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DEVELOPMENT OF A COMPUTER PROGRAM FOR MODELING THE HEAT EFFECTS ON A RAILROAD TANK CAR

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FINAL REPORT

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16. Abstract

A mathematical model has been programmed in FORTRAN IV that represents the response to a fire environment of a railroad tank car laden with a volatile, flammable fluid. Inputs to the program include total mass of lading per foot of tank length, tank length, number and flow area of relief valves, their opening and closing pressure, thickness and thermal conductivity of exterior insulation, an array of the thermodynamic properties of the lading, its initial condition, and heat transfer coefficient and fire temperature at various points on the tank. Output includes tank pressure, temperatures of the liquid and vapor, temperatures of the interior surface of the shell, mass of liquid remaining, and location of the liquid level. These are printed for the end of every computing interval, thus indicating the history of each.

Computer solutions have been obtained using input data representing problems for which explicit solutions are available and good agreement was achieved. Attempts to represent fire tests were not completely successful but computer results are encouraging. Recommendations are made for further improvements, some of which require more fire test data.

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Liquefied Petroleum gases, tank cars, heat transfer, self - Pressurization

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FOREWORD

This project was conducted under Contract No. 2-35982 by Calspan Corporation of Buffalo, New York, for the Technical Analysis Division of the National Bureau of Standards (NBS). Dr. David E. Gilsinn acted as project leader for NBS, and technical supervision at Calspan was provided by F.A. Vassallo.

Acknowledgment is made to Mr. Vassallo, who was always available for technical assistance, and to Dr. Gilsinn and NBS for numerous suggestions and aid with many details. Assistance of a general nature was afforded by NBS on questions such as the establishment of priorities for modifications to the mathematical model and the structuring of this report. Credit is due NBS for assistance on specific items such as proposals for incorporating the thermal stress correction and the superheated vapor condition. In addition, NBS provided the proof in Appendix III for the parabolic temperature profile of the shell over the vapor space and some of the literature sources for the properties of propane.

Engineering

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I. INTRODUCTION

During the course of a previous project, a thermodynamic model was formulated by Calspan Corporation (formerly Cornell Aeronautical Laboratory, Inc.) to describe the response of a railroad tank car loaded with propane to a fire environment following a derailment. This initial model was devised as a part of a larger research program to identify the causes of tank car disasters, under contract to the Federal Railroad Administration.

The objective of the project described by this report was to develop a computer-based model of the heat effects on a railroad tank car that can be used in the design of tank cars, their equipment, and insulation. Details of this objective are listed under separate tasks below, as specified by the contract:

Task I - Development of Scaled Non-Insulated Tank Car Model

1. Extend the initial tank car thermodynamic model previously developed by [Calspan Corporation] to include additional factors encountered in actual tank car fires, i.e., non-constant flame temperatures around the tank, non-constant heat emissivities, and variations in lading conditions. The model should also be extended to allow for variations in the tank car and pressure relief valve geometry.
2. Calibrate the model incorporating the data which has been gathered from scaled tank car fire tests conducted by the Naval Ordnance Laboratory (NOL) for the Department of Transportation (DOT).
3. Present the model (briefing with draft documentation) for review by the technical monitor after calibration (#2).
4. Deliver documentation and computer programs compatible with UNIVAC 1108 for the non-insulated tank car.

5. Deliver a report on the technical aspects and calibration of the model.

Task II - Develop Scaled Insulated Tank Car Model

1. Modify the model developed in Task I to take into account the extra thermodynamic effects created by insulation. In so doing, provide a capability to treat insulation as a parameter in order to consider the effect of various insulation materials upon the thermodynamics of the tank car.
2. Calibrate this model with test data to be generated from scaled tests to be conducted by NOL.
3. Provide a documented program compatible with UNIVAC 1108 for running this model.
4. Provide a final report on the calibration and the technical aspects of the analysis performed in #1 and #2.

Task III - Model Refinement Based Upon Full Scale Tank Car Fire Tests

1. Recalibrate and if necessary refine the models developed in Tasks I and II to take into account the the conditions and thermodynamic experiences of the tank car and lading encountered during full scale fire tests to be conducted by NOL.
2. Provide a documented computer program compatible with UNIVAC 1108 for running the full scale tank car fire model.
3. Provide a final report on the technical aspects and calibration of the model described in #1.

The objectives of the project have been met insofar as possible without benefit of complete fire test data. The computer model has been formulated and is operational on the IBM 370 computer at Calspan. Source decks have been converted to the BCD mode for use at NBS and were delivered and received by NBS.

A brief description of the model, including its capabilities and its limitations, is presented in Section II, which starts on the next page. In addition, it reveals the sequence of development of the program. Section III shows results of the calibration effort and determination of the validity of the model. Sample print-out from the computer is shown. Section IV consists of an explanation of the program that follows the computing sequence, step by step. This explanation includes mathematical proofs, or justification, for all but the obvious formulae used in constructing statements. The information given in Section V along with the list of FORTRAN nomenclature should be all that is necessary to a user of the program. Finally, conclusions and recommendations are given in separate sections.

II. DESCRIPTION OF THE MODEL

General Remarks on the Model

The formulation of the mathematical model was started by adapting many of the features of the original model of Reference 1. This model provided basic schemes for representing a cylindrical steel shell of infinite length that was enveloped in fire. Fire temperature and heating rate were each specified by a single value that applied at all points around the cylinder. The tank contained an amount of propane that was specified by input, as was its initial enthalpy and thermodynamic properties. The program computed the position of the liquid surface in the tank, the mass of liquid, the mass of vapor, the pressure, shell temperatures and their distribution around the circumference, and the temperature of the lading, which was assumed to be uniform throughout both vapor and liquid. Furthermore, these were always in the saturated condition. If a specified valve opening pressure was exceeded, a mass of either liquid or vapor was subtracted to represent flow out a valve, which could be oriented at any position on the circumference.

The original model has been extended to permit propane vapor to be superheated and to provide for nonconstant flame temperatures and heat input around the tank and along its length. At the present time, it can accommodate several safety or relief valves anywhere along the car, although the circumferential positions of all are specified by a single angle, i.e., all are in one line. These and other geometrical features of the tank are described by input data.

All input data pertinent to the lading are grouped together to facilitate provision for ladings other than propane. However, several formulae used in the program are valid for propane only. These are the equation of state for vapor, the expression for variable specific heat of the vapor, and the formula used to compute heat transfer coefficient to the liquid, which is a correlation of data from propane tests.

The model is capable of treating the case of the insulated tank car with one or two layers of insulation external to the steel shell. Its thermal conductivity may vary with temperature and is described completely by inputs to the program so that the use of various insulations can be studied to determine their effect upon the thermodynamics of the tank car contents. Most materials either decompose or melt and flow at some elevated temperature. In order to represent this effect, an upper temperature limit is assigned to the insulation. After the outer surface of the insulation reaches this limit, the thickness of the insulation diminishes with time until it disappears completely.

Another feature is the provision for the possibility of shell failure due to expansion of liquid, in the shell-full condition. If the safety valves cannot relieve liquid sufficiently fast to compensate for the expansion of liquid, the pressure will rise rapidly, causing rupture. The program monitors the allowable tank pressure, which is a function of local shell temperature level and its temperature gradient, for a given steel. If tank pressure exceeds the allowable limit, the computation stops and burst is indicated.

Figure 1 shows the geometry of the model, and important dimensions are given by their FORTRAN names.

Model Assumptions

The primary assumptions made in constructing the model are summarized below. These include several that are fundamental to the methodology of the mathematical model and contribute to its utility in evaluating response of tank cars to a fire environment.

- Temperatures of the bulk of the liquid and in the vapor space are assumed to be uniform at any given time, although the two temperatures may differ. No heat transfer across the liquid-vapor interface is assumed.
- The heat transfer coefficient on the inside surface of the tank shell in contact with vapor is uniform and

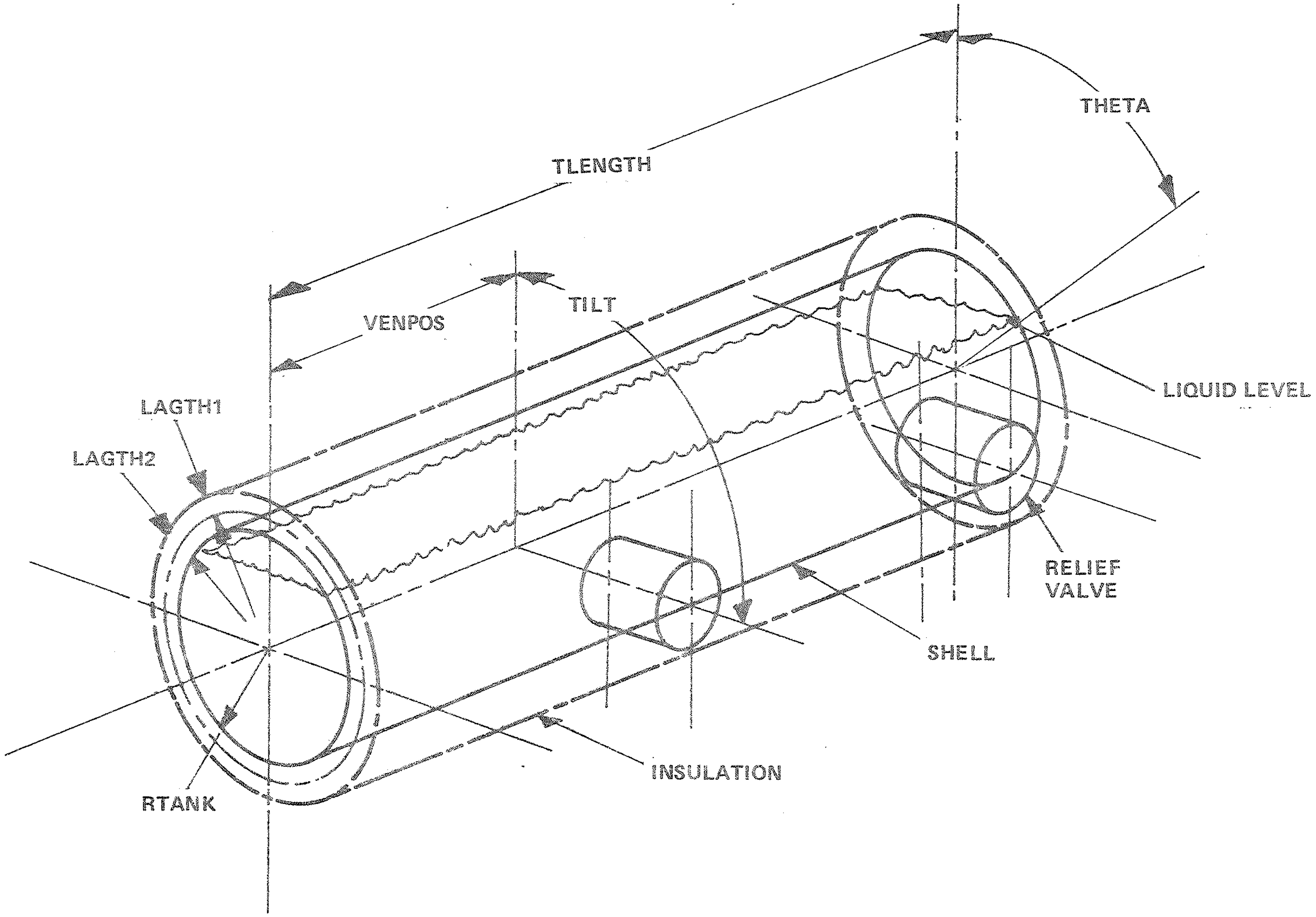

Figure 1 CONFIGURATION OF TANK CAR MODEL

constant. The heat transfer coefficient for liquid is variable with pressure and temperature difference between shell and liquid.

- Conduction of heat in the tank car shell in a direction parallel to the axis of the tank is assumed to be negligible. This is consistent with the concept of moderate gradients in the conditions of the environment in this same direction.
- Thermal properties of the shell do not change with temperature, but thermal conductivity of the insulation may vary.
- The location of the liquid surface is identified only by the angle to the centroid of the particular element of the tank car shell which it contacts. In all other respects, the surface is assumed to be confined to a horizontal plane.

Development of the Computer Program

The computer program in its present form is the result of several stages of development. A significant part of this effort was devoted to the representation of a proper response of tank pressure to a high-frequency sequence of relief valve activity and to the computation for the new state conditions of the mix of vapor and liquid after the addition of heat over a computing interval. Tank pressure is affected significantly by both these phenomena--the valve action and the addition of heat--and they interact so that the two cannot be treated independently.

The method used in the original model for predicting new mix conditions (i.e., pressure, enthalpy, and specific volume for both vapor and liquid as well as their proportions) was combined with a fixed computing interval. Therefore, it usually computed a change in pressure during the interval just before the time of valve opening that was excessive, resulting in a tank pressure higher than necessary to open the valve. In a similar fashion, the tank pressure after valve closing could be substantially below valve closing pressure. This artificial situation was aggravated by increasing the computing interval. The effect is to require a much finer computing interval in order to simulate a reasonable tank pressure response to valve action than would be necessary to satisfy other requirements of the computtation. For example, a computing interval (DELTA) of 2 seconds was used for most of the exercises done at Calspan with the new program, and this yielded results that were otherwise very satisfactory, as will be demonstrated later. In addition, the method used for predicting new mix conditions was approximate, whereby the changes in quantities during the computing interval were based upon the conditions at the time previous to the interval. The approximate method, in its latest stage of development, is explained in detail in Appendix I.

