BALLIST - A Computer Program to Empirically Predict the Bumper Thickness Required to Prevent Perforation of the Space Station by Orbital Debris

Supplemental Final Report

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1. Introduction

There are many engineering applications where predictions of the behavior of a physical system must be made based on a database of experimental results. In these instances, either the phenomenon is too complicated to treat analytically or numerically, or the funding, expertise, or time required to do so is not available. Empirical approaches of this nature have always played a fundamental role in engineering design.

This report describes a computer program called BALLIST that is intended to be a design tool for engineers. BALLIST empirically predicts the bumper thickness required to prevent perforation of the Space Station pressure wall by a projectile (such as orbital debris) as a function of the projectile's velocity. "Ballistic" limit curves (bumper thickness VS projectile velocity) are calculated and are displayed on the screen as well as being stored in an ASCII file. A Whipple [1] style of spacecraft wall configuration is assumed as shown in Fig. 1. The predictions are based on a database of impact test results. NASA Marshall Space Flight Center [2] currently has the capability to generate such test results. Numerical simulation results of impact conditions that can not be tested (high velocities or large particles) can also be used for predictions.

BALLIST is written in Microsoft® BASIC and is designed to run on an MS-DOS based personal computer. All of the features of BALLIST are linked together in the seamless environment of a pull down menu system. An integrated, on line, user modifiable, help file is provided to assist the user with the menu choices. A software user guide is provided in Section 2 of this report.

Three different empirical prediction techniques are used to generate three ballistic limit curves. The prediction techniques are described in Sections 3 through 5. Three curves are generated to allow the user to compare the results of the prediction schemes. Typically, results are more reliable where the three prediction schemes produce similar results. The ballistic limit curves are graphically illustrated on the screen and are also stored in an ASCII file. The ASCII file allows the results to be used in other applications as well as providing a means of archiving results.

This program assumes that all of the empirical data has the same: bumper material (typically 6061-T6 AL), bumper stand-off (typically 4"), MLI position (or all no MLI), pressure wall material (typically 2219-T87 AL), and projectile material (typically 1100 AL). Thus, data sets containing, for instance, test results for different bumper materials should not be used to make predictions using this program. WARNING - the correct units must be used! The correct units are given in this report and listed in the help file.

2. Software User Guide

2.1 Computer System Requirements

BALLIST was written using the Microsoft® BASIC Professional Development System. An EGA or VGA graphics card and monitor, and an Intel 80286, 80386, or 80486 CPU is required to run the software. A math coprocessor must be available. Approximately 2 MB of hard disk space is required to install and run BALLIST.

2.2 Software Installation and Execution

The software can be installed by first creating a subdirectory on the hard disk and then copying all of the files from the floppy disk into that subdirectory. The program is started by typing BALLIST. The functions of BALLIST can be selected from the keyboard or by the mouse as will now be described.

WARNING - Be sure you are using the correct units! Any consistent set of units may be used. However, the units indicated below are recommended since they are typically used by the orbital debris research community.

Standard Operating Procedure -

After starting the program, the standard procedure for running BALLIST is as follows. First, the impact parameters file (CRVIMPAC.PAR) is edited (under FILE menu) to reflect: the data file containing the empirical data, the data file to be used for storing the results, the impact angle, the projectile diameter, the pressure wall thickness, the minimum and maximum projectile velocities, and the number of calculation points. The dialog box associated with these parameter inputs is shown in Fig. 2. The FILE menu structure is shown in Fig. 3(a). The BALLIST family of programs and data files is illustrated in Fig. 4.

Then, the impact results data file is edited (data records added, deleted, or viewed) if necessary by making appropriate picks from the FILE menu [Fig. 3(a)]. The dialog boxes used to maintain the impact results data file are shown in Fig. 5. Next, the ballistic limit curves are calculated [under RESULTS menu shown in Fig. 3(b)] by using three interpolation functions: nondimensional, inverse-R, and polynomial fit. The ballistic limit curves can be viewed or listed on the screen by using the appropriate menu picks under the RESULTS menu. The help document can be viewed from the help menu shown in Fig. 3(c).

The procedures described above can be performed by selecting tasks from the menu. The menu can be activated by clicking with the mouse, or by pressing the <ALT> key. Menu commands can be selected by using the mouse, by using the arrow keys and pressing <ENTER>, or by typing the red letter of each command. A more detailed description of the menu commands of BALLIST will now be provided.

Main Menu - FILE

ADD TO IMPACT DATA FILE:

This allows the user to add data records to the impact test results file. This file contains the data used for making empirical predictions of impact damage to the pressure wall. The dialog box associated with this menu pick is shown in Fig. 5(a). Note that certain typical data inputs have been placed in the edit boxes as defaults. This menu pick runs the program CRVDBASE.EXE. The first record in the impact parameters file, CRVIMPAC.PAR, contains the name of the impact testing results file that will be operated on. This filename can be changed by selecting the EDIT IMPACT PARAMETERS FILE menu pick, which is described below. A typical data record in the impact test results file consists of the following items (same format as the MLITemp [3] program database):

1. test ID number
2. source of the data
3. test date
4. bumper material name
5. bumper thickness (inches)
6. bumper standoff (inches)
7. pressure wall material name
8. pressure wall thickness (inches)
9. projectile material name
10. projectile diameter (inches)
11. impact angle (degrees) - this is the angle between the normal to the bumper and the line of travel of the projectile.
12. projectile velocity (km/sec)
13. major axis of bumper hole (inches)
14. minor axis of bumper hole (inches)
15. average MLI hole diameter (inches)
16. average pressure wall hole diameter (inches)

NOTE- Data items *1,2,3,4,6,7,9,13,14,15* are not actually used to make predictions, so a value of -1 (or some other *number*) can be input for these data items for the purposes of the BALLIST program.

The user can move from edit box to edit box in the editor window by pressing the <TAB> key, by pressing the <ENTER> key, or by pressing the up or down arrow keys. The user can move around within an edit box of an edit window using the <HOME>, <END>,

and side arrow keys. A button at the bottom of the edit window (add to database, cancel this data entry, exit program) can be activated by pressing <ENTER> after a button has been selected using the <TAB> or arrow keys. The mouse can also be used to move between edit boxes and buttons.

REMOVE FROM IMPACT DATA FILE:

This allows the user to remove records from the impact test results file. This file contains the data used for making empirical predictions of impact damage to the pressure wall. The dialog box associated with this menu pick is shown in Fig. 5(b). This menu pick runs the program CRVDBDEL.EXE. The first record in the impact parameters file, CRVIMPAC.PAR, contains the name of the impact test results file that will be operated on. This filename can be changed by selecting the EDIT IMPACT PARAMETERS FILE menu pick, which is described below.

VIEW IMPACT DATA FILE:

This allows the user to view records in the impact testing results file. This file contains the data used for making empirical predictions of impact damage to the pressure wall. The dialog box used for viewing the data records is shown in Fig. 5(c). This menu pick runs the program CRVDBOUT.EXE. The first record in the impact parameters file, CRVIMPAC.PAR, contains the name of the impact test results file that will be operated on. This filename can be changed by selecting the EDIT IMPACT PARAMETERS FILE menu pick, which is described below.

EDIT IMPACT PARAMETERS FILE:

This allows the user to view and edit the impact parameters file, CRVIMPAC.PAR. The dialog box used for this purpose is shown in Fig. 2. This menu pick runs the program IMPAEDIT.EXE. CRVIMPAC.PAR specifies the following information related to predicting the ballistic limit curves (required units shown in brackets):

1. filename of the impact test results data file
2. filename of the file to be used to store the output from the ballistic limit prediction programs
3. impact angle (degrees) - this is the angle between the normal to the bumper and the line of travel of the projectile .
4. projectile diameter (inches)
5. pressure wall thickness (inches)
6. minimum (lower limit) projectile velocity for calculation purposes (km/sec)

7. maximum (upper limit) projectile velocity for calculation purposes (km/sec)
8. the number of calculation data points to be used for plotting ballistic limit curves (minimum = 2)

File CRVIMPAC.PAR is an ASCII file so it can be viewed and edited with a text editor if so desired.

The user can move from edit box to edit box in the editor window by pressing the <TAB> key, by pressing the <ENTER> key, or by pressing the up or down arrow keys. The user can move around within an edit box using the <HOME>, <END>, and side arrow keys. A button at the bottom of the edit window (save changes and exit, exit program) can be activated by pressing <ENTER> after a button has been selected using the <TAB> or arrow keys. The mouse can also be used to move between edit boxes and buttons.

CURRENT DIRECTORY FILENAMES:

This menu pick causes the names of the files in the current directory to be listed on the screen. This may be useful if the user forgets the name of a data file.

DOS SHELL:

This menu causes a DOS shell to be created. This will allow the user to copy files and perform other tasks without leaving the BALLIST program permanently. Entering "exit" causes the DOS shell to close.

EXIT:

This menu pick will end the BALLIST program.

Main Menu - RESULTS

CALCULATE BALLISTIC LIMIT CURVES:

This menu pick will cause ballistic limit curve predictions to be made using: the "nondimensional" function prediction algorithm (CRVNONDM.EXE program executed), the "inverse R" function prediction algorithm (program CRVINVR.EXE is executed), and the "polynomial" function prediction algorithm (program CRVPOLY.EXE is executed). These prediction algorithms are described in Sections 3 through 5. The predictions are based on the empirical data contained in the impact test results data file named in the impact parameters file (CRVIMPAC.PAR). The impact parameters associated with the prediction are also contained in file CRVIMPAC.PAR. File CRVIMPAC.PAR can be edited from the EDIT IMPACT PARAMETERS FILE menu pick under the FILE main menu. The ballistic limit

curve data points are written to the results data file named in the impact parameters file CRVIMPAC.PAR. After the ballistic limit curves have been calculated they will be graphically displayed on the screen (see VIEW BALLISTIC LIMIT CURVES described below).

While the nondimensional function prediction technique is running the current sum of the residuals squared is displayed on the screen so that the user can monitor the least squares fitting process. As described in Section 3, an optimizer is used to minimize the sum of the residuals squared by adjusting the coefficients of the nondimensional function. The optimizer uses random numbers so the final sum of the residuals squared will vary from run to run even if the same impact test results data file is used. If multiple runs are used then the results of the run with the lowest final sum of the residuals squared should be taken as the best answer (best fit). The last set of nondimensional function coefficients are saved in an ASCII file called CRVNONDM.PAR. To save time, these previously calculated coefficients can be used in new analyses instead of recalculating coefficients, provided that the impact test results data file did not change. The user is prompted for whether old coefficients should be used or new coefficients calculated.

VIEW BALLISTIC LIMIT CURVES:

This menu pick will cause the three ballistic limit curves (bumper thickness versus projectile velocity such that the pressure wall is not perforated) to be graphically displayed on the screen. The data contained in the results data file named in the impact parameters file (CRVIMPAC.PAR) is plotted. The results of previous analyses (not just the most recent) can be displayed on the screen by placing the filename in the CRVIMPAC.PAR file. The bumper thickness axis has been adjusted so that bumper thicknesses up to three times the average of all calculated bumper thicknesses are displayed on the screen. This is done so wild points (ie. probably unreliable) will not upset an appropriate display of the remaining data. Calculated bumper thicknesses greater that this amount are represented by an open circle at the top of the plot. If a perforation stopping bumper thickness could not be calculated for a given projectile velocity then the thickness stored in the results data file is set to -1 and plotted as an open circle on the velocity axis of the ballistic limit plots. The calculated data points are connected together with line segments except for the "-1" data points.

VIEW BALLISTIC LIMIT DATA:

This menu pick causes the results data file (named in the impact parameters file CRVIMPAC.PAR) to be listed on the screen. The results of previous analyses (not just the most recent) can be displayed on the screen by placing the filename in the CRVIMPAC.PAR file.

Main Menu - HELP

VIEW HELP DOCUMENT:

This menu pick will cause program HELPCURV.EXE to run which displays document HELPCURV.DOC.

2.3 Typical Results

A typical set of impact test results data is provided with the software in file BALLIST.DAT. This file was created using the BALLIST software package and may of course be modified and viewed by the user. An analysis was run using this impact data to create the results data file contained in Fig. 6. Fig. 7 displays a bitmap image of the computer screen showing the ballistic limit curves (bumper thickness versus projectile velocity) plotted from the data of Fig. 6. Note that the polynomial fit function produced one wild point that went off-scale (open circle at top of plot) and could not find a perforation stopping bumper thickness for another point (open circle at bottom of plot). The results shown in Figs. 6 and 7 are typical results. The accuracy of the results obtained depend on the accuracy of the impact test results on which they are based. The accuracy of the results also depends on the degree to which the impact test results span the prediction variable space. If most of the data is for a small part of the prediction space (narrow bumper thickness range and so forth) then the prediction algorithms will be required to extrapolate, thereby potentially producing poor predictions.

3. Nondimensional Parameter Prediction Technique

In many applications it has been found that empirical functions are best represented in terms of nondimensional parameters. Reynolds number is an example of a nondimensional parameter that has found widespread use in the empirical equations of fluid mechanics. Program CRVNONDM.EXE uses an empirical function based on nondimensional parameters of the following form which is derived from functions provided in [4]:

$$\frac{D_{pw}}{D} = C_1\left(\frac{V}{V_s}\right)^{C_2}\left(\frac{T_b}{D}\right)^{C_3}\left(\frac{T_p}{D}\right)^{C_4}(\cos\theta)^{C_5} + C_6 \qquad (1)$$

where as shown in Fig. 1: D is the projectile diameter. V is the velocity of the projectile. T_b is the bumper thickness. T_p is the thickness of the pressure wall. θ is the impact angle. V_s is the speed of sound in the bumper material. C_i are coefficients to be fit from the data. and D_{pw} is the average diameter of the pressure wall hole. Here it is assumed that all of the records in an impact results data file have the same bumper material and so the V_s factor in Eq. 1 can be incorporated into the C_1 term.

The function coefficients are determined for a given set of data by using an optimization routine to minimize the sum of the residuals squared (SR2). A residual is calculated by subtracting

a measured value of D_{pw} from that calculated by using Eq. 1. The residual is squared so that it is the magnitude of the residual that is significant in the calculations. The sign of the residual is given no importance. If the measured data obeyed the form of Eq. 1 and the C_i coefficients were properly fit then the SR2 would be zero. However, Eq. 1 is not exact and there is typically a significant amount of scatter in the data so the SR2 is in general non-zero. The idea is to adjust the six coefficients C_i to minimize the discrepancy between the measured and calculated (Eq. 1) values. The nature of the optimization routine will now be described.

The first step in the optimization process is to select an initial point in the optimization space - an initial set of values for the function coefficients, C_i. Here the initial values of the function coefficients were all set to zero. The final values of the function coefficients could be positive, negative or zero. Since Eq. 1 is nonlinear it is possible that entirely different sets of coefficients can produce essentially the same goodness of fit. This effect was reported in [5].

The next step in the optimization process is to develop an optimization space search vector. The optimizer moves from the current point in the optimization space to some improved point (lower SR2) in the design space along the search vector. The method chosen here for search vector selection is based on Powell's method [6]. This is a zero order method that does not require the calculation of the gradient vector. Powell's method is modified as follows. Initially, a number of search vectors equal to the number of function coefficients are created. The components of these vectors are random numbers between -1 and +1. The components of each random search vector are then scaled such that the largest component has a magnitude of unity. These vectors are stored as columns of a "search matrix". Next, the SR2 is evaluated at the current point in the optimization space and at optimization points given by +/- the search domain parameter times the first column of the search matrix. The search domain parameter is initially set to unity and then gradually reduced to 0.01 as the optimization iterations proceed. This allows for rapid movements to the vicinity of the minimum in the SR2 function initially, and then fine movements at the end of the optimization process to accurately locate the minimum of the SR2 function. If either of the +/- optimization points has a lower SR2 than that of the current optimization point, then that optimization point will become the new optimization point. Otherwise, the optimization point does not change. The search vector multiplier (+/- search magnitude parameter or zero) used with the search vector is stored for later use. This procedure is then repeated with the remaining columns of the search matrix.

A new search vector is created after using all of the search vectors in the search matrix. This new vector is created by vectorially adding together all of the search vectors times their search vector multipliers. The new search vector is a vector sum of previous successful search vectors since unsuccessful search vectors have search multipliers of zero. Thus, the new search vector represents (stores) the trend of the optimization process. The new search vector is scaled such that its' largest component is unity and then is used to replace the first column of the search matrix. The procedure is repeated, a new search vector is determined, and then used to replace

the second column of the search matrix, and so forth until only the last column of the search matrix remains untouched. Then, an entirely new search matrix is created using the random number generator, and the process continues.

If at any time in the iterative process a new search vector has a magnitude of zero (implying that all current search directions are not beneficial), then a new random search matrix is created immediately. The random number generator uses a seed based on the number of seconds from midnight on the computer's clock. Thus, each successive run of the optimizer will use a different set of search vectors. Currently, the program runs three times to help ensure that the global minimum of SR2 has been located in the optimization space.

Once the coefficients C_i have been determined by the optimizer then Eq. 1 can be used to solve for the T_b required to produce no pressure wall perforation ($D_{pw} = 0$) for a specified impact angle, projectile diameter, projectile velocity, and pressure wall thickness. Considering the form of Eq. 1, it can be seen that the shape of the ballistic limit curves (bumper thickness to produce no pressure wall perforation versus projectile velocity) will be monotonically increasing or decreasing. Thus, "u-shaped" ballistic limit curves can not be generated. This characteristic is not shared by the prediction methods discussed in the following two sections.

4. Inverse R Prediction Technique

The usual procedure for making predictions from experimental data is to assume some form for the equation relating the independent variables to the dependent variable, such as that discussed in Section 3 of this report. The equation typically contains empirical coefficients, the values of which are determined from a fit to the experimental data. The final result is a closed-form equation for making predictions.

This approach has been found to work very well for many engineering applications, however there are some disadvantages. A suitable form for the prediction equation must be developed. This is often difficult. Generally, a single set of empirical coefficients are used to make predictions over a wide range of values of the independent variables. Thus, the best information in the database for making a prediction with a particular set of independent variables can not be used to best advantage.

In this section, a unique method (called inverse R) for making empirical predictions based on experimental data is discussed. The method uses a very general form of prediction equation that can be applied in the same manner to all problems. Thus, the user is not required to develop a suitable form for the prediction function. Also, the method automatically takes advantage of the most appropriate information in the database while making a prediction. The accuracy of this method for making predictions has been confirmed [7].

The inverse R method consists of four main steps which will now be described.

STEP 1. Normalize the Independent Variables

In general, the independent variables can vary greatly in magnitude. This technique requires that all variables be of the same order of magnitude. This is accomplished by scaling the independent variables such that their mean value is unity.

STEP 2. Select a Series of Points in the Data Domain for Interpolation

Two general requirements for prediction schemes are: the method should be capable of smoothing the data to (hopefully) cancel out the random scatter typically present in experimental measurements, and the technique should allow for making extrapolations outside of the domain of the measured data. Here these requirements are satisfied by using the data to make 5 interpolations from within the domain of the data, which are then used for predicting the dependent variable (pressure wall hole diameter) at some point of interest. The 5 "interpolation" points should provide for sufficient smoothing of the data and also capture the trend characteristics of the data for extrapolation.

Fig. 8 provides an illustration of how the interpolation points would be selected for a hypothetical case with two independent variables. An identical approach is used for the case of an arbitrary number of independent variables. In Fig. 8, the independent variables are in the plane of the page, and the dependent variable takes the form of a surface out of the plane of the page. First, a "prediction vector" is drawn from the origin through the point in the domain where a prediction of the dependent variable is required, which is called the "target" point. Then the "min" and "max" points (Fig. 8) are located on the prediction vector by considering the intersection points of perpendiculars from the data points to the prediction vector. The closest intersection point to the origin defines the min point, and that of the farthest, the max point. Five equally spaced points (interpolation points) on the prediction vector between the min and max points are then used for the next step in the prediction process.

STEP 3. Estimate Values of the Dependent Variable at Interpolation Points

Next, values for the dependent variable (pressure wall hole diameter) must be estimated at the 5 interpolation points. The following equation is used for this purpose:

$$D_{pw} = \frac{\sum(D_{pwi} / R_i^{N-1})}{\sum(1 / R_i^{N-1})} \qquad (2)$$

where: D_{pw} is the predicted value of the pressure wall hole diameter, D_{pwi} is the measured pressure wall hole diameter of the i-the data point, N is the number of independent variables, and

R_i is the "distance" from the i-the data point to an interpolation or prediction point. The summation is over all of the points in the impact results data file. The distances, R_i, are determined by the usual formula for determining the "distance" between two points in an N-dimensional space:

$$R_i^2 = \sum_{j=1}^{N} (x_{j,i} - x_{j,INT})^2 \qquad (3)$$

where: $x_{j,i}$ and $x_{j,INT}$ are the j-the coordinates (independent variables) of the data point and the point to be predicted, respectively. The need for scaling the independent variables is evident from considering the form of Eq. 3.

The form of Eq. 2 will now be considered. It is assumed that if all measured data points are the same "distance" R from an interpolation point then all the measured data should be given equal weight. This is illustrated for the case of two independent variables (N = 2) in Fig. 9. This can be interpreted as allocating each data point some "characteristic length of influence," S, that subtends an angle $\phi = S/R = S/R^{N-1}$ as indicated in Fig. 9. The ϕ is a weighting factor. For the constant R case shown in Fig. 9, all data points would be given the same weight. Fig. 10 illustrates the case for which the data points are considered to be equally valid (same S), but are located different distances from the interpolation point. Here, the weight factors will be of the form $\phi_i = S/R_i^{N-1}$, and thus data points closer to the interpolation point will be given a higher weight. The value of the dependent variable at an interpolation point can be estimated from $D_{pw} = \Sigma\phi_i D_{pwi}/\Sigma\phi_i$ which leads to Eq. 2. Note that a value for S is not required as it cancels out of the equation.

The three-dimensional (three independent variables) application of this procedure leads to equations identical in form to those used for determining view factors in the field of radiation heat transfer [8]. The inverse R method can be interpreted as follows. The measured data points are "radiating" information to the interpolation point. The farther the data point is away, the weaker the "radiation" (lower weight given to the information). In principle, the method can easily be extended to any number of independent variables.

STEP 4. Fit a Polynomial Through the Interpolation Points and Make Prediction

The final step in the prediction process involves fitting a quadratic polynomial through the 5 interpolation points and then using the polynomial to make a prediction of the dependent variable at the target point. The polynomial describes how the dependent variable behaves as a function of distance along the prediction vector. Errors in the 5 interpolation points tend to get smoothed by the polynomial.

The inverse R prediction technique is used to predict the bumper thickness required to prevent perforation of the pressure wall in the following manner. First, the impact test results database is searched to find the minimum and maximum bumper thicknesses used in the testing. Then, the inverse R prediction technique as described above is used to predict the pressure wall hole diameter for these bumper thicknesses and three equally spaced intermediate bumper thicknesses (total of 5 predictions). Finally, a line was fit through these 5 prediction points (pressure wall hole diameter versus bumper thickness) and the bumper thickness required for no pressure wall perforation is extrapolated from this line.

5. Polynomial Function Prediction Technique

In this section, the polynomial function prediction technique is described. This method is based on the concepts of the finite element method (FEM). FEM uses relatively low order polynomials to interpolate functions (such as stresses) over a small portion of the domain where the function is active (called an element). The coefficients of the polynomial are derived from known values of the function of interest at points called nodes on the boundary of the element. For this application, the "nodal" values of the function of interest (pressure wall hole diameter) were measured experimentally and thus are known quantities. This prediction technique involves selecting a sufficient number of experimental data points (nodes) to form an "element" and then determining the coefficients of the polynomial from this data. The effectiveness of this prediction technique was reported in [5].

Ideally, the nodes "closest" to the prediction point should be used to evaluate the polynomial coefficients and thus make a prediction. However, the set of closest nodes may not form a linearly independent set of data making it impossible to solve for the polynomial coefficients. Thus, remoter nodes must be considered in an attempt to find a linearly independent set of data. The technique used for selecting remoter nodes is discussed below.

In general, the independent parameters will vary greatly in magnitude. The polynomial function approach to prediction requires a reasonable scheme for determining "distances" between data points in impact parameter space. This is accomplished in the program by scaling the independent variables such that their mean value is equal to unity. Having scaled the independent variables, the usual formula for determining the distance, R_i, between two points (experimental data point "node" and the prediction point) in a multidimensional space can be used:

$$R_i^2 = \sum_{j=1}^{N} (x_{j,i} - x_{j,INT})^2 \qquad (4)$$

where $x_{j,i}$ and $x_{j,INT}$ are the j-th coordinates (N independent variables) of the data point and the point to be predicted or interpolated, respectively.

The form of the polynomial will now be considered. FEM theory dictates that a "complete" polynomial should produce the best results [9]. Here there are five independent variables (bumper thickness, pressure wall thickness, projectile diameter, impact angle, projectile velocity), $x_{j,i}$ (j = 1 to 5), associated with the i-th experimental data point to consider. It was decided to use $\Delta x_{j,i}$ ($=x_{j,i} - x_{j,\,INT}$) values in the polynomial equation to simplify the calculations. The lowest order complete polynomial for this case is:

$$D_{pw} = C_1 + C_2*\Delta x_{1,i} + C_3*\Delta x_{2,i} + C_4*\Delta x_{3,i} + C_5*\Delta x_{4,i} + C_6*\Delta x_{5,i} \qquad (5)$$

where the C_i are the polynomial coefficients to be determined by fitting Eq. 5 to 6 data points. Eq. 5 allows for a linear variation of D_{pw} along each coordinate axis in the independent variable space. Allowing for a quadratic variation in damage would provide a better fit to the data. Unfortunately, a complete quadratic function with 5 variables would require too many linearly independent experimental data points to be of practical use.

Coefficient C_1 is the prediction of D_{pw} at the point in the function space where the prediction is required, since this is the value of Eq. 5 when all $\Delta x_{j,i}$ are set equal to zero. If one or more independent variables does not vary in the impact test data file then program CRVPOLY.EXE will sense this and automatically take that variable(s) out of Eq. 5.

The method used to select the linearly independent set of data points from the database for determination of the polynomial function coefficients will now be discussed. For illustration purposes, assume that three independent variables are active, and, thus, four linearly independent data points are required to fit coefficients C_1 through C_4. First, the four closest data points to where the prediction is required are tested for linear independence. If they are linearly independent, then the coefficients can be determined and the prediction made. If the four closest points are not linearly independent, then groups of four data points (closest data point plus three others) are selected from the closest five data points and tested for linear independence. The first linearly independent set of data points found are used for coefficient determination. If a set of suitable data points is not found, then sets of four data points from the closest six data points are tested and so on.

The number of ways to choose r items from n items, C(n,r), is given by the following equation:

$$C(n, r) = \frac{n!}{(n - r)!\, r!} \qquad (6)$$

From Eq. 6, there are 20 ways to choose 3 items from 6 items. Thus, as shown in Fig. 11, 20 sets of data would have to be tested for linear independence when selecting four data point sets (the

closest plus three other data points) from the closest seven data points. Note in Fig. 11 that the closest data sets are tested first and data point 1 is always used.

The polynomial function prediction technique is used to predict the bumper thickness required to prevent perforation of the pressure wall in the following manner. First, the impact test results database is searched to find the minimum and maximum bumper thicknesses used in the testing. Then, the polynomial function prediction technique as described above is used to predict the pressure wall hole diameter for these bumper thicknesses and three equally spaced intermediate bumper thicknesses (total of 5 predictions). Finally, a line was fit through these 5 prediction points (pressure wall hole diameter versus bumper thickness) and the bumper thickness required for no pressure wall perforation is extrapolated from this line.

6. Recommendations

The following recommendations are offered:

- The units suggested in this report should be used when creating or adding to impact results database files.

- Data points for which there was no perforation of the pressure wall should not be used in the impact results database file. This is because no perforation data are in a sense inconsistent - some data points may have been closer to perforation of the pressure wall than other data points yet all data points are rated the same at no perforation.

- Impact results data points should be selected that span the prediction space.

- Hydrocode results should be used as data points to extend the upper velocity range of the predictions if so desired.

- Several analysis runs should be made to confirm that the best coefficients have been found (lowest sum of the residuals squared) for the nondimensional function.

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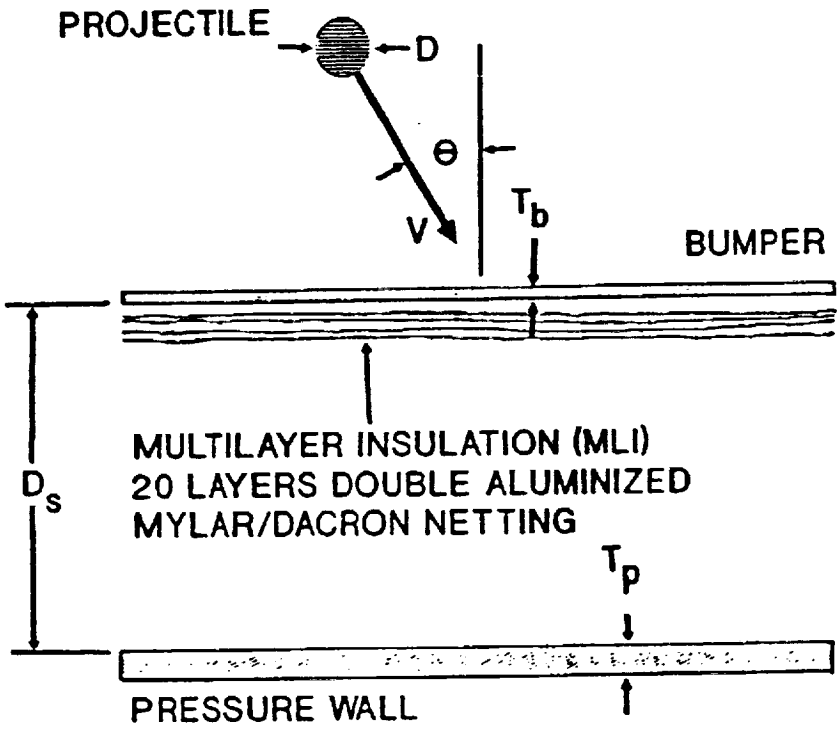


Fig. 1 Schematic drawing of spacecraft wall configuration.

EDIT IMPACT PAR

Impact Data File: ballist.dat Results Data File: results.dat

Impact Angle: 45 Projectile Diam.: 0.25

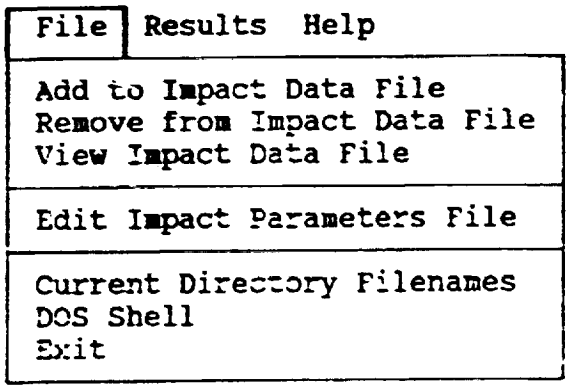
Pressure Wall Thickness: 0.125

Min. Proj. Vel.: 4 Max. Proj. Vel.: 7

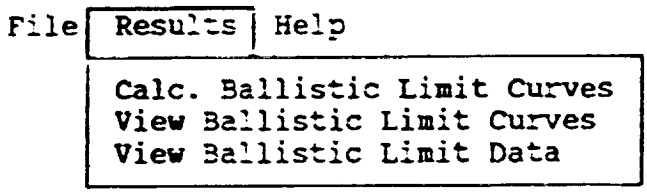
Number of Calculation Points: 20

< Save Changes and Exit > < Exit Program >

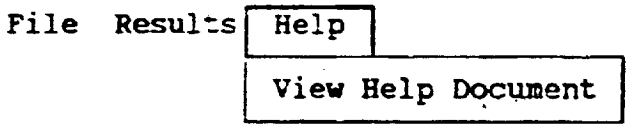
Fig. 2 Dialog box for editing the input parameters file.



(a) File menu picks.



(b) Results menu picks.



(c) Help menu picks.

Fig. 3 Pull down menu structure.

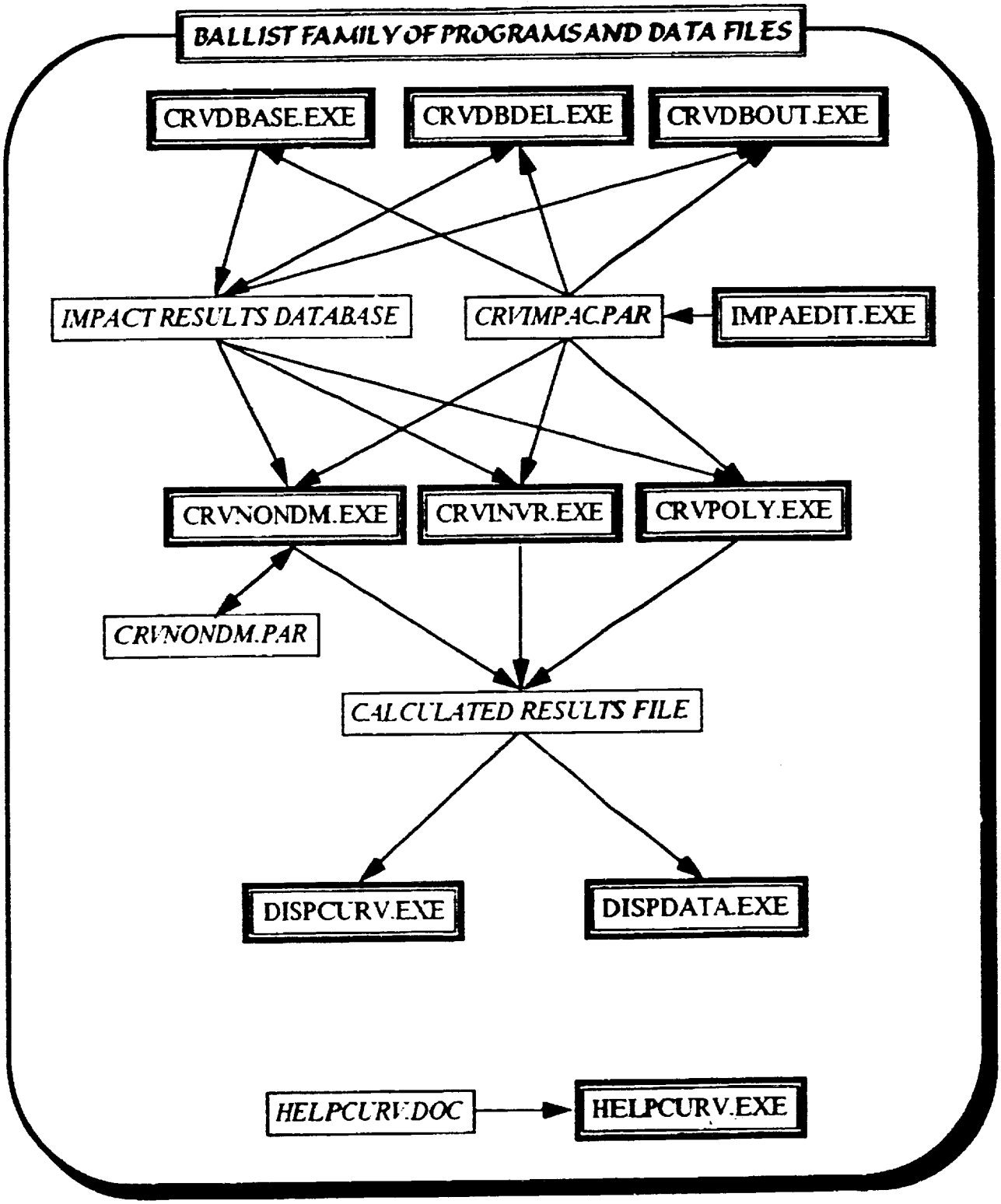
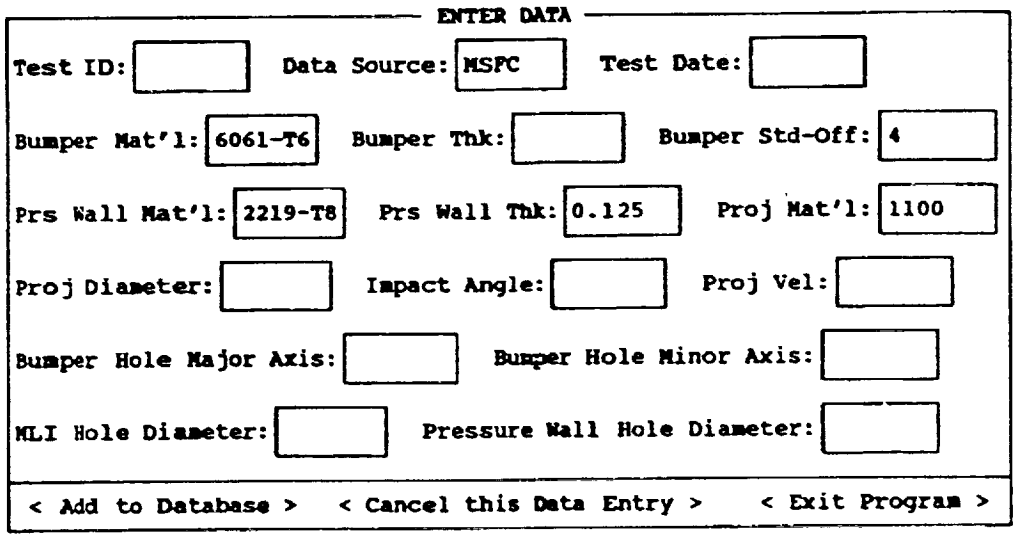
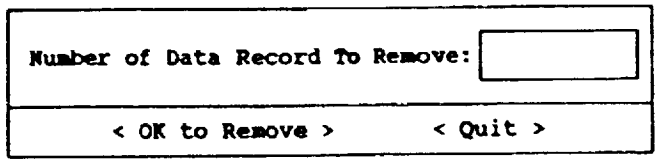


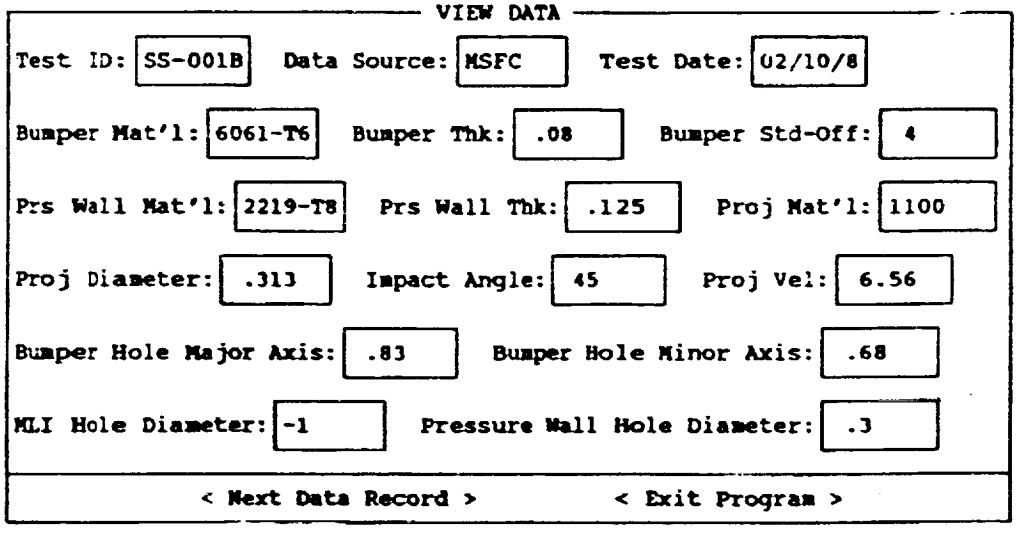
Fig. 4 Programs and data files of the BALLIST program.



(a) Add records to the database.



(b) Remove records from the database.



(c) View records in the database.

Fig. 5 Dialog boxes used to maintain the empirical results data file.

```
Pressure Wall Thickness:  .125
Projectile Diameter:  .25
Impact Angle:  45

Time: 15:31:43   Date: 12-01-1991

Results (velocity, bumper thickness)

Nondimensional Function:
 4.000D+00       1.133D-01
 4.158D+00       1.127D-01
 4.316D+00       1.122D-01
 4.474D+00       1.117D-01
 4.632D+00       1.113D-01
 4.789D+00       1.108D-01
 4.947D+00       1.103D-01
 5.105D+00       1.099D-01
 5.263D+00       1.095D-01
 5.421D+00       1.091D-01
 5.579D+00       1.087D-01
 5.737D+00       1.083D-01
 5.895D+00       1.080D-01
 6.053D+00       1.076D-01
 6.211D+00       1.073D-01
 6.368D+00       1.069D-01
 6.526D+00       1.066D-01
 6.684D+00       1.063D-01
 6.842D+00       1.060D-01
 7.000D+00       1.057D-01

Inverse-R Function:
 4.000D+00       1.560D-01
 4.158D+00       1.475D-01
 4.316D+00       1.401D-01
 4.474D+00       1.339D-01
 4.632D+00       1.287D-01
 4.789D+00       1.246D-01
 4.947D+00       1.212D-01
 5.105D+00       1.183D-01
 5.263D+00       1.161D-01
 5.421D+00       1.148D-01
 5.579D+00       1.145D-01
 5.737D+00       1.157D-01
 5.895D+00       1.186D-01
 6.053D+00       1.239D-01
 6.211D+00       1.323D-01
 6.368D+00       1.456D-01
 6.526D+00       1.668D-01
 6.684D+00       2.018D-01
 6.842D+00       2.598D-01
 7.000D+00       3.512D-01

Polynomial Function:
 4.000D+00       6.720D-02
 4.158D+00       6.713D-02
 4.316D+00       6.763D-02
 4.474D+00       6.807D-02
 4.632D+00       6.891D-02
 4.789D+00       6.803D-02
 4.947D+00       6.806D-02
 5.105D+00       6.771D-02
 5.263D+00       6.768D-02
 5.421D+00       6.768D-02
 5.579D+00       1.252D-01
 5.737D+00       5.214D-02
 5.895D+00       9.478D-01
 6.053D+00       7.694D-02
 6.211D+00       6.998D-02
 6.368D+00      -1.000D+00
 6.526D+00       6.315D-02
 6.684D+00       6.760D-02
 6.842D+00       6.850D-02
 7.000D+00       6.871D-02
```


Fig. 6 Typical results data file.

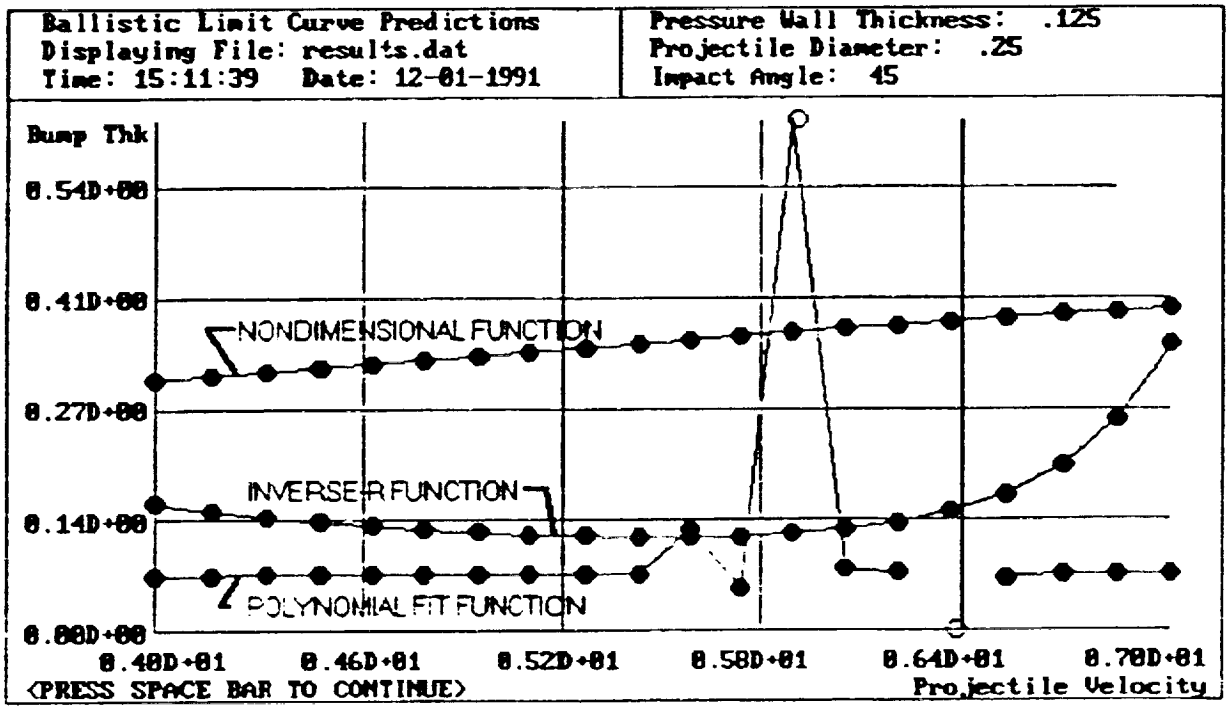


Fig. 7 Bitmap image of ballistic limit curves.

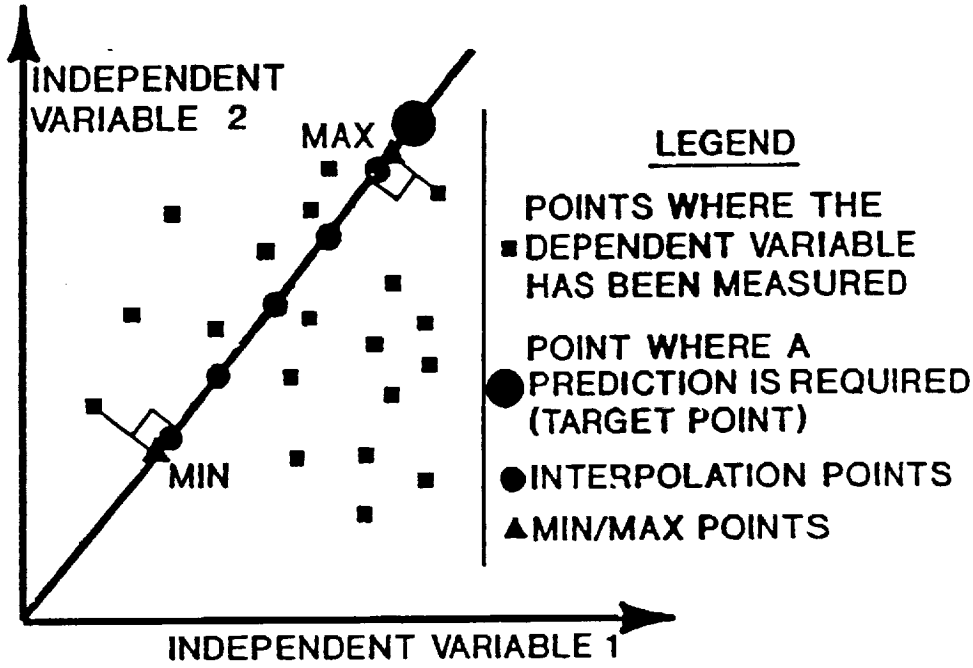


Fig. 8 Technique for selecting interpolation point locations for the case of two independent variables.

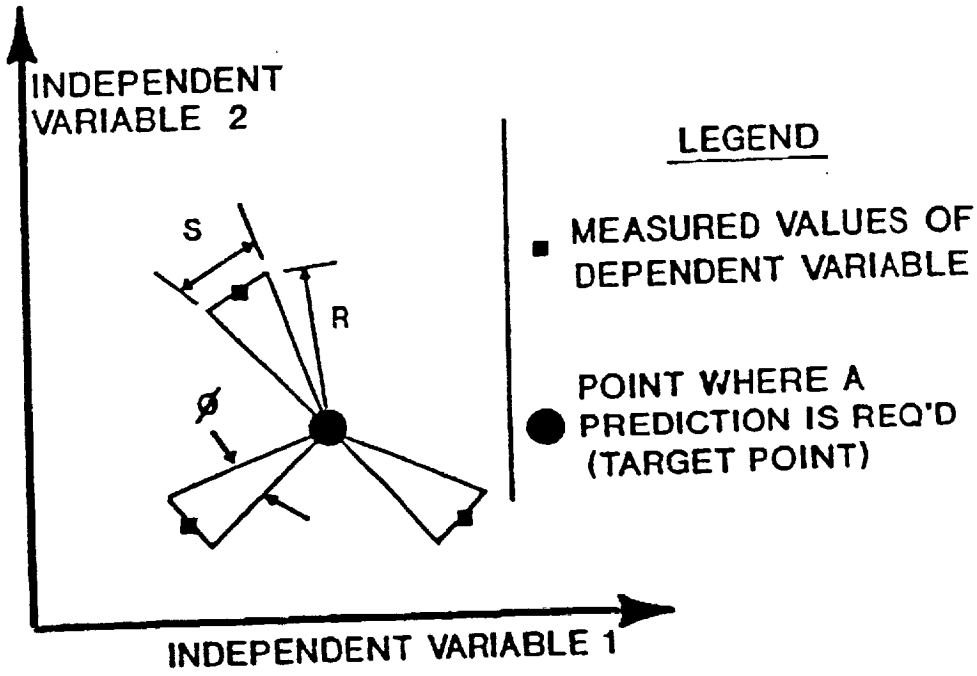


Fig. 9 Interpolation scheme for equally spaced data points.

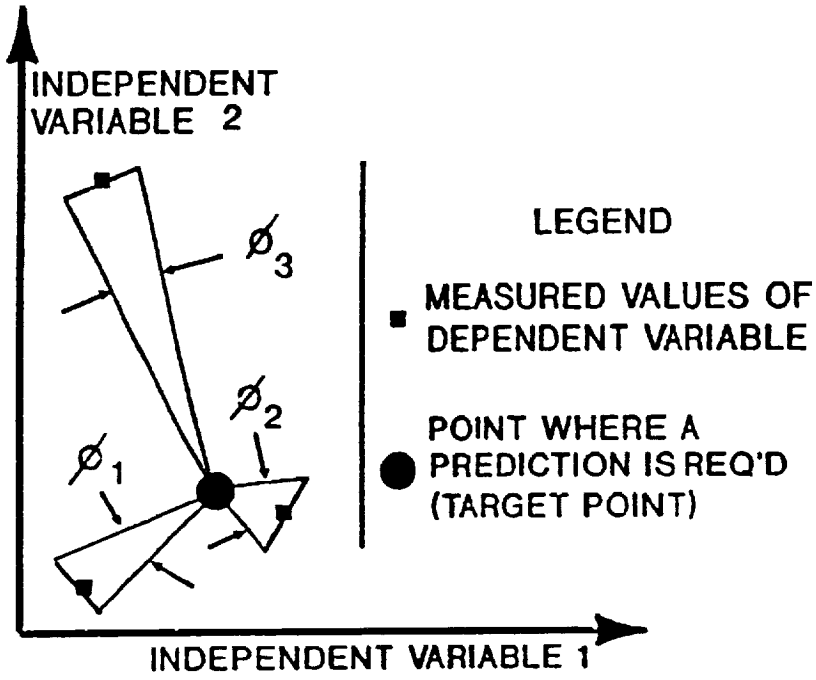


Fig. 10 Interpolation scheme for unequally spaced data points.

Order In Which Data Sets Are Tested For Linear Independence	Data Points Selected To Form Set Of Four (Ordered From Closest To Prediction Point To Farthest)						
	1	2	3	4	5	6	7
1	1	2	3	4			
2	1	2	3		4		
3	1	2	3			4	
4	1	2	3				4
5	1	2		3	4		
6	1	2		3		4	
7	1	2		3			4
8	1	2			3	4	
9	1	2			3		4
10	1	2				3	4
11	1		2	3	4		
12	1		2	3		4	
13	1		2	3			4
14	1		2		3	4	
15	1		2		3		4
16	1		2			3	4
17	1			2	3	4	
18	1			2	3		4
19	1			2		3	4
20	1				2	3	4

Fig. 11 Scheme for selecting four data point sets from the closest seven nodes for polynomial damage function coefficient determination.