYS USER'S MANUAL cited before.

ALPHA (Array-no default)
Array of permanent deformation materials property parameters for the n layers (see also GNU).

AMPLITUd (Default is 80.0)
The mean intensity of repeated loadings in psi.

BETA (Default is 0.113)
This parameter describes the variation in the time-temperature shift factor as a function of temperature.

COEFK1 (Default is 0.0)
Coefficient of variation for STRNCOEF.

COEFK2 (Default is 0.0)
Coefficient of variation for STRNEXP.

CORLCOEF (Default is 0.0)
The coefficient B in the system's spatial auto-correlation function.

CORLEXP (Default is 1.0)
Part of the exponent in the system's spatial auto-correlation function.

DURATION (Default is 0.5)
The mean duration of repeated loading in the random load analysis.

ENDOFJOB (Option selector)
Specifies that no more data remains to be run and execution of VESYS G may now be terminated.

ENDOFRUN (Option selector)
Specifies that all data needed for the current run has been read and execution may begin.

GNU (Array - no default)
Array of permanent deformation materials property parameters for the n layers (see also ALPHA).

K1K2CORL (Default is 0.0)
Correlation coefficient for STRNCOEF and STRNEXP.
LABDATA (Array-no default)
The array of data which are to be curve-fitted to a Dirichlet series in a TYPE 4 run. The array TCURVE represents the time at which the corresponding points in LABDATA are taken. There must be exactly NTCURVE elements in this array.

LAMBDA (Array-no default)
The array of average daily traffic in the Damage Model. Each element of this array represents the traffic rate at the corresponding point in the TRANDOM array.

LOADING (Default is 1.0)
In the TYPE 2 analysis, this represents the intensity of applied loading in psi.

NTCURVE (Default is 1.0)
The number of points in the TCURVE and LABDATA array.

NTEMPS (Default is 1.0)
The number of points in the TEMPS array.

NTRANDOM (Default is 1.0)
The number of points in the TRANDOM and LAMBDA arrays.

NSTATIC (Default is 1.0)
The number of points in the TSTATIC, LAYER1,...LAYERX arrays.

PSIFAIL (Default is 2.5)
The minimum acceptable serviceability, defined as (PSI)_F.

QUALITYO (Default is 5.0)
The mean serviceability index at time zero.

RADIUS (Default 6.0)
The radius of the applied loading in inches.

REFTEMP (Default is 70.0)
The reference temperature at which the master creep compliance curves in LAYERX are given.

STDEVO (Default 0.0)
The standard deviation of the initial serviceability index in the performance model. The mean of this initial serviceability index is given by QUALITYO.

STRNCOEF (Default 1.0)
The value of the coefficient K1 in the Miner's law formulation for damage.

STRNEXP (Default 0.0)
The value of the coefficient K2 in the Miner's law formulation for damage.
TCURVE  (Array-no default)
The array of times used in a TYPE 4 run. They are the
times (in. sec.) at which the LAMBDA are taken.

TEMPS  (Array-no default)
Array of temperatures in °F to be used in the damage
model.

TITLE  (Array-no default)
This keyword specifies that the next card contains a
heading which is to be printed on the output at the
beginning of each run until replaced by a new TITLE.

TOLERANCE  (Default 50.0)
Minimum acceptable reliability of the pavement expressed
as a percent. Reliability is the probability that
serviceability has not reached PSIFAIL at or before
some given time.

TSTATIC  (Array-no default)
Array of time at which creep compliance data (LAYERX)
were taken. These times are in seconds.

TRANDOM  (Array-no default)
Array of times at which a printout of the values
computed in the damage model is desired.

TUNITS  (Default 5.0)
Specifies the units of time which were used in the
TRANDOM array.
1.0 = seconds
2.0 = minutes
3.0 = hours
4.0 = days
5.0 = months
6.0 = years

TYPE  (Default 1.0)
This is the basic control variable for the program.
It specifies which type of analysis is to be performed.
The following codes are used:
1.0 = Primary Response Analysis and Damage/
  Performance analysis
2.0 = Primary Response Analysis only
3.0 = Damage/Performance Analysis only
4.0 = Curve-Fitting only

UNLOAD  (Option selector)
This command specifies that the vertical displacement
response factor for unloading are to be computed.
VCAMP (Default is 400.0)
The variance of the repeated loading intensity distribution.

VCDUR (Default 0.0)
The variance of the duration of the repeated loadings.
4. EXAMPLES

The purpose of this chapter is to present examples illustrating the use of the program for different TYPE analyses. The first example is to perform the TYPE5 run for predicting the pavement layer properties from the measured pavement surface deflection profiles, and then using the moduli so determined to perform the TYPE2 run for the same pavement system for analyzing the pavement primary responses. The second example illustrates the TYPE1 run for a three layer pavement system in which the pavement layer properties are considered to be time-dependent and probabilistic.

4.1 EXAMPLE ONE - TYPE5 and TYPE2 RUN

The pavement system to be studied in this example was the "WEST Pavement", one of the two 10 ft. by 10 ft. prototype flexible pavements constructed by the FHWA in the structural laboratory at Fairbank Highway Research Station as described in detail by Kenis [6]. The WEST pavement consisted of 2.63 inches of asphalt concrete surface, 8.39 inches of crushed stone base course and about 7 ft. (considered to semi-infinite in this analysis) of clay. The construction of the prototype pavement and the physical property characterizations of the materials are described in [6]. During the construction, various instrumentations, strain gages, pressure cells were placed at the various locations in the pavement system. The loading system for the prototype pavement allowed for static (creep) loading and repetitive (dynamic) loading. During the loading, various pavement responses (strains, stresses and surface deflections) at various locations were recorded. In this example, which was identified as Test 22 in [6], the loading was a repetitive type with 0.1 sec. load duration and 0.9 sec.
rest period. The geometry of the prototype pavement and the loading is shown in Fig. 7.

The purposes of this example are (1) to perform TYPE5 run to determine the moduli for the asphalt concrete, the crushed stone and the clay of the prototype pavement under the loading conditions as shown in Fig. 7 and utilizing the measured surface deflections, and (2) to perform TYPE2 run to determine the pavement primary responses (stresses, strains, and deflections) at various locations for the same prototype pavement using the moduli determined in (1). In Appendix 3, the predicted pavement primary responses (strains at various locations) were compared with the measured strain responses for the pavement under various loading conditions.

The inputs and the outputs for this example are shown in Appendix 1.

For the inputs shown in Appendix 1, CARD 1 to 19 are for the TYPE5 run. In TYPE5 run, the values in CARD 15, 17 and 19 are the initial assumed moduli for layers 1, 2 and 3 respectively. The other cards are self-explanatory. CARD 20, ENDOFRUN signals the end of the run. CARD 21 to 26 are for the next run, in this case the TYPE5 run as indicated by CARD 21. Since no new TITLE, LOADING, RADIUS, NLAYER, THICK and POISSON are included in this run, the program will use the same corresponding values in the previous run. Also, no LAYER1, LAYER2, LAYER3 values are included, in this case the program will automatically assume the latest LAYER1, LAYER2, and LAYER3 values in the previous run. Since the previous run is a TYPE5 run, the latest values for LAYER1, LAYER2 and LAYER3 are 4,304,490, 14,775, and 64,598 respectively, the final estimated layer moduli from the inverse solution (see the output printout from TYPE5 run).
Figure 7. Pavement System for Example One.
The TYPE5 output printout as shown in APPENDIX 1 are self-explanatory. The first portion of the printout displays the input information. The second portion of the printout displays the predicted layer moduli.

In some cases, the convergence cannot be achieved under criteria specified in the computer program. If one of the non-convergence criteria met a message such as

"
"

will be displayed in the PROBLEM OUTPUT instead of the predicted moduli. The most probable cause for causing this to happen is the initial assumed moduli are too far from the "actual" moduli. It is suggested that the user rerun the case using a new set of initial assumed moduli. Due to the numerical procedure used in the program, the convergence is more sensitive to the over-estimation of the moduli (initial assumed moduli greater than the "actual" moduli) than under-estimation. The program has the capability of providing additional information to assist the user in selecting the proper new set of initial assumed moduli when non-convergence occurs. For this information, the reader is referred to the APPENDIX 2 Program Documentation.

4.2 EXAMPLE TWO - TYPE1 Run

The inputs of this example are shown in APPENDIX 1. Due to the time-dependent and the probabilistic nature of the layer moduli, the inputs for the LAYER1, LAYER2 and LAYER3 are much more lengthy than that of the example one. In CARD 4, NTSTATIC = 11, this indicates that the time-dependent properties of the layer moduli (layer 1 only) are input at eleven time intervals as specified by TSTATIC (CARD 14, 15, 16). For LAYER1 (CARD 17 and 18 to 20) it should have eleven pairs of values
associated with the MEAN and COEFFICIENT OF VARIATION (COV) of the modulus of LAYER1 material at the corresponding eleven time interval. LAYER2 and LAYER3 are considered to be elastic, thus, the MEAN and COV are the same for all the time periods (CARD 21 to 31). CARD 32 to 60 are for the distress analysis. The meaning of the commands used in this part of the inputs has been explained in Section 3.5.

The outputs from this example is too length to be included in this report. They are presented in a separate report.
REFERENCES


APPENDIX 1

SAMPLE INPUTS AND OUTPUTS
<table>
<thead>
<tr>
<th>NAME</th>
<th>CHARGE OR REFERENCE NUMBER</th>
<th>DATE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TITLE</th>
<th>TEST</th>
<th>TYPE</th>
<th>LOADING</th>
<th>RADIUS</th>
<th>NLAYER</th>
<th>NDEFLICTS</th>
<th>THICK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>8Ø</td>
<td>6</td>
<td>3</td>
<td>5</td>
<td>2.63</td>
</tr>
<tr>
<td>RDEFLICT</td>
<td>Ø 7.75</td>
<td>13.5</td>
<td>2Ø0.5</td>
<td>3Ø0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| DEFLECT | Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø ØØØØ Ø .....
A.2.1 Macro Program Structure

The VESYS G INVERSE package contains the following five major programs which are further divided into subroutines.

MAIN - handles all data input and stores it in a form suitable for use by the other subcomponents.

CURVIT - performs a least squares curve-fitting technique using Dirichlet series.

PRIME - computes closed-form probabilistic solution, mean and deviation of the stress, strain and deflection at the prescribed positions for a n-layer viscoelastic pavement system.

INVERSE - compute layer moduli from surface deflection inputs.

RANDOM - computes the pavement response to a repeated load, the pavement distress (rutting, cracking and slope variance), and the pavement serviceability.

The macro flow chart of the overall program is shown in Fig. A-1.

Since the major difference between VESYS IIM and VESYS G-INVERSE is in PRIME, and INVERSE the remaining part of this Appendix will be concentrated on discussion of these two programs.

A.2.2 PRIME Program

The Primary Response Program consists of the following subroutines:

PRIME - reads in all input data.

NLAYER - computes closed-form solutions (mean and deviation) of stresses, strains and deflections.
Figure A.1. Macro Flow Chart of VESYS G-INVERSE Including TYPE 5 Run.
PART - computes integration, m.

COEF - computes $A_i, B_i, C_i, D_i, dA_i, dB_i, dC_i, dD_i$.

TERMS - computes matrix $X_i$ and $\partial X_i / \partial E_j$.

DMULT - matrix multiplication.

BESSEL - evaluates Bessel functions $J_0$ and $J_1$.

FINTG1 - evaluates integration and performs deterministic calculation of stresses, strains and deflection.

FINTG2 - evaluates integration and performs probabilistic solution of deviations of stresses, strains and deflection.

PROBL - evaluates variances.

The interrelationship of these subroutine is illustrated in Fig. A.2.

The main PRIME program acts essentially as a supervisor program handling all input and output operations. It also computes the permanent deformation and system GNU and ALF which are to be used in RANDOM for pavement rut depth computation. A flow chart for this subroutine is shown in Fig. A.3. The NLAYER subroutine is the main subroutine which computes the stresses, strains and deflections. A flow chart for this subroutine is shown in Fig. A.4.
FIGURE A.2. PROGRAM STRUCTURE OF PRIME
START

SET INPUT VARIABLES

CHECK IF POINTS FOR OUTPUT AT ZCRACK AND ZRUT

YES

CURVE FIT COMPLIANCE

FIND CORRECT MODULUS AND VARIATION AT TIME T

T<NTO

CALL NLAYER

T<NT0

CURVE FIT SYSTEM RESPONSES

NO

ADD POINTS IN ZZ ARRAY

BYPASS = TRUE?

YES

DETERMINE SYSTEM a AND μ

CALL RANDOM

RETURN

NO

RETURN

FIGURE A.3. FLOW CHART FOR PRIME
START
PRINT HEADINGS AND INPUT VARIABLES
SET UP ITERATION COUNT VARIABLES
1
2
GET SYSTEM RESPONSES
GET SYSTEM VARIATIONS
RETURN

1
START ON NEW R
CALL PART
CALL COEF
CALL BESSEL
START ON NEW 2
CALL FINTG1
CALL FINTG2
IZT<IZ
PRINT STRESSES
PRINT STRAINS AND DISPLACEMENTS
IRT<IR
2

FIGURE A.4. FLOW CHART FOR NLAYER
A.2.3 INVERSE Program

The Moduli Prediction Program consists of the following subroutines:

INVERSE - reads in all input data

PART -

BESSEL - same as used in PRIME

TERMS -

DMULT -

CONSTN - computes $A_i$, $B_i$, $C_i$, $dA_i$, $dB_i$, $dC_i$, $dD_i$.

TINTEG - evaluates integration and performs deterministic calculation of deflections.

FSOLV - solves matrix equation $AX = B$.

FINV - calculates $dE_i$, computes closer approximation of $E_i$ and checks for convergence.

Essentially, the only difference between the INVERSE program and the PRIME program is that a new subroutine to do least square minimization is added in INVERSE and it is made simpler since only surface deflections are needed as output from static analysis.
Figure A.5. FLOW CHART FOR INVERSE.
APPENDIX 3

COMPARISONS OF PREDICTIONS WITH PROTOTYPE PAVEMENT TEST RESULTS
Table 6. Predicted vs. Measured Strains in the Prototype Pavement System

<table>
<thead>
<tr>
<th>Gage No.</th>
<th>Position (in.)</th>
<th>t = 0.05 sec.</th>
<th>t = 100 sec.</th>
<th>TEST 22</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Measured, Predicted</td>
<td>Measured, Predicted</td>
<td>Measured</td>
</tr>
<tr>
<td>1</td>
<td>0 2.63</td>
<td>-0.06 +0.0996</td>
<td>-0.04 +0.119</td>
<td>-0.10</td>
</tr>
<tr>
<td>2</td>
<td>7.5 0</td>
<td>-0.012 -0.0034</td>
<td>-0.008 +0.0063</td>
<td>~0</td>
</tr>
<tr>
<td>3</td>
<td>7.2 0</td>
<td>-0.092 -0.0609</td>
<td>+0.096 -0.0704</td>
<td>-0.110</td>
</tr>
<tr>
<td>4</td>
<td>6.2 2.63</td>
<td>-0.072 0.076</td>
<td>-0.072 +0.0885</td>
<td>-0.110</td>
</tr>
<tr>
<td>5</td>
<td>5.7 2.63</td>
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<td>-0.035 +0.0232</td>
<td>-0.025</td>
</tr>
<tr>
<td>6</td>
<td>12.2 0</td>
<td>+0.045 -0.0297</td>
<td>+0.046 -0.031</td>
<td>+0.070</td>
</tr>
<tr>
<td>7</td>
<td>0 0</td>
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<td>-0.145 -0.115</td>
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</tr>
<tr>
<td>8</td>
<td>12.3 2.63</td>
<td>-0.023 0.0312</td>
<td>-0.020 +0.031</td>
<td>-0.050</td>
</tr>
</tbody>
</table>

Strain Unit = $10^{-3}$ in./in.
Test 22 (80 psi, Repetitive Loading, 35°F)
Test 6 (40 psi, Creep Loading, 75°F)

Predicted Moduli (psi)

\[ \begin{align*}
E_1 &= 1,992,517 \\
E_2 &= 13,038 \\
E_3 &= 160,250 \\
\end{align*} \]

\[ \begin{align*}
E_1 &= 1,219,402 \\
E_2 &= 21,429 \\
E_3 &= 66,679 \\
\end{align*} \]