The method used in the present model for predicting the new state conditions is iterative and is designed to give a more accurate solution. It represents the state conditions of the liquid by means of the table of equilibrium saturated values, and the vapor state by means of an equation of state and a relation for the specific heat of superheated vapor. The masses of liquid and vapor, and their enthalpies before and after the time interval, are related by the equations for conservation of mass and energy. The resulting situation is akin to a set of simultaneous equations containing as many unknowns as there are equations. They are solved by an iterative procedure, which starts by estimating a new value for pressure. The heat input required to produce this estimated pressure is then computed through the use of thermodynamic relations. This is compared to the heat input actually transmitted through the shell to the lading as computed from fire source conditions. These two heat inputs should be the same, and if they are not, the computation is repeated using a new value for pressure that is based upon the departure from the proper value of heat input. The iteration continues until a pressure is obtained that results in a heat input that is acceptably close to the proper value.

Before the pressure obtained by iteration is accepted, it must meet another criterion, which is a tolerance test on valve action. A tolerance of 3 percent of the valve actuating pressure is used. If the tank pressure exceeds the valve opening pressure while the valve is still closed or if the tank pressure descends to less than valve closing pressure while it is open, the computing interval is reduced by a third and the iteration is repeated until a pressure and a computing interval that satisfy both criteria are obtained.

Recent NOL tests of a scaled tank car in a fire revealed that temperatures throughout most of the vapor space can exceed the saturated vapor temperature considerably. Consequently, steps were taken to incorporate the superheated vapor state. The basic iteration procedure has been retained, but the vapor properties corresponding to the estimated pressure are obtained from an equation of state for superheated vapor rather than the equilibrium tables for saturated conditions as before. These tables are used only for state conditions of the liquid.

The provision for insulation around the steel shell was made within the framework of the logic for computing the temperature of each element of the steel shell. Essentially, insulation reduces the heat flow to the steel shell for a given heat transfer coefficient on the outer surface of the tank by causing the outer surface temperature to be higher than otherwise. This fact is used directly in deriving the procedures for computing temperatures. It can be seen from the FORTRAN listing that two distinct surface temperatures are computed, T0(N, IDELX) and TSURF(N, IDELX). The former is the outer surface temperature of the steel shell and the latter is the temperature of the outer surface of the tank car. If it is not insulated, the two temperatures are one and the same. More details of the insulation features are presented in Section IV.

The existence of temperature gradients within the steel shell is accompanied by thermal stresses which are superimposed upon other stresses that prevail. Thermal stresses usually aggravate the stress situation. Of particular interest, of course, are the stresses caused by pressurization. It was desirable to make use of the existing burst pressure tables for the steel used in tank car shells so a thermal stress pressure increment was added to the tank pressure to produce a working pressure, PALL, which is then compared with the burst pressure that corresponds to shell temperature. If PALL exceeds the burst pressure, the computation stops.

Additional refinements to the program can be envisioned that should result in improving its capabilities. Among these are a more detailed representation of two-phase flow through the valve and a model describing energy transfer through the vapor space. A complete list of recommendations is made in Section VII.

III. INVESTIGATIONS INTO THE VALIDITY OF THE MODEL

Model Calibration by Comparisons with the Fire Tests

The program has been run successfully on the IBM 370 computer. Most of these exercises were intended to represent the NOL tests involving a model tank containing propane in a fire. This tank was 12 feet long, 2 feet in diameter, and the shell was 0.653 in. thick. A single full-scale valve was provided at an uppermost location.

The fire test that yielded the most data was the first test using propane, called NOL test No. 3. However, the data from this test consisted mostly of thermocouple temperature histories in the shell and the lading. No measurements of heat transfer, liquid level or valve displacement were obtained, and pressure traces were of only fair resolution.

The shell temperatures of test No. 3 were used in a computer program at NBS to generate heat transfer rates from the fire. When these coefficients were used in the tank car computer program in an attempt to reproduce the conditions that were used to generate them, the results obtained were found to be inconsistent. The computed shell temperatures rose much more rapidly than those obtained in the test, the computed time of initial valve opening was later than that of the test, and the time when the liquid disappeared completely was much earlier than indicated in the test.

This failure to obtain agreement led to an investigation to determine the values for heating rate and its history that would be required for inputs to the program in order to generate what can be considered the three important features of the test, i.e., initial valve opening time, time to complete loss of liquid, and shell temperatures. Two versions of the program were used in the exercises, one that assumed the vapor to be always in the equilibrium saturated condition and another that provided for the superheated vapor condition.

It was found that a history of HEATX = 32 Btu/ft^2-hr-°F for the first 76 seconds, dropping linearly to 18.4 at 80 seconds and constant thereafter, yielded the test value for complete loss of liquid at 450 seconds, using the saturated vapor version. The shell temperatures near the end of this time were nearly the same as the test temperatures, but all computed values were generally higher than test values previously. Shell temperature plots were printed by the computer and are shown as Figure 2, for external surface temperature. A curve was drawn on each plot to show the temperature measured during the test for the same point on the shell.

Figure 3 presents a plot of tank pressure history printed by the computer. It is obvious that the printer resolution is not good enough to show actual pressure fluctuations when the relief valve is functioning. However, the situation in the tank at each of the limiting pressures of valve operation is presented very clearly by the computer print-out, which occurs for every computing interval. A sample is shown by Figure 4, which includes a sufficient amount of print-out to show a complete valve cycle after closing at 268.09 psia (at 133.33 seconds), followed by a gradual tank pressure rise to 283.93 psia, whereupon the valve opens, resulting in a pressure drop over the next 0.6 second. Figure 5 presents the history of the angle to the liquid level for this particular case. Notice that the ordinate is $(1 - \theta)$, i.e., the angle from the lowermost point to the liquid level. The quality of resolution of the print-out is evident here.

Both versions of the program predicted the initial valve opening time correctly, which was indicated to be 78 seconds during the test.

Another comparison that can be made is based upon lading temperatures. At 450 seconds during NOL test No. 3, none of the three thermocouples at the highest level in the vapor space had reached 500°F, whereas the superheated vapor temperature was computed to be over 1000°F at this time. Furthermore, test temperatures of vapor indicated a variation with distance above the liquid level. This means that the state of the vapor is nonuniform throughout the vapor space and varies in degree of superheat from zero at

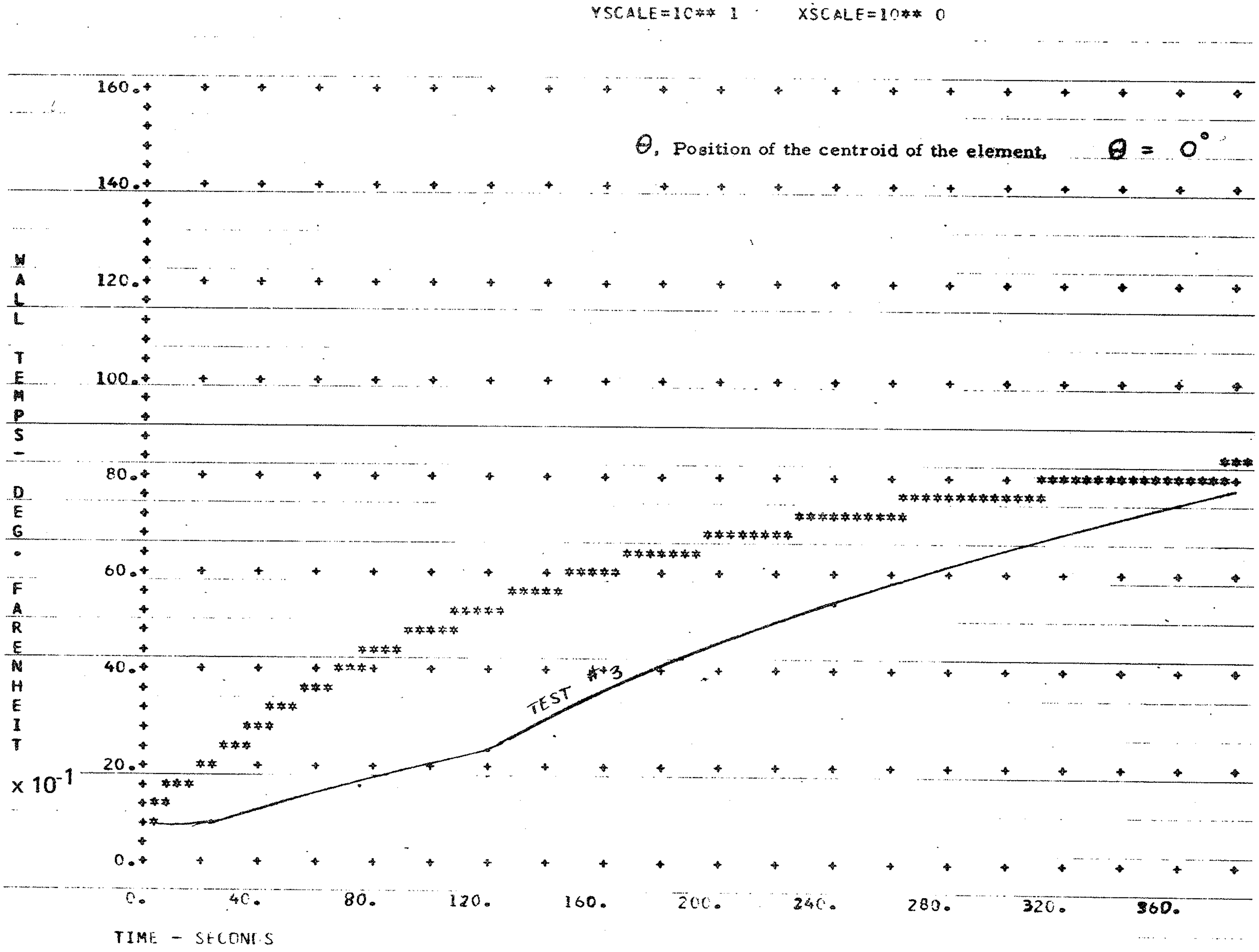

Figure 2a EXTERNAL SURFACE TEMPERATURE HISTORY OF THE SHELL

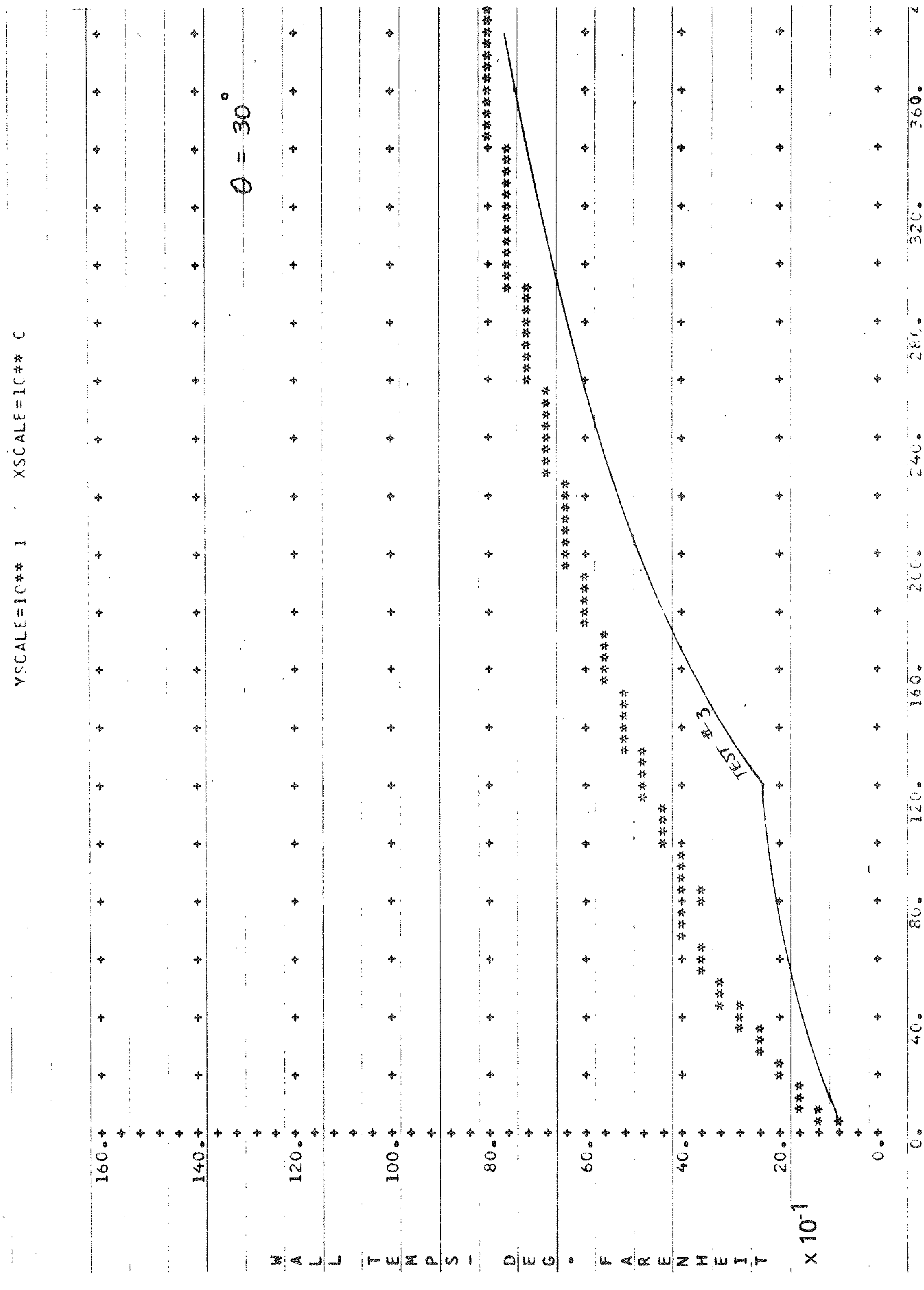

Figure 2b EXTERNAL SURFACE TEMPERATURE HISTORY OF THE SHELL

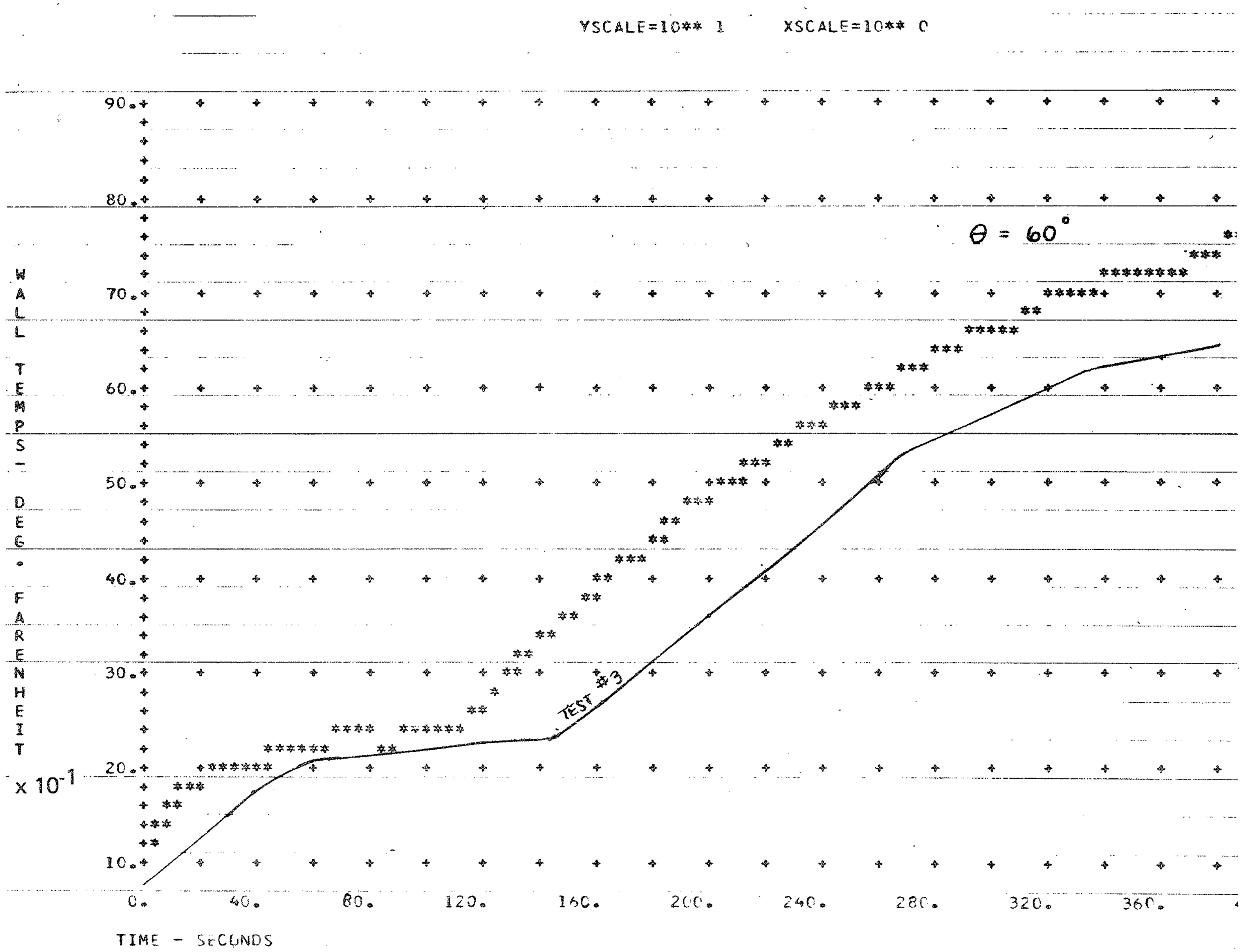

Figure 2c EXTERNAL SURFACE TEMPERATURE HISTORY OF THE SHELL

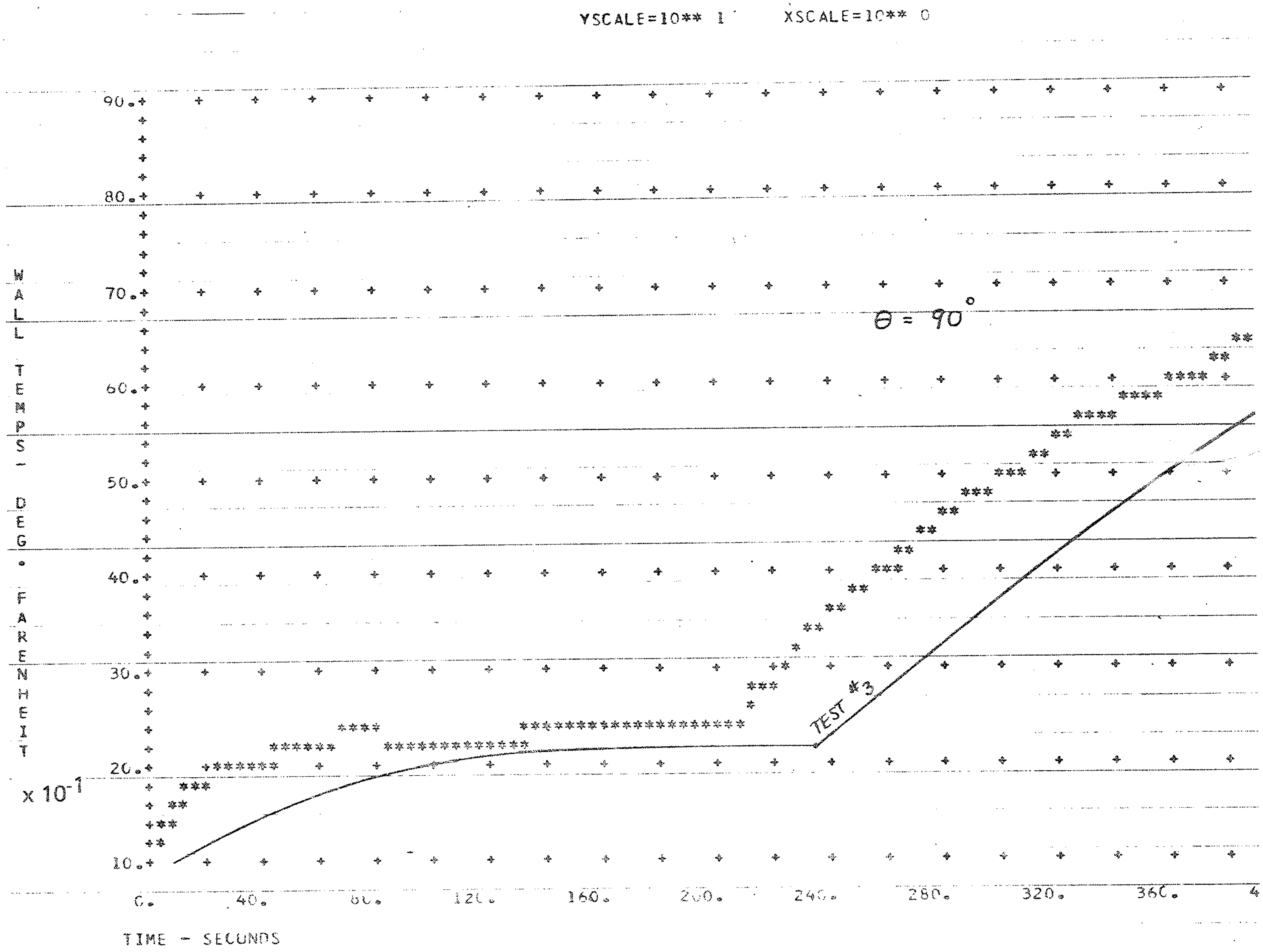

Figure 2d EXTERNAL SURFACE TEMPERATURE HISTORY OF THE SHELL

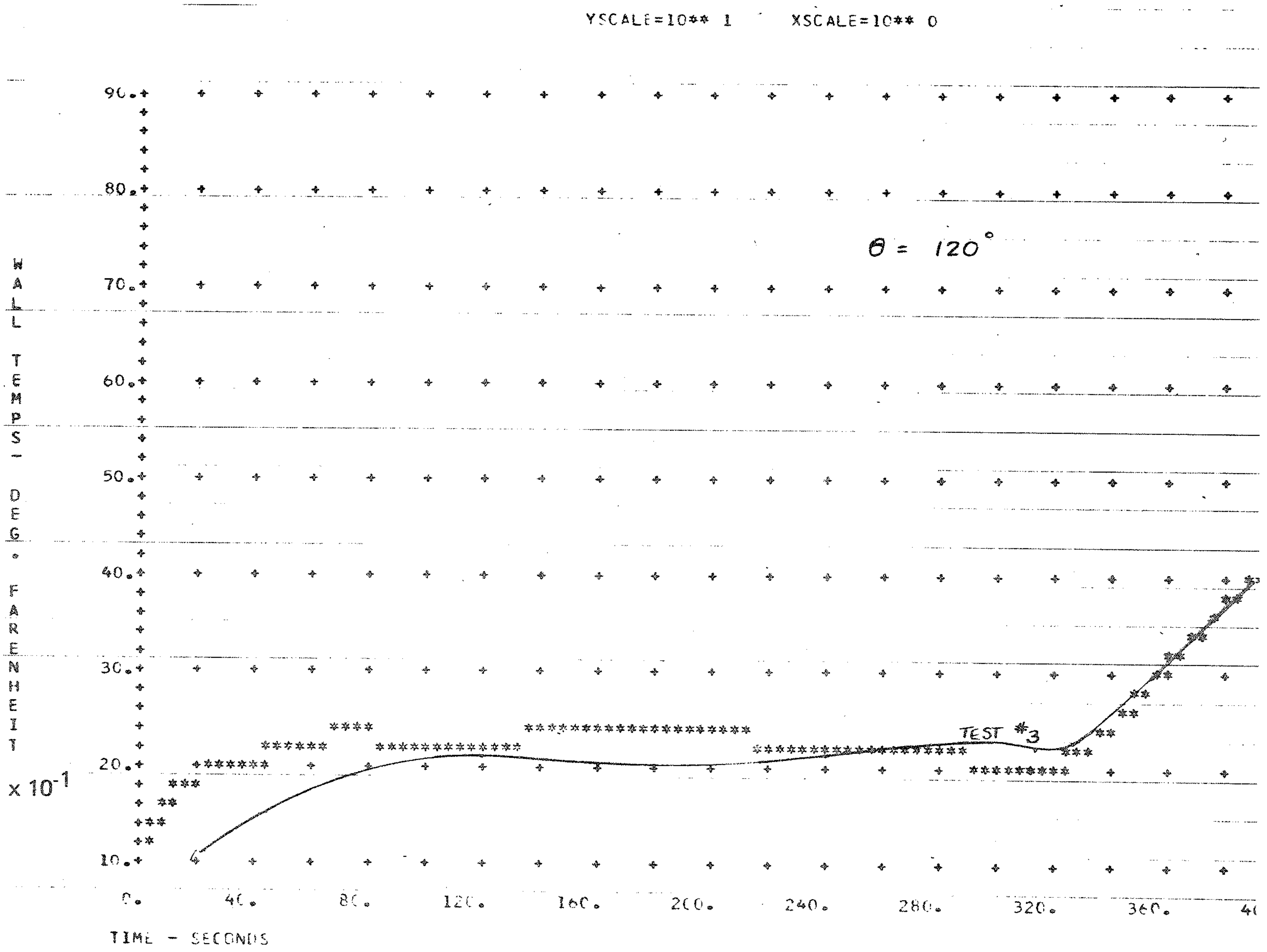

Figure 2e EXTERNAL SURFACE TEMPERATURE HISTORY OF THE SHELL

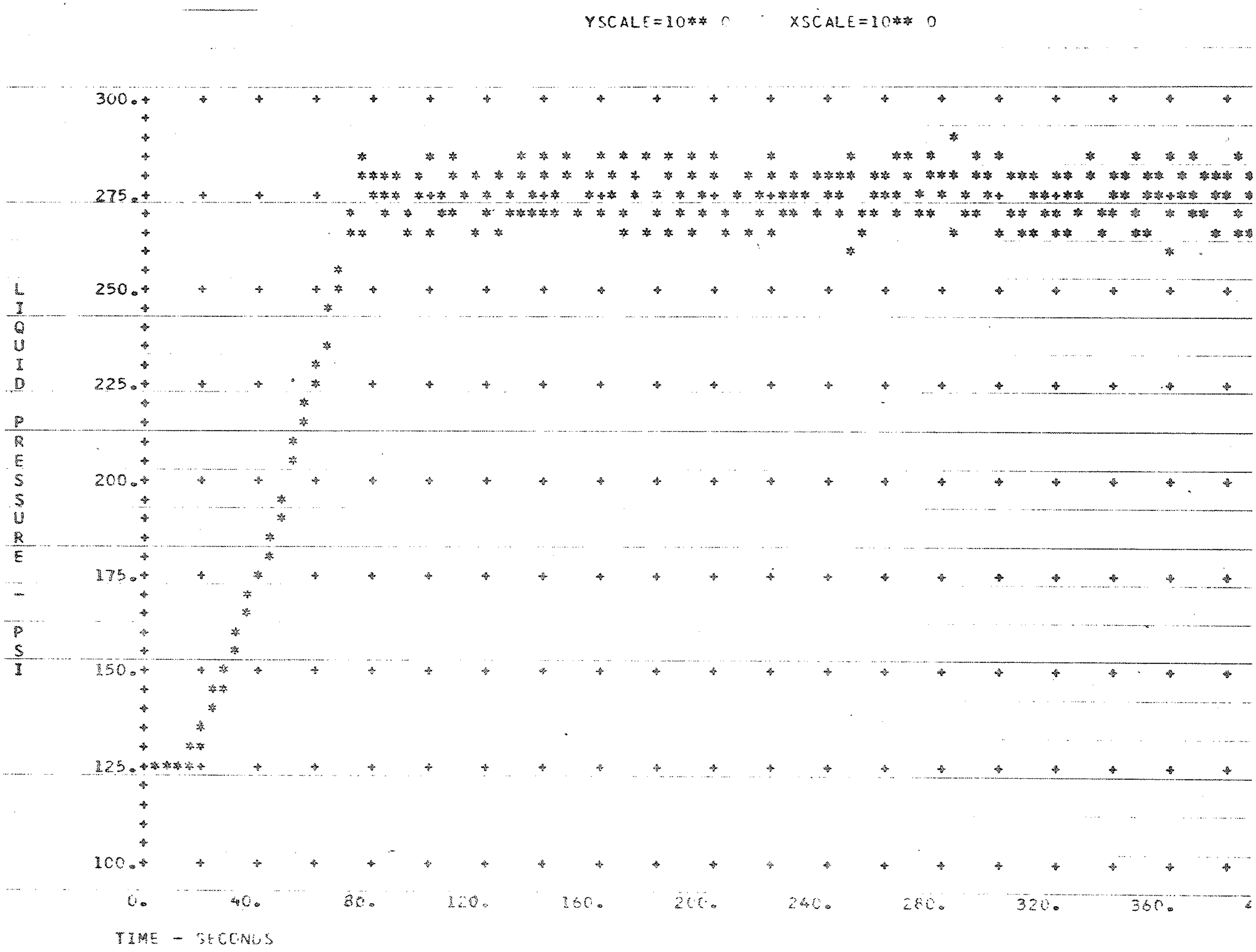

Figure 3 TANK PRESSURE HISTORY

```
                                        AXIAL STATION NO.    1

  TIME       130.74 SECONDS
                                   INTERNAL SURFACE TEMPERATURES OF STEEL SHELL

 AT        0.0        15.00      30.00      45.00      60.00      75.00      90.00     105.00     120.00     135.00
         528.42      492.87     474.09     399.81     278.44     184.78     182.14     182.06     182.06     182.06

 AT      150.00      165.00     180.00
         182.06      182.06     182.06

 TANK PRESSURE  LIQUID TEMPERATURE  LIQUID ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)
      278.96          131.36                286.22          69.34            2.51             0.0           547.36

 ANGLE TO LIQUID  CIRCUM. STRESS  LONG. STRESS  SHEAR STRESS    QINTO       QGSUM       QLSUM     T(N=1)
        62.93          4856.16        2428.08       1214.04     24814.68       5.55       57.73      534.73

  TIME       132.74 SECCNDS
                                   INTERNAL SURFACE TEMPERATURES OF STEEL SHELL

 AT        0.0        15.00      30.00      45.00      60.00      75.00      90.00     105.00     120.00     135.00
         531.16      496.04     477.06     403.24     282.91     185.20     182.28     182.19     182.19     182.19

 AT      150.00      165.00     180.00
         182.19      182.19     182.19

 TANK PRESSURE  LIQUID TEMPERATURE  LIQUIC ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)
      282.95          132.57                287.12          69.33            2.51             0.0           550.06

 ANGLE TC LICUID  CIRCUM. STRESS  LONG. STRESS  SHEAR STRESS    QINTO       QGSUM       QLSUM     T(N=1)
        62.68          4929.48        2464.74       1232.37     24812.70       5.59       57.73      537.46

  TIME       133.33 SECONDS
                                   INTERNAL SURFACE TEMPERATURES OF STEEL SHELL

 AT        0.0        15.00      30.00      45.00      60.00      75.00      90.00     105.00     120.00     135.00
         537.69      503.56     484.15     411.41     293.47     186.61     182.72     182.60     182.59     182.59

 AT      150.00      165.00     180.00
         182.59      182.59     182.59

 TANK PRESSURE  LIQUID TEMPERATURE  LIQUIC ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)
      268.09          128.00                283.74          69.31            2.52        11721.58           556.46

 ANGLE TC LICUID  CIRCUM. STRESS  LONG. STRESS  SHEAR STRESS    QINTO       QGSUM       QLSUM     T(N=1)
        62.43          4656.39        2328.20       1164.10     24806.53       1.71       17.10      543.94
```

Figure 4 SAMPLE PRINTOUT SHOWING CONDITIONS IN TANK DURING A COMPLETE CYCLE OF VALVE OPERATION

```
                                         AXIAL STATICN NO.      1

  TIME       135.33 SECONDS
                                   INTERNAL SURFACE TEMPERATURES OF STEEL SHELL

 AT       0.0        15.00      30.00      45.00      60.00      75.00      90.00     105.00     120.00     135.00
        540.36      506.64     487.05     414.77     297.77     186.75     182.77     182.64     182.63     182.63

 AT     150.00      165.00     180.00
        182.63      182.63     182.63

 TANK PRESSURE  LIQUID TEMPERATURE  LIQUID ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLCW RATE  TSURF(N=1)
     271.24           128.99               284.46          67.23            2.42            0.0           559.12

 ANGLE TC LIQUID  CIRCUM. STRESS  LONG. STRESS  SHEAR STRESS    QINTO       QGSUM       QLSUM    T(N=1)
      66.26           4714.45        2357.22       1178.61      24805.96       5.87       57.71     546.61

  TIME       137.33 SECONDS
                                   INTERNAL SURFACE TEMPERATURES OF STEEL SHELL

 AT       0.0        15.00      30.00      45.00      60.00      75.00      90.00     105.00     120.00     135.00
        543.03      509.71     489.96     418.12     302.04     187.24     182.91     182.77     182.76     182.76

 AT     150.00      165.00     180.00
        182.76      182.76     182.76

 TANK PRESSURE  LIQUID TEMPERATURE  LIQUID ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)
     275.30           130.25               285.38          67.22            2.42            0.0           561.75

 ANGLE TO LIQUID  CIRCUM. STRESS  LONG. STRESS  SHEAR STRESS    QINTO       QGSUM       QLSUM    T(N=1)
      66.07           4789.02        2394.51       1197.25      24803.96       5.92       57.70     549.27

  TIME       139.33 SECONDS
                                   INTERNAL SURFACE TEMPERATURES OF STEEL SHELL

 AT       0.0        15.00      30.00      45.00      60.00      75.00      90.00     105.00     120.00     135.00
        545.69      512.76     492.85     421.45     306.27     187.75     183.06     182.90     182.89     182.89

 AT     150.00      165.00     180.00
        182.89      182.89     182.89

 TANK PRESSURE  LIQUID TEMPERATURE  LIQUID ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)
     279.36           131.48               286.31          67.20            2.43            0.0           564.37

 ANGLE TO LIQUID  CIRCUM. STRESS  LONG. STRESS  SHEAR STRESS    QINTO       QGSUM       QLSUM    T(N=1)
      65.84           4863.51        2431.75       1215.88      24801.98       5.97       57.69     551.92
```

Figure 4 (cont.) SAMPLE PRINTOUT SHOWING CONDITIONS IN TANK DURING A COMPLETE CYCLE OF VALVE OPERATION

```
                                        AXIAL  STATION NO.     1
 TIME      141.33 SECONDS
                               INTERNAL  SURFACE TEMPERATURES OF STEEL SHELL

AT        0.0        15.00      30.00      45.00      60.00      75.00      90.00     105.00     120.00     135.00
        548.34     515.80     495.74     424.77     310.46     188.28     183.21     183.03     183.02     183.02

AT      150.00     165.00     180.00
        183.02     183.02     183.02

TANK PRESSURE  LIQUID TEMPERATURE  LIQUID ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)
     283.46          132.72             287.24           67.18           2.43             0.0          566.98

ANGLE TO LIQUID  CIRCUM. STRESS  LONG. STRESS  SHEAR STRESS    QINTO      QGSUM      QLSUM    T(N=1)
     65.62          4938.93        2469.47       1234.73     24799.97      6.02      57.69    554.55

 TIME      141.93 SECONDS
                               INTERNAL  SURFACE TEMPERATURES OF STEEL SHELL

AT        0.0        15.00      30.00      45.00      60.00      75.00      90.00     105.00     120.00     135.00
        554.65     523.01     502.60     432.69     320.36     189.98     183.68     183.43     183.42     183.42

AT      150.00     165.00     180.00
        183.42     183.42     183.42

TANK PRESSURE  LIQUID TEMPERATURE  LIQUID ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)
     268.26          128.06             283.78           67.16           2.44         11741.36         573.17

ANGLE TO LIQUID  CIRCUM. STRESS  LONG. STRESS  SHEAR STRESS    QINTO      QGSUM      QLSUM    T(N=1)
     65.38          4659.67        2329.84       1164.92     24793.81      1.84      17.09    560.82

 TIME      143.93 SECONDS
                               INTERNAL  SURFACE TEMPERATURES OF STEEL SHELL

AT        0.0        15.00      30.00      45.00      60.00      75.00      90.00     105.00     120.00     135.00
        557.23     525.96     505.42     435.93     324.39     190.14     183.72     183.47     183.46     183.46

AT      150.00     165.00     180.00
        183.46     183.46     183.46

TANK PRESSURE  LIQUID TEMPERATURE  LIQUID ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)
     271.46          129.06             284.51           65.10           2.34             0.0          575.74

ANGLE TO LIQUID  CIRCUM. STRESS  LONG. STRESS  SHEAR STRESS    QINTO      QGSUM      QLSUM    T(N=1)
     69.00          4718.39        2359.19       1179.60     24793.26      6.29      57.67    563.40
```

Figure 4 (cont.) SAMPLE PRINTOUT SHOWING CONDITIONS IN TANK DURING A COMPLETE CYCLE OF VALVE OPERATION

```
                                        AXIAL STATION NO.     1

    TIME       145.93 SECONDS
                                  INTERNAL  SURFACE  TEMPERATURES  OF  STEEL  SHELL

 AT         0.0       15.00       30.00       45.00       60.00       75.00       90.00      105.00      120.00      135.00
          559.81     528.90      508.23      439.18      328.40      190.73      183.88      183.60      183.59      183.59

 AT       150.00     165.00      180.00
          183.59     183.59      183.59

 TANK PRESSURE  LIQUID TEMPERATURE  LIQUID ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)
       275.54          130.32             285.44           65.08            2.35             0.0            578.28

 ANGLE TO LIQUID  CIRCUM. STRESS  LONG. STRESS  SHEAR STRESS     QINTO        QGSUM         QLSUM     T(N=1)
       68.83           4793.41        2396.70       1198.35     24791.23        6.34         57.66      565.97


    TIME       147.93 SECONDS
                                  INTERNAL  SURFACE  TEMPERATURES  OF  STEEL  SHELL

 AT         0.0       15.00       30.00       45.00       60.00       75.00       90.00      105.00      120.00      135.00
          562.39     531.83      511.03      442.40      332.37      191.32      184.03      183.73      183.72      183.72

 AT       150.00     165.00      180.00
          183.72     183.72      183.72

 TANK PRESSURE  LIQUID TEMPERATURE  LIQUID ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)
       279.71          131.59             286.39           65.05            2.35             0.0            580.81

 ANGLE TO LIQUID  CIRCUM. STRESS  LONG. STRESS  SHEAR STRESS     QINTO        QGSUM         QLSUM     T(N=1)
       68.62           4869.97        2434.98       1217.49     24789.25        6.38         57.65      568.53


    TIME       149.93 SECONDS
                                  INTERNAL  SURFACE  TEMPERATURES  OF  STEEL  SHELL

 AT         0.0       15.00       30.00       45.00       60.00       75.00       90.00      105.00      120.00      135.00
          564.94     534.74      513.82      445.62      336.31      191.93      184.19      183.86      183.85      183.85

 AT       150.00     165.00      180.00
          183.85     183.85      183.85

 TANK PRESSURE  LIQUID TEMPERATURE  LIQUID ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)
       283.93          132.86             287.35           65.03            2.36             0.0            583.33

 ANGLE TO LIQUID  CIRCUM. STRESS  LONG. STRESS  SHEAR STRESS     QINTO        QGSUM         QLSUM     T(N=1)
       68.41           4947.58        2473.79       1236.89     24787.25        6.43         57.64      571.07
```

Figure 4 (cont.) SAMPLE PRINTOUT SHOWING CONDITIONS IN TANK DURING A COMPLETE CYCLE OF VALVE OPERATION

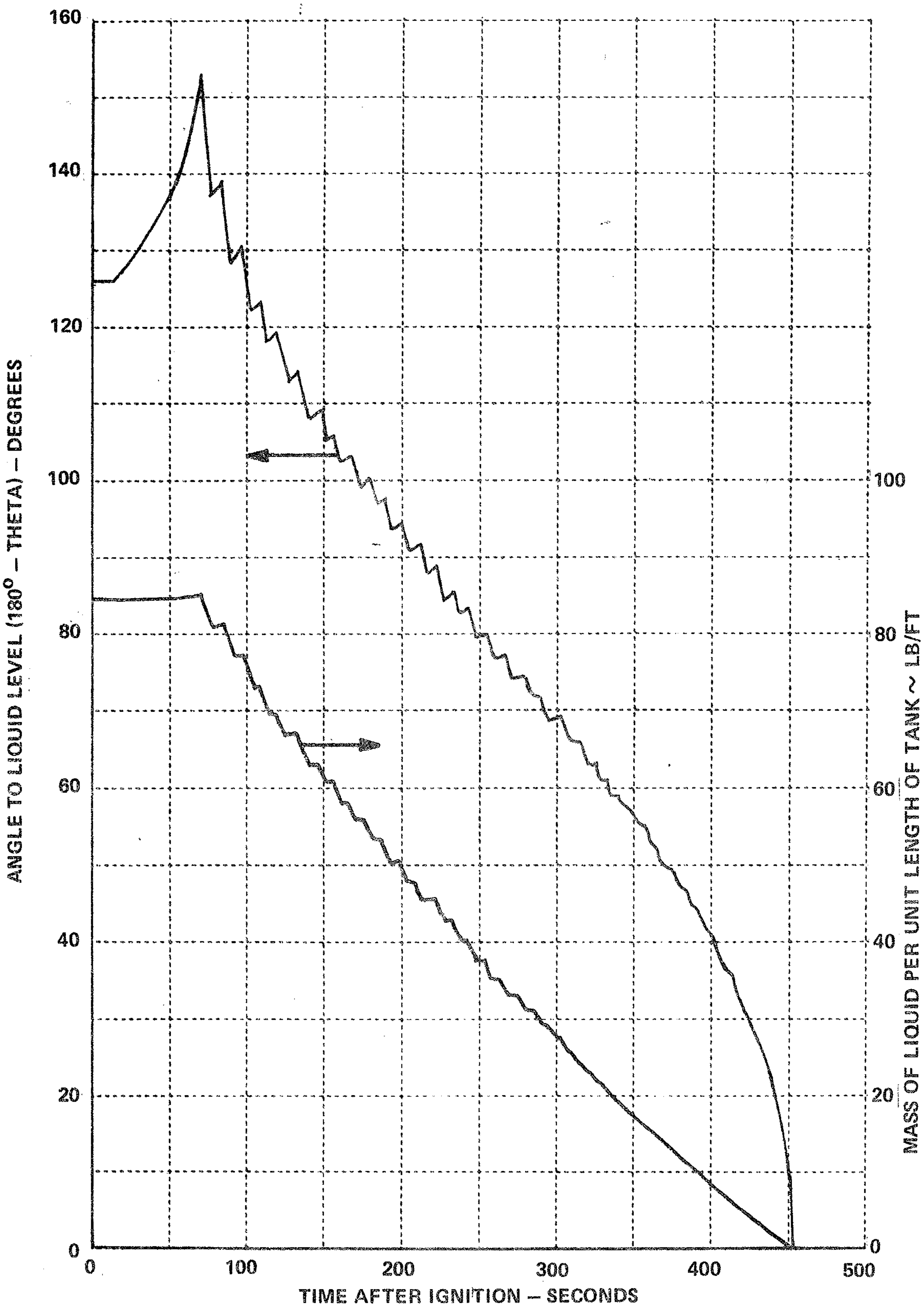

Figure 5 HISTORY OF THE LIQUID LEVEL OF PROPANE IN A SCALED TANK

the liquid level to a maximum at the uppermost level. It can be concluded that the assumption of uniform superheat is no better than one of uniform saturated vapor for representing the thermodynamic state of the vapor.

The variable HEATX problem was modified somewhat, which included a reduction in relief valve area (VAREA) to 0.01, and it was used to exercise the superheated vapor version of the program. This problem provides a severe test of the program because it causes small rate of change in several of the variables, such as mass of liquid and vapor. The result of this effect was that the program required a tighter test during iteration to preclude instability. With superheat the computation proceeded to 1699.6 seconds, at which point the allowed computer time expired. The last print-out sheet is shown in Figure 6. It can be seen that temperatures are climbing very slowly. Incidentally, this particular exercise ran out to the longest time of any of those that were submitted, and it is interesting to take note of the computing time required. This was 20 seconds on the IBM 370/165 computer system.

Initial relief valve opening time was computed at 74 seconds for the saturated vapor version and at 72 seconds for the superheated vapor version. The subsequent valve flow rate was 2122.4 lbs./hr. for the first case and 1448 lbs./hr. for the second. Other conditions are very little different between the two cases. Sample sheets from the print-out are presented by Figures 7 and 8. These show the conditions at initial valve opening time.

Model Exercises with Problems of Known Solution

Because of the lack of test data by which calibration could be accomplished, a different approach was taken to the question of validating the program. This was one of applying the program to the solution of a practical problem for which a theoretical solution is available and then comparing the two solutions. There are, in fact, two problems of known solution.

```
                                    AXIAL STATION NO.     1

  TIME      1695.6C SECONDS
                           INTERNAL SURFACE TEMPERATURES OF STEEL SHELL

 AT      0.0        15.CC       30.00       45.00       60.00       75.00       90.00      105.00      120.00      135.00
       1002.91    1001.59     997.95      985.03      966.64      905.99      724.36      142.73      138.29      138.25

 AT    150.0C     165.CC      180.00
       138.25     138.25      138.25

 TANK PRESSURE  LIQUID TEMPERATURE  LIQUIC ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)
       273.20         129.60                 284.91          41.04            1.48             0.0          1015.28

 ANGLE TC LIQUID  CIRCUM. STRESS  LONG. STRESS  SHEAR STRESS     QINTO       QGSUM       QLSUM     T(N=1)
       95.81          4750.38        2375.19       1187.60      26581.52       0.33       15.09     1007.04


  TIME      1697.60 SECCNDS
                           INTERNAL SURFACE TEMPERATURES OF STEEL SHELL

 AT      0.0        15.00       30.00       45.00       60.00       75.00       90.00      105.00      120.00      135.00
       1003.29    1001.97     998.34      985.44      967.07      906.41      724.56      142.96      138.45      138.40

 AT    150.0C     165.00      180.00
       138.40     138.40      138.40

 TANK PRESSURE  LIQUID TEMPERATURE  LIQUIC ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)
       274.56         130.02                 285.21          41.04            1.48             0.0          1015.65

 ANGLE TC LIQUID  CIRCLM. STRESS  LONG. STRESS  SHEAR STRESS     QINTO       QGSUM       QLSUM     T(N=1)
       95.77          4775.31        2387.65       1193.83      26578.99       0.34       14.25     1007.41


  TIME      1699.60 SECONDS
                           INTERNAL SURFACE TEMPERATURES OF STEEL SHELL

 AT      0.0        15.00       30.00       45.00       60.00       75.00       90.00      105.00      120.00      135.00
       1003.66    1002.35     998.72      985.84      967.49      906.82      724.76      143.29      138.68      138.63

 AT    150.00     165.00      180.0C
```

Figure 6 SAMPLE PRINTOUT FOR CASE OF LIMITED RELIEF-VALVE OPENING

```
                                        AXIAL STATION NO.      1

   TIME        74.00 SECONDS
                                INTERNAL SURFACE TEMPERATURES OF STEEL SHELL

 AT        0.0        15.00       30.00       45.00       60.00       75.00       90.00      105.00      120.00      135.00
         415.49      415.47      413.80      322.38      179.74      177.26      177.24      177.24      177.24      177.24

 AT      150.00      165.00      180.00
         177.24      177.24      177.24

 TANK PRESSURE  LIQUID TEMPERATURE  LIQUID ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)
      267.53          127.83                 283.61          84.92            3.09         1448.06          437.03

 ANGLE TO LIQUID  CIRCUM. STRESS  LONG. STRESS  SHEAR STRESS     QINTO        QGSUM        QLSUM     T(N=1)
       25.93          4646.11        2323.05       1161.53     25961.48        0.93        74.83     422.67


   TIME        76.00 SECONDS
                                INTERNAL SURFACE TEMPERATURES OF STEEL SHELL

 AT        0.0        15.00       30.00       45.00       60.00       75.00       90.00      105.00      120.00      135.00
         419.67      419.64      417.68      322.21      180.46      177.41      177.38      177.38      177.38      177.38

 AT      150.00      165.00      180.00
         177.38      177.38      177.38

 TANK PRESSURE  LIQUID TEMPERATURE  LIQUID ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)
      271.89          129.19                 284.61          84.02            3.02            0.0           441.14

 ANGLE TO LIQUID  CIRCUM. STRESS  LONG. STRESS  SHEAR STRESS     QINTO        QGSUM        QLSUM     T(N=1)
       34.37          4726.39        2363.20       1181.60     25955.32        0.99        74.81     426.83


   TIME        78.00 SECONDS
                                INTERNAL SURFACE TEMPERATURES OF STEEL SHELL

 AT        0.0        15.00       30.00       45.00       60.00       75.00       90.00      105.00      120.00      135.00
         423.85      423.81      421.54      322.07      181.17      177.56      177.52      177.51      177.51      177.51

 AT      150.00      165.00      180.00
         177.51      177.51      177.51

 TANK PRESSURE  LIQUID TEMPERATURE  LIQUID ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)
      275.98          130.45                 285.54          84.05            3.03            0.0           445.25

 ANGLE TO LIQUID  CIRCUM. STRESS  LONG. STRESS  SHEAR STRESS     QINTO        QGSUM        QLSUM     T(N=1)
       33.32          4801.51        2400.75       1200.38     25953.21        0.93        74.80     430.98
```

Figure 7 SAMPLE PRINTOUT FOR SUPERHEATED VAPOR CASE

```
                                       AXIAL STATION NO.      1

 TIME       68.00 SECONDS
                                 INTERNAL SURFACE TEMPERATURES OF STEEL SHELL

AT       0.0       15.00       30.00       45.00       60.00       75.00       90.00      105.00      120.00      135.00
       388.38     388.37      387.70      305.82      152.41      151.67      151.66      151.66      151.66      151.66

AT     150.00     165.00      180.00
       151.66     151.66      151.66

TANK PRESSURE  LIQUID TEMPFRATURF  LIQUID ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)
    275.00         130.15               285.31           84.74           3.04             0.0            432.96

ANGLE TO LIQUID  CIRCUM. STRFSS  LONG. STRESS  SHEAR STRESS     QINTO        QGSUM         QLSUM     T(N=1)
     31.34           4783.49        2391.74       1195.87      52506.72        2.80        151.30     403.24

 TIME       70.00 SECONDS
                                 INTERNAL SURFACE TEMPERATURES OF STEEL SHELL

AT       0.0       15.00       30.00       45.00       60.00       75.00       90.00      105.00      120.00      135.00
       398.05     398.04      397.15      314.39      163.54      162.17      162.16      162.16      162.16      162.16

AT     150.00     165.00      180.00
       162.16     162.16      162.16

TANK PRESSURE  LIQUID TEMPERATURE  LIQUID ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVF FLOW RATE  TSURF(N=1)
    281.69         132.19               286.84           84.79           3.06             0.0            433.29

ANGLE TO LIQUID  CIRCUM. STRESS  LONG. STRESS  SHEAR STRESS     QINTO        QGSUM         QLSUM     T(N=1)
     29.41           4906.32        2453.16       1226.58      41790.84        2.87        120.42     409.80

 TIME       72.00 SECONDS
                                 INTERNAL SURFACE TFMPFRATURES OF STFEL SHFLL

AT       0.0       15.00       30.00       45.00       60.00       75.00       90.00      105.00      120.00      135.00
       406.37     406.35      405.24      328.60      179.71      177.75      177.74      177.74      177.74      177.74

AT     150.00     165.00      180.00
       177.74     177.74      177.74

TANK PRESSURE  LIQUID TEMPERATURE  LIQUID ENTHALPY  MASS OF LIQUID  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)
    277.44         130.90               285.87           84.83           3.08          2122.38           427.90

ANGLE TO LIQUID  CIRCUM. STRFSS  LONG. STRFSS  SHEAR STRFSS     QINTO        QGSUM         QLSUM     T(N=1)
     27.25           4828.31        2414.16       1207.08      25704.08        2.93         74.07     413.54
```

Figure 8 SAMPLE PRINTOUT FOR SATURATED VAPOR CASE

The first is the addition of heat to a fluid confined in a constant volume, which is representative of the tank car before initial valve opening occurs. From elementary thermodynamic principles the total amount of heat absorbed by a given mass of a fluid, which may be partly vapor, is equal to the mass of the fluid times its change in internal energy. Using this relation, the total heat input to the fluid that is required to produce a given pressure within its container may be predicted from the final specific internal energy of the fluid that corresponds to this pressure. This correspondence is provided by thermodynamic tables of properties of the substance for the equilibrium condition between its vapor and liquid.

The second problem that can be analyzed simply is one of steady heat input and evaporation at constant pressure, which is representative of the process of vapor relief from a tank car that is heated at a constant rate subsequent to initial relief valve opening. In this case, the total amount of heat required to evaporate all liquid is equal to the mass of liquid times its heat of vaporization. Of course, the pressure is not perfectly constant in a tank with a relief valve that frequently pops open and closed. Instead, it fluctuates between the valve closing value and the valve opening setting. However, the pressure difference between the two values is small compared to the pressure level so that steady evaporation is approximated.

Both problems can be solved in a single computer run, inasmuch as the second problem represents a situation that occurs subsequent to that of the first problem. The inputs to the program were as follows: a constant heat transfer coefficient equal to 32.0 Btu/ft^2-hr-°F at an environmental temperature of 1800°F, an initial temperature of 70°F, a total fluid mass of 85 lbs. per foot of tank length, a valve opening pressure of 280 psia, and a valve closing pressure of 265 psia. A computer run was made for each version of the program, with vapor saturated and superheated. Results are presented in Table I.

TABLE I

RESULTS OF COMPUTER RUNS FOR CONSTANT HEAT INPUT

	Computed by Program		
	Saturated Version	Superheated Version	Theoretical Value
Time to initial valve opening - seconds	78	79	--
Total heat input at valve opening - Btu/ft of length	3430	3410	3400
Time for complete liquid loss - seconds	300.7	18 lbs/ft of liquid remaining at 480 sec	--
Total heat input between time of initial valve opening and time for complete liquid loss - Btu/ft of length	10,020	--	10,178

Inputs to the program for these runs were:

HEATX = 32.0
TEMPX = 1800.0
HF1 = 245.7
MTOT = 85.0
PR = 280.0
PRL = 265.0
VAREA = 0.055
CD = 0.65
HGT = 10.0

The saturated vapor version predicted an initial valve opening time of 78 seconds. During this time, the total heat input to the fluid was revealed to be 3430 Btu/ft. The simple analysis using the difference in internal energy between the initial condition of 70°F where pressure = 124.4 psia, and a tank pressure of 280 psia is 3400 Btu/ft. Agreement is, therefore, excellent between the two results.

The other part of the problem, time for complete liquid loss, was indicated to be 300.7 seconds by the program; and the heat input during this heating period (equal to 216.7 seconds after initial valve opening) was integrated and found to be 10,020 Btu/ft. The heat of vaporization at the average pressure is 120 Btu/lb. The theoretical solution for heat input = 84.82 x 120 = 10,178 Btu/ft, and agreement is again achieved with these particular computer results.

The superheat version of the program predicted an initial valve opening time of 79 seconds. Again, good agreement between the simple solution and computer results was obtained for the constant volume problem.

The exercises on the simple problems demonstrate that both versions of the program function as intended in representing the response of the tank to a constant heating rate. It is reasonable to expect that performance of the superheat version before valve opening be similar to the other version, inasmuch as both versions treat the liquid as saturated and because the greatest proportion of heat added is absorbed by the liquid over most of the heating period. This is the reason for the response of the vapor to have little effect upon the result. Such is not the case after the liquid level drops substantially.

Additional Exercises

An insulated scaled tank in a fire was simulated by the use of input data representing realistic insulation but a very severe fire environment (HEATX = 30.0, TEMPX = 1800). The total thickness of the insulation and its skin was 3/8 in., which was the magnitude of insulation thickness for recent NOL tests. Thermal conductivity was 0.06 Btu/hr-ft-°F, and the problem was solved for two decomposition temperatures (TDCMP), 600°F, representing an organic type, and 1500°F, which represents a mineral type. In addition, computations were made for a bare tank using these inputs.

By comparing the results, it was found that for the 600°F insulation and assuming superheated vapor, the shell temperatures remained lower than for the bare tank at first, but at 135 seconds, all the insulation had disappeared from the top of the tank. Afterward, shell temperatures of the tank that had been insulated rose faster than did those of the bare tank, and the results were reasonable in other respects, also.

The 1500°F insulation example was permitted a full 20 seconds on the IBM 370 using the superheat version of the program. The problem was computed to 1597.26 seconds, at which time 13.08 lbs/ft of liquid remained. A relief valve area of 0.01 in.^{2} was used (which corresponds to the observed valve displacement of 1/8 in.), which was approximately the same as observed during the second insulated tank test. During most of the time, the heating rate to the shell was 9000 Btu/ft^2-hr, which was considerably more than the 3000 Btu/ft^2-hr estimated for the fire test. In addition, the hottest part of the shell was indicated to be 1040°F. By comparison, the computation for the bare tank showed that it emptied to a mass of liquid equal to 19 lbs/ft in 467.4 seconds, at at this time the shell was 1161°F at the hottest point. Significant results are summarized in Table II.

These examples indicate that further development is needed. In particular, the model could benefit by incorporating features such as the radiation interchange between the shell surface contacting vapor and the liquid surface, and a model for heat transport through the vapor, in order to promote a better representation of both the vapor and shell temperatures. These examples also demonstrate that the program functions generally as desired, i.e., it is fundamentally valid, and that the superheated vapor version offers considerable promise for fulfilling the ultimate objective.

TABLE II

COMPARISON OF RESULTS FOR EFFECT OF INSULATION

	Insulated Tank		Bare Tank
Decomposition temperature of insulation - °F	600	1500	
Time at loss of all insulation - seconds	135	1597	
Time for temperature of top of shell to exceed 1000°F - seconds	307	1204	215
Valve area (VAREA) - ft^2	0.01	0.01	0.055

Inputs to the program for these runs were:

HEATX = 30 Btu/ft^2-hr-°F

TEMPX = 1800°F

HF1 = 245.7 Btu/lb

MTOT = 85.0 lb/ft

PR = 280.0 psia

PRL = 265 psia

CD = 0.65

HGT = 10 Btu/ft^2-hr-°F

FK2 = 0.06 Btu/ft-hr-°F

LAGTH2 = 0.375 in.

IV. THEORETICAL DEVELOPMENT

Explanation of the Program and Theory

The computer program consists of a main routine and several subroutines. The bulk of the computing is done by MAIN, which calls the subroutines for special purposes. All input is set up by the INPUT subroutine, which also contains write and format statements for print-out of input data. Subroutine OUTPUT contains the general purpose write and format statements for printing the results that define the conditions in the tank. The FORTRAN names for all input variables are listed and identified in the section on "FORTRAN Nomenclature." The units cited are those which must be used for each variable. An explanation of the computational variables is provided, also.

Subroutine HUNTEM is a table look-up procedure used to obtain values from input data arrays.

Subroutine FPLT is a Lagrangian interpolation procedure for obtaining intermediate values for the thermodynamic properties of the lading from the input data array of specific volume (liquid and vapor), pressure, temperature, and latent heat versus enthalpy.

A printer plot subroutine is included called PLOTR, which provides the option of obtaining plots of shell temperature histories and tank pressure history. This option is achieved by giving the value 1.0 to the input variable, PLOT. Subroutine PLOTR calls subroutine PLOTTR, which contains most of the logic of the plotting scheme. It is supported by subroutines NORMAL, AXSCAL, and GRID in the plotting function.

The computation is cyclic, in that it proceeds completely through the statements of the main routine for each time interval. However, before the cycling starts, some preliminary assignment statements are made to provide consistency between input data and the computational variables, e.g., KP = GAMMA. (GAMMA is a more descriptive name for the ratio of specific heats because the Greek letter γ is usually used to signify it in textbooks.)

Then some of the computational variables are collected into groups for subsequent use, e.g., AEL, DA, CRV, etc.

The computation starts with a table look-up for the thermodynamic properties that correspond to HF1, the specific enthalpy of liquid at time 1, based upon the initial temperature of the lading. In order to obtain the properties for the exact value of HF1, the Lagrangian interpolation statement is invoked (FPLT). Thus, the quantities PL, VF, VG, and HL are determined for the initial condition. Then, HG is obtained from HG = HF + HL and shell temperatures are initialized to TL.

Initializing continues by computing the separate masses of liquid and vapor from MTOT, VOL, and the specific volumes. A test on ML sends the computation to 31, if MTOT exceeds ML, where VOLL and VOLG are computed from masses and specific volumes. If ML equals or exceeds MTOT, they are set equal at 32; and the mass of gas is deliberately set equal to 0, as is its volume.

The program is capable of treating the liquid-full tank, and this includes the representation of shell burst due to liquid expansion. A part of this capability is to insure that the input values of HF1, MTOT, and VOL are consistent so that the computed ML is not greater than MTOT. This is achieved by overwriting ML at statement 32. If the tank is not liquid-full, the sequence is go to statement 50.

If no gas or vapor is present, the DO 40 loop is entered for the purpose of identifying the length elements that have vents. If a vent is present at a boundary between elements, each element is treated as having access to half the vent area.

Then the operation continues through the logic that tests for tank rupture due to expansion of liquid. First, the volume of fluid, TOPM, that the vents will pass during the time interval, DELTA, is computed. If the change in the volume of liquid due to expansion exceeds TOPM, rupture is presumed to occur. If not, the tank is considered to be full of liquid, so the volume of liquid is set equal to VOL at 45 and a new ML is computed. Then the new MTOT (resulting from loss of fluid by relief) is set equal to ML.

The next steps involve the determination of the liquid level, specifically, the angle THET that measures its position. THET is half the included angle of the segment of a circle that is described by the points of the intersection of the level surface with the tank. The area of the segment of a circle is:

$$A = \frac{1}{2} r^2 \; (Y - \sin Y) = \frac{1}{2} r^2 \; (W)$$

Rearranging and multiplying by π / π,

$$\frac{A}{\frac{1}{2} r^2} = \frac{2\pi A}{\pi r^2} = \frac{2\pi \text{ VOLG}}{\text{VOLG} + \text{VOLL}} \equiv V$$

Once V is computed, it is used to step off in a search routine for Y, which is provided by statements 55 and 57 and the following GO TO statement. The test is on the integer difference between V and W, and as soon as it becomes less than 1×10^{-3}, THET is computed from THET = 0.5 * Y. It is printed out as the angle to the liquid in degrees.

After computing some collections of variables, DAO and D, a number of quantities are assigned new names for storage so that they can be recovered after statement 75, which is a pivot for recycling the later logic when it is necessary to reduce the computing interval, DELTA. In this case, corrections must be made to DAO, CON, and D. This is accomplished through the use of the index, M.

Next in order is some logic in a large loop that determines the heat input to the lading and the temperature of each shell element. Each pass through the loop (DO 200) treats one element. The first step is to obtain the heat transfer coefficient, HEATX, from the data by table look-up and interpolation (HEATX versus ANG need not be specified in increments of shell element width). The same is done for TEMPX, the fire temperature. Then the element touched by the liquid level is identified (NG). The heat transfer rate into any element from the environment (QINTO) is computed from HEATX and TEMPX. If the element being examined is above the element NG, the gas heat transfer coefficient, HGT, is used to obtain QG, the heat into the vapor. QG is integrated as QGSUM during subsequent passes through the loop. Then QG is corrected to obtain QGT, the heat loss from the shell element. If the element is below NG, the route is to 100 to set up the computation for liquid heat transfer coefficient, HTCL. It depends upon TI, inside surface temperature of the shell, as does the heat transfer rate. TI is estimated from the average shell temperature for the previous time, and from QINTO. The formula for heat transfer coefficient is a curve fit to experimental data, Reference 2, for propane exposed to a horizontal surface. It depends upon tank pressure as well as the temperature difference between shell surface and bulk of the liquid. The quality of the curve fit is demonstrated in Table III*.

Next, the shell element temperature is computed from a relation that is derived in Appendix II. This permits a new surface temperature to be computed. At the beginning of the computation, the surface temperature (TSURF (N, IDELX)) is set to a temperature slightly (30°) above TL to induce a smoother start. The inside and outside surface temperatures of the shell, TI and T0, (N, IDELX) are computed from relations representing a parabolic temperature profile passing through T(N, IDELX) for elements of the shell above the liquid level. It can be shown analytically that the parabolic profile is valid for a slab of finite thickness with the heat flowing out one side equal to a small proportion of the heat entering the other side. A proof for this is presented in Appendix III.

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*A comparison of the tabulated values shows the lower limit of the range of good fit to correspond to a heat transfer rate of 20, 000 But/ft^2-hr with degradation increasing as the rate decreases.

TABLE III

VALIDITY OF EQUATION FOR CURVE FIT TO BOILING HEAT TRANSFER RATE

Experimental Data from Reference 2			
Pressure - psia	θ_s, Temperature Difference, Wall and Liquid Bulk - °F	$\dot{q}$, Heat Transfer Rate - Btu/ft^2-hr	Computed Heat Transfer Rate from Equation of Curve Fit - Btu/ft^2-hr
168	18.4	28,850	27,300
170	14.9	19,380	16,300
168	11.0	13,180	7,500
245	23.3	65,600	64,100
240	19.5	40,300	40,100
248	16.1	27,600	25,000
245	14.7	17,060	19,070
295	15.6	31,200	29,300
295	13.3	20,100	19,400
378	15.2	41,200	41,200
375	19.9	88,300	82,600
375	17.7	54,750	60,800
375	13.3	28,100	29,500

$$\frac{\dot{q}}{\theta_s^{2.55}} = 15.0 + 0.0642 \times 10^{-6} P^{3.347}$$

or

$$h = HTCL = \frac{\dot{q}}{\theta_s} = \left(15.0 + 0.0642 \times 10^{-6} P^{3.347}\right)\theta_s^{1.55}$$

The temperature profile through the shell at elements below the liquid level is assumed to be linear, which is a valid approach for the case of a slab of finite thickness that is transmitting most of the net incident heat. This statement is similar to stating that the rate of heat storage in the steel shell is negligible compared to the rate of heat conducted through it. Consequently, in the heat conduction equation (Equation 1 of Appendix II) the term $\rho c \ \partial T/\partial t \rightarrow 0$. In addition, for the case of uniform heating around the tank, $\partial^2 T/\partial \theta^2 = 0$, and the equation reduces to $d^2T/dr^2 + 1/r \ dT/dr = 0$. This may be simplified to $d^2T/dr^2 = 0$ for r large compared to δ, the thickness of the shell, which enters the problem as a boundary condition. Integrating, $dT/dr = c$, which indicates linearity, and the boundary condition, $dT/dr\big|_w = \dot{q}/k$ establishes the value of c. ($\dot{q}$ is the heat transfer rate at the surface, w.)

The condition of negligible heat storage may be justified by comparing the heat storage rate with the heat transmitted to the liquid during a fire. Test results show that the rate of temperature rise of the portion of the shell that contacts liquid averages only 1/2°F/second when a heating rate equal to 40,000 Btu/ft^2-hr is imposed upon it because the temperature of the shell is controlled by that of the liquid. The corresponding rate of heat storage, $\rho c \delta \ dT/dt \simeq 3600$ Btu/ft^2-hr. Subtracting this from the imposed heating rate yields the rate of heat transmission to the liquid, which is over 90 percent of the total.

Provision is made in the program for the variation of thermal conductivity with temperature of any insulation used to cover the tank shell. Two separate layers of different materials are allowed. In preparation for computing thermal conductivity of the insulation, its average temperature (either TK1 or TK2) is defined in terms of the prevailing heat transfer rate, thicknesses, and outside and inside surface temperatures. Then thermal conductivity of each layer is computed (KK1 and KK2) as a linear variation from a reference value (FK1 and FK2), which is specified as input data at the reference temperatures, TEM1 and TEM2. This permits TSURF (N,IDELX) to be computed from heat transfer rate, thicknesses and temperature of the outside surface of the shell.

As soon as the outer surface of the insulation reaches the decomposition temperature, TDCMP, the program is directed to statement 1942 where a procedure for computing a reduced thickness of insulation begins. The first calculation for thickness, THK at 150, reduces the outer layer to a thickness that will just support the established temperature gradient with an external temperature of TDCMP. (Temperature gradient is dictated by QINTO/KK1.) After THK reduces completely to LAGTH2, the thickness of the inner layer of insulation, a second computation, for THK, dominates the procedure and it operates by using the ratio QINTO/KK2. The insulation surface temperature, TSURF(N, IDELX) is maintained at TDCMP as long as any insulation remains, and this is defined by statement 160. TINT(N, IDELX) is an indexed variable for internal surface temperature of the shell to be stored for print-out.

It is conceivable that all insulation can be decomposed after a time, in which case TSURF is equated to T0(N, IDELX).

Next, a signal is set (FLIQ) to indicate whether vapor or liquid flows out each valve, depending upon TILT, the roll orientation of the valves, and THE, the liquid level. Some computed variables are initialized, some values are saved, and the valve positions are again identified for each element of length. The program is then ready to check for valve opening. If the valves were previously open, FLG would be 1; and this would cause entry to a test for valve closing (statement 235). If the tank pressure, PL, has dropped below the valve closing pressure, FLG is reset to 0. Next, a test for valve opening causes flow rate equations to be bypassed if they are still closed, in which case the computation flows to statement 350.

If the valves are closed for the previous computation but PL has risen sufficiently to exceed PR, the opening pressure, FLG would be reset to 1; and either a liquid flow rate or a vapor flow rate is computed for each valve depending upon whether FLIQ is 1 or 0. The derivations for the flow rate equations are given in Appendix IV. Sums are obtained for total liquid flow, MR1 and for total vapor flow, MR2.

Next, an iteration scheme is invoked for determining the new state conditions of the mix. Two separate schemes are provided, the open valve case and the closed valve case.

The open valve case begins at statement 300 followed by a summing of the flow rates through the valves and a correction to MTOT for the mass lost by relief. Iteration on pressure starts by arbitrarily assigning it a new name, PL2, and 95 percent of its previous value. Then the property subroutine FPLT is called to get the corresponding equilibrium values for VF and HF. The correct values for liquid and vapor masses are established and enthalpy of the vapor is then computed from a heat balance equation for the vapor. Then the specific heat of the vapor, CPG, is obtained from HG and PL2 by an equation which is a curve fit to data tables (Reference 3). (Its quality of fit is evaluated in Table IV*.) This permits the computation of TG. Next, VG is computed from the equation of state for the vapor, which was also obtained by a curve fit to the tables of Reference 3. (The validity of this equation is demonstrated by Table V**.) The revision of this value requires revision, in turn, of the mass of liquid and the mass of vapor.

At this point, all requirements have been satisfied for computing QIN, the heat input to the lading during the computing interval that is necessary to justify the pressure rise to PL2. After assigning QIN a new name, TEST, it is used to find the departure of QIN from the actual heat input over the computing interval, PREV. This difference is called DELQ2. Then a test is made whereby DELQ2 is compared to a small percentage of the absolute value of (PREV + 10.0). If it is greater than this percentage, the test is not satisfied and PL is corrected by means of a linear extrapolation to the value of PL for which DELQ2 goes to zero. DELQ1 and PL1 are reset to DELQ2

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*The tabulated values demonstrate a good fit to specific heat data from the saturation condition to 400°F and 400 psi. As either pressure or temperature are increased beyond this, the fit degrades slowly.

**A good fit is demonstrated by the table over the whole temperature and pressure range of interest to present tank car studies.

TABLE IV

VALIDITY OF EQUATION OF CURVE FIT FOR AVERAGE SPECIFIC HEAT

P, Pressure psi	T, Temperature °F	H, Enthalpy Btu/lb	$\bar{C}_p$, Average Specific Heat	
			Ref. Value from H/T	From Equation of Curve Fit
200	200	450.0	0.682	0.681
	240	470.1	.672	.676
	280	492.6	.666	.669
	300	503.7	.663	.665
	340	526.6	.658	.659
	360	538.3	.656	.655
250	160	420.4	.678	.684
	200	443.5	.672	.678
	240	466.0	.666	.672
	340	523.6	.654	.655
300	160	424.4	.684	.680
	200	446.2	.676	.673
	240	468.0	.669	.667
	340	524.3	.655	.650
400	240	459.2	.656	.660
	400	555.9	.646	.633
600	240	439.6	.628	.649
	400	548.4	.637	.616
	600	649.4	.612	.576

$$\bar{C}_p = 0.829 - 0.000298\,H - 0.00009\,(P - 50)$$

TABLE V

VALIDITY OF EQUATION FOR CURVE FIT FOR VAPOR STATE DATA

T, Temperature °F	V_g, Specific Volume ft^3/lb	P, Pressure - psia	
		From Ref. 4	From Equation of Curve Fit
100	0.5144	200.0	207.0
200	.7038	203	203.7
250	.6080	250	248.3
300	.6706	250	247.7
300	.3910	400	395.6
400	.4731	400	393.8
450	.3683	500	491.4
500	.4312	500	492.0
600	.4043	600	592.0
700	.3858	700	690.5
800	.3721	800	791.2
1000	.3532	1000	994.5

$$P = \frac{0.2433\ T}{V_g - 0.052} - \frac{23.081}{V_g^2}$$

and PL2, respectively. The iteration count, ICOUNT, is raised by one, and the iteration is repeated, starting at 320. If ICOUNT is excessive, i.e., if it exceeds 10, the computer is stopped. If the test on DELQ2 is passed, the computation goes to 330 for a test to prevent tank pressure from dropping to values less than the valve closing pressure, which would be unrealistic. If PL has dropped to less than PRL in order to satisfy the iteration procedures, the time interval is reduced and the computer is routed back to statement 75, the pivot where new computations start for all quantities dependent upon DELTA. It is necessary to reduce the time interval until the mass lost by relief valve flow is satisfactory for a reduction of tank pressure to PRL. An index, M, counts at 340 the number of times the computing interval is divided so that the initial computing interval can be restored.

The closed valve case starts, following statement 350, with an arbitrary increase in tank pressure, called PL2. Then FPLT is called, for HF and VF. As in the open valve case, ML2 and MG2 are defined, HG, CPG, TG, and VG are computed. Then ML2 and MG2 are recomputed preparatory to computing QIN. In the case when valves are open, QIN is an enthalpy difference; but for valves closed, it is an internal energy difference, which must be determined by subtracting the flow work terms, (PL x VF) + (PL x VG), from the enthalpy, because internal energy is not otherwise available. The constant is obtained by converting square inches to square feet and ft-lbs to Btu's, i.e., 144/778 = 0.1851.

After setting QIN = TEST, the departure of QIN from PREV is computed as DELQ2. (PREV is the total heat input over the computing interval.) The same kind of test is made comparing PL to 1.03 times PR, and the subsequent logic is similar to that of the valve open case, except that the limiting tank pressure for the valve closed is the set point for valve opening, PR. The computing interval is shortened until this pressure limit is satisfied.

Then the DO 450 loop is entered, which checks for tank rupture due to overpressure by vapor expansion. For each shell element, a table look-up

V. USER DOCUMENTATION

All input variables are collected into several groups, each of which is assigned a namelist name, such as LADING. This reduces the extent of the READ statements and simplifies data formatting as will be explained below. COMMON statements are used to assign all input variables, a feature that facilitates familiarization with the program in that the same name for a given variable is used throughout the whole program. In addition, the dimensions of all subscripted variables are given by the COMMON statements and the sequence for keypunching data for double subscripted variables is explained below. An alphabetical list of input variables is given under the Nomenclature section, which also indicates the units that must be used when specifying data for each variable. In general, the English system of units is used: feet, hours, Btu, pounds, except that shell and insulation thicknesses are in inches and time and the computing interval are in seconds. Specific requirements are presented below.

1. Format of Data Cards

The use of NAMELIST is of assistance in the organization of the data cards. Of course, it requires that a few rules be followed, but all of the FORTRAN language requirements can be satisfied by separate cards that, once keypunched, can be used repeatedly. These are the cards bearing each NAMELIST name. Then only those cards that are keypunched with data need be changed when different values of these data are desired. For example, the IBM 370 system requires that the first input card for each grouping of data under a NAMELIST name have a blank first character and "&" for the second, immediately followed by the NAMELIST name. However, a separate card can be used for each NAMELIST name, and all these can be treated as permanent cards. The data cards that give values for input variables in a given NAMELIST list can be packed behind the name card, and these are the only ones that need be changed. The only requirements for keypunching data are that the first character be blank and that each value be followed by a comma. Any number of values, one or more, can be punched on a card until it is filled to column 72. This means that each card may carry only one value, if desired. The namelist names and their associated inputs are listed in Table VI.

2. Heat Transfer Coefficient (HEATX)

The heat transfer coefficient may vary with location on the circumference from 0 to 180° (ANG), with time (TIMET), and with distance along the tank or station (IDELX). The same is true of the fire temperature (TEMPX) which is used with heat transfer coefficient in the program to compute the heat transfer rate to the external surface of the tanks. Consequently, for each value of HEATX, corresponding values of ANG, TIMET, and IDELX must be provided. These quantities serve TEMPX as well as HEATX. For example, assume that there are four values of HEATX for each ANG, three sets of these four values for different times, and a set of these 12 values for each of two stations, 24 values in all. Then the data for HEATX is keypunched in a sequence that is explained in the following sample (let each data value here be represented by a system of code numbers that identify its correspondence with ANG, TIMET, and IDELX, i.e., the first digit refers to the angle ANG, the second, time, and the third identifies station, IDELX):

```
HEATX = 111, 211, 311, 411, 112 , 212, 312, 412, 121, 221, 321, 421, 122,
        222, 322, 422, 131, 231, 331, 431, 132, 232, 332, 432, 56*0.,
```

Notice that the number of values necessary for specifying HEATX are equal to (NEL) (10.0) (NX). To clarify this, take the second number from the end, 432. The 432 indicates that the number to be provided between the commas, at this position in the sequence of the whole array, is the value of the heat transfer coefficient at the fourth element of the periphery, at the third time value and for the second station. Notice also that there are a number of values equal to (NEL) (10.) (NX). Zeros are used here but any finite number may be used to avoid retrieval of enormous numbers by the computer, which would upset the interpolation procedure.

TABLE VI

INPUT VARIABLE NAMES AND THEIR ASSOCIATION WITH NAMELIST NAMES

Namelist Name	Input Variable Listed After the Namelist Name
INPUT	HEATX, TEMPX, TIMET, TILT, ANG, NX, PITCH
LADING	HFT, LT, TLT, PLT, VGT, VFT, GAMMA, GASCON, HGT
BURST	TTT, PBT
GENRL	DELX, VENPOS, VAREA, CPTNK, EI, EFIRE, FKS, RHOTNK, CD, DELTA, HF1, MTOT, NEL, PR, THICK, RTANK, PRL, EMO, TLENTH, TDCMP, CINS1, CINS2, TEM1, TEM2, LAGTH1, LAGTH2, FK1, FK2, PLOT, TPLOT, NRAD

The dimensions of HEATX are (30, 10, 6) so the maximum number of data values is 1800.

3. Fire Temperature (TEMPX)

The dimensions of TEMPX are the same as for HEATX, and because TEMPX relates to the same independent variables as HEATX, the sequence of input data is the same.

4. Number of Circumferential Elements and ANG

The number of values that must be keypunched for ANG is NEL + 2, and NEL cannot exceed 28. The last two values are false values, but they must be nonequal and slightly different than the previous one to insure proper interpolation. Example: ANG = ... 160., 180., 190., 200., where 180. is the last one of significance to the problem.

5. Finish Time and TIMET

The second value from the last in the TIMET data set should be well beyond the expected finish time for the problem. This is required for proper interpolation. The maximum number of values in this data set is 10.

6. Rapidly Varying Inputs

Rapid changes or step changes in HEATX and TEMPX should be represented by two closely spaced data points both before and after the step in order to permit accurate interpolation.

7. Lading Properties

Provision has been made for inputting the thermodynamic properties of saturated lading as an array of LT, HFT, TLT, PLT, VFT, and VGT. All values of one variable are keypunched before starting those of the next. Example: HFT = 100., 110., 120., 130., ... 290., TLT = 70., 72., 73.9., ... 210. A maximum of 25 values for each variable may be used. Some sources of properties of hydrocarbons are given as References 3, 5, and 6.

VI. CONCLUSIONS

The body of data available from fire tests is limited. Consequently, it precludes full and complete program "calibration." The program presently exists in two versions, one treating vapor as uniformly superheated and the other as saturated. The validity of each version in representing a tank car in a fire has been discussed in terms of results obtained by exercising the program on a variety of problems.

The saturated vapor version, although it could be provided data to produce the correct time to evacuation of liquid, predicted low vapor temperatures and shell temperatures that were generally high by comparison with test.

The superheated vapor version was also capable of producing the correct time to evacuation of liquid, but it predicted temperatures of both vapor and shell that were much higher than test values.

The insulation features of the program performed well in producing the typical effects of external insulation on a tank, such as reduction of heat absorbed by the tank and the diminution of this effect as the insulation degraded because of overheating.

The computer program was more successful in solving problems for which analytical solutions are available. Both versions of the program, the superheated vapor version and the saturated vapor version, produced excellent results when used to solve the problem of steady heat addition at constant volume. The saturated vapor version of the program gave results that were in good agreement with an analytical solution for the problem of steady heat addition at constant pressure with evaporation.

In all the exercises, very good resolution of pressure variation is provided by the program by virtue of the nature of the iteration process for finding the state of the time-dependent liquid-vapor mix.

It can be concluded that the saturated vapor model is, at present, better in most respects for representing a tank car in a fire. However, all evidence indicates that there is some degree of superheat within the vapor space and that it varies throughout. Because it is possible to model this effect, the superheated vapor version of the program offers more promise for further development.

VII. RECOMMENDATIONS

Further development of the superheated vapor version of the model is needed before accurate prediction can be made of all the features of the performance of a tank car in a fire. Several recommendations for this development are presented.

1. A model of the energy transport through the vapor space should be constructed so that a realistic vapor temperature field is indicated. The achievement of this also depends upon determination of a valid and representative heat transfer coefficient from the tank shell to the vapor. Such a value might be extracted from test data, given a good model for the energy transport.

2. In both versions, the liquid is presently treated as being saturated. This produces an indicated temperature of the liquid that rises and falls with pressure as the relief valve opens and closes. The change in temperature is about 6°F for a pressure change of 20 psi. To accomplish a uniform effect such as this throughout a large body of liquid may require a larger exchange of energy than possible in the time available. Therefore, some means should be provided in the program to account for this effect of nonequilibrium.

3. The calculation for the flow characteristics of two-phase flow should be improved in the program, both for the case where the fluid starts to flow out the valve as a liquid and for the case where it starts as a vapor. In both cases, the program should actually follow the procedure described in Appendix IVB, which is a more complete representation of two-phase flow.

4. The program should be extended to provide for a pitched attitude of the car.

5. The program should be modified to provide a capability for representing tank protection by means of intumescent paint.

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FORTRAN NOMENCLATURE

Input Nomenclature

1. Input Specific to Lading

ALPHA	Thermal expansion coefficient of liquid	cu. ft/°F
GAMMA	Ratio of specific heats	
GASCON	Gas constant	
HGT	Gas heat transfer coefficient for internal tank car environment	Btu/ft^2-hr-°F
HLT	Liquid heat transfer coefficient for internal tank car environment	Btu/ft^2-hr-°F
HFT	Specific enthalpy of saturated liquid	Btu/lb
LT	Heat of vaporization	Btu/lb
MTOT	Total mass in tank car per unit length	lbs/ft
PLT	Pressure values for enthalpy and volume data	psi
TLT	Temperature values for enthalpy and volume data	°F
TS	Sonic temperature	
VFT	Specific volume of saturated liquid	cu. ft/lb
VGT	Specific volume of saturated vapor	cu. ft/lb

2. General Input

A	Relief valve flow area	ft^2
ANG	Angle values for HEATX data	degrees
CINS1,2	Slopes of lines describing variation of thermal conductivity with temperature. 1 refers to outer layer, 2 to the inner one.	
CP	Specific heat of tank car shell material	Btu/lb-°F
CD	Relief valve flow coefficient	
DELX	Longitudinal element size	ft

DELTA	Computing interval	sec
EI	Emissivity of inside surface of tank car shell	
EMO	Emissivity of outside surface of tank car shell	
FK1,2	Thermal conductivity of insulation at reference temperature	Btu/ft-hr-°F
FKS	Thermal conductivity of shell material	Btu/ft-hr-°F
HEATX	Heat transfer coefficient external to tank car	Btu/ft^2-hr-°F
LAGTH1,2	Thicknesses of insulation layers. 1 refers to the outer layer, 2 to the inner one.	inches
NEL	Number of tank car shell elements around circumference	
NRAD	Control number for circumferential element temperature plots. NRAD = 1 means a plot will be generated for every element, NRAD = 2 will produce a plot for every second element, etc., starting with the first one.	
NX	Number of elements along tank car (longitudinal)	
PBT	Burst pressure of tank	psi
PITCH	Pitch angle defining tank car attitude	degrees
PR	Relief valve opening pressure	psi
PRL	Relief valve closing pressure	psi
RHOSK	Density of protective skin over insulation	lb/cu. ft
RHOTNK	Density of tank car material	lb/cu. ft
RTANK	Inside radius of tank car shell	ft
SKTHK	Thickness of protective skin over insulation	inches
TDCMP	Temperature where insulation loses its effectiveness	°F

TEM1,2	Reference temperatures for thermal conductivities of insulation layers. 1 indicates temperature for outer layer, 2 for the inner one	°F
TEMPX	Fire temperature values for each HEATX value	°F
TIMET	Time table for HEATX data	sec
THICK	Tank car shell thickness	inches
TILT	Roll angle to relief valve centerline	degrees
TFI	Initial temperature of liquid	°F
TLENTH	Length of tank car	ft
TLT	Temperature table corresponding to burst pressure	°F
TPLOT	Time interval between points on pressure plot	seconds
VOL	Total internal volume of tank car per unit length	ft^3/ft
VENPOS	Distance to each vent from end of car defining vent position	ft

Computational Variables

AEL	Medial area of each element of the tank car shell	
CON CRV D DA DAO	Collections of variables	
DTHETA	Included angle of each tank car element	
DELX	Length of each tank car element	
FLG	Signal for valve closed (FLG = 0) or open (FLG = 1)	
FLIQ	Signal to indicate valve below liquid level (FLIQ = 1) or above (FLIQ= 0)	
HF	Specific enthalpy of liquid	Btu/lb
HG	Specific enthalpy of vapor	Btu/lb
HTCL	Liquid heat transfer coefficient	$\mathrm{Btu/ft^2/hr\text{-}{}^\circ F}$
KK	Thermal conductivity of shell	
KP	GAMMA	
MG	Mass of gas in tank car per unit length	lb/ft
ML	Mass of liquid in tank car per unit length	lb/ft
MR	Mass flow of material through relief valve per unit length	lb/sec-ft
MR1	Mass flow of liquid relieved	lb/sec-ft
MR2	Mass flow of vapor relieved	lb/sec-ft
PL	Pressure in tank car	psi
PS	Sonic pressure for gas flow through valve	psi
QG	Gas heat transfer rate per unit area for one element of tank car shell	$\mathrm{Btu/ft^2\text{-}hr}$
QGT	Heat loss from element of shell	$\mathrm{Btu/ft^2\text{-}hr}$
QGSUM	Total heat input to the internal gas environment from the tank car wall	Btu
QINTO	Heat transfer rate per unit area applied to the outside wall of the tank car	$\mathrm{Btu/ft^2\text{-}hr}$

QL	Liquid heat transfer rate per unit area for one element of the tank car shell	Btu/ft^2-hr
QLSUM	Total heat input from the tank car wall to the liquid	Btu
SIG C	Circumferential stress in tank car shell	lb/in^2
SIG T	Transverse stress in tank car	lb/in^2
T(N,IDELX)	Average temperature of tank car shell element	°F
TAU	Shear stress at 45° plane in tank car shell element	lb/in^2
TE	Fire temperature	°F
TG	Temperature of gas in tank car	°F
THET	Angle from $\theta = 0$ to liquid-gas interface at tank car shell	degrees
THETA	Position of the centroid of each element of the tank car shell	radians
THK1,2	Thickness of effective insulation	
TI	Temperature of inside surface of tank car shell element	°F
TL	Temperature of liquid in tank car	°F
TO	Temperature of outside surface of tank car shell element	°F
TS	Sonic temperature for gas flow through relief valve	°R
TSURF	Surface temperature of protective skin	°F
UC	Critical velocity	ft/sec
VF	Specific volume of liquid in tank car	ft^3/lb
VG	Specific volume of liquid in tank car	ft^3/lb
VOLG	Volume of gas in tank car per unit length	ft^3/lb
VOLL	Volume of liquid in tank car per unit length	ft^3/lb

APPENDIX I

APPROXIMATE METHOD FOR PREDICTING THE NEW MIX CONDITIONS

The method used in the original model to compute the state conditions of the new mix after a computing interval was approximate because it was based entirely upon conditions at the beginning of the interval. It has been discontinued but is presented here for the sake of completeness.

Previous to computing the new mix conditions, it is necessary to establish the heat input to the tank shell, the mass of gas, MG, and liquid, ML, in the tank, and the total heat input to the liquid as well as to the gas. These are done by the existing methods explained elsewhere.

Then, the following equations are used to compute the increase in the heat content of the liquid in the container. Two specific cases exist. The first case is that for which no mass is lost through the relief valves. The second case distinguishes between liquid or gas flow out each relief valve. The index M indicates time for purposes of this explanation and was not a computing index. The program is recycled to execute computations for a new time. Equilibrium conditions between liquid and vapor were assumed to prevail.

Case 1:

$$\mathrm{MR} = 0$$

$$\mathrm{DMG(M)} = \frac{(\mathrm{MG(M)} - \mathrm{MG(M-1)})}{\mathrm{DELTA}} \cdot 3600$$

$$\mathrm{DHF} = \frac{(\mathrm{QLSUM(M)} + \mathrm{QGSUM(M)} - \mathrm{DMG(M)} \cdot \mathrm{L(M)} \cdot \frac{\mathrm{DELTA}}{3600}\ )}{\mathrm{ML(M)} + (\mathrm{DML(M)}\ \frac{\mathrm{DELTA}}{3600}}$$

Case 2:

For liquid flow through the relief valve, if one connects with the element $\triangle X$,

$$\mathrm{MR1(M, X)} = 192000 \cdot \mathrm{CD} \cdot \mathrm{A}$$

For gas flow through the relief valve, if one connects with the element ΔX,

$$MR2(M, X) = \frac{CD \cdot A \cdot UC(M)}{VC(M)}$$

where $$UC(M) = GAMMA \cdot 32.2 \cdot GASCON \cdot (TL(M) + 460) \exp(\frac{2}{GAMMA + 1}))^{\frac{1}{2}}$$

and $$VC(M) = \frac{GASCON \cdot (TL(M) + 460)^{\frac{2}{GAMMA+1}}}{PL(M) \left(\frac{2}{GAMMA+1}\right)^{\frac{2}{GAMMA+1}}}$$

The total mass loss is computed:

$$MR(M) = \sum_{X=1}^{X=NX} MR1(M) + \sum_{X=1}^{X=NX} MR2(M)$$

and the remaining mass is inventoried:

$$MTOT(M) = MTOT(M-1) - MR(M) \cdot \frac{DELTA}{3600}$$

Then the enthalpy of the remaining liquid is determined:

$$DHG = HG(M) - HG(M-1)$$

$$DHF = \frac{\sum_{N=1}^{N=NX} QLSUM(M, X) + \sum_{N=1}^{N=NX} QGSUM(M, X) - (DMG + MR) \cdot L \cdot \frac{DELTA}{3600} \cdot MG \cdot DHG}{ML(M) + DML - MR) \cdot \frac{DELTA}{3600}}$$

$$HF(M+1) = HF(M) + DHF$$

The value of HF(M + 1) as computed above is then used in conjunction with the liquid-vapor saturation tables to obtain values of PL(M + 1), TL(M + 1), VF(M + 1), VG(M + 1), and L(M + 1).

APPENDIX II

DERIVATION OF FORMULA FOR T(N, IDELX)

The unsteady heat conduction equation in a polar coordinate system in terms of r, radius, θ, angle, and constant thermal properties is:*

$$\rho c \frac{\partial T}{\partial t} = \frac{k}{r^2} \frac{\partial^2 T}{\partial \theta^2} + k \frac{\partial^2 T}{\partial r^2} + \frac{k}{r} \frac{\partial T}{\partial r} \qquad (1)$$

When this is expressed as a difference equation, using central differences, and transformed to a curvilinear system in r and y using $\Delta y = r\Delta\theta$, it becomes:

$$\rho c \left(\frac{T_t - T_{t-1}}{\Delta t} \right) = k \left(\frac{T_{y+1} - 2T_y + T_{y-1}}{\Delta y^2} \right) + k \left(\frac{T_{r+1} - 2T_r + T_{r-1}}{\Delta r^2} \right) + \frac{k}{r} \left(\frac{T_{r+1} - T_{r-1}}{\Delta r} \right) \qquad (2)$$

Equation 1 must be accompanied by boundary conditions and initial values in order to use it to describe a problem. For example, the heat transfer rate (k dT/dr) may be specified at the boundaries and a specified uniform temperature may be given as the initial value.

Now the use of Equation 2 implies a quasi-steady treatment for an infinitesimal time interval. Furthermore, the size of elements of the tank shell, as measured by Δy, that would be practical for computation is considerably greater than the shell thickness. Consequently, it is practical to consider the element thickness, Δr, to be the same as shell thickness. These two considerations mean that the terms for conduction in the radial direction may be expressed in terms of the boundary conditions. Using a part of the shell in contact with the vapor as an example,

$$k \frac{\left(T_{r+1} - 2T_r + T_{r-1} \right)}{\Delta r^2} + \frac{k}{r} \frac{\left(T_{r+1} - T_{r-1} \right)}{\Delta r} = \text{(heat conducted through the insulation minus QGT)/thickness}$$

---

*Carslaw, H. S., and Jaeger, J. C., Conduction of Heat in Solids, Oxford University Press, 1959.

The heat conducted through the insulation minus QGT is equal to (neglecting the effect of its mass):

$$\mathrm{QINTO}\left(1+\frac{\mathrm{THK}}{\mathrm{RTANK}}\right)-\mathrm{QGT}$$

where the quantity in parenthesis corrects for the area change with radius. Putting it in terms of the grouped variables:

$$\frac{\mathrm{QINTO}}{\mathrm{THICK}}\left(1+\frac{\mathrm{THK}}{\mathrm{RTANK}}\right)-\frac{\mathrm{QGT}}{\mathrm{THICK}}\simeq\frac{\mathrm{DAO}\cdot\mathrm{QINTO}-\mathrm{D}\cdot\mathrm{QGT}}{\mathrm{THICK}\cdot\mathrm{AEL}\cdot\mathrm{DELTA}}$$

Substituting this into Equation 2 and using $\mathrm{CRV}=\mathrm{C}\cdot\mathrm{RHO}\cdot\mathrm{THICK}\cdot\mathrm{AEL}$ and $\mathrm{CON}=\mathrm{KK}\cdot\mathrm{THICK}\cdot\mathrm{DELTA}/\mathrm{AEL}$

$$\begin{aligned}\frac{\mathrm{CRV}\cdot(\mathrm{T}(\mathrm{N},\mathrm{IDELX})-\mathrm{T}'(\mathrm{N},\mathrm{IDELX})}{\mathrm{THICK}\cdot\mathrm{AEL}\cdot\mathrm{DELTA}} &= \frac{\mathrm{DAO}\cdot\mathrm{QINTO}-\mathrm{D}\cdot\mathrm{QGT}}{\mathrm{THICK}\cdot\mathrm{AEL}\cdot\mathrm{DELTA}}\\ &+\frac{\mathrm{CON}\cdot\mathrm{AEL}\ \ (\mathrm{T}(\mathrm{N}+1,\ \mathrm{IDELX}))}{\mathrm{THICK}\cdot\mathrm{DELTA}\cdot(\mathrm{AEL})^2}\\ &-(\mathrm{CON}\cdot\mathrm{AEL})-\frac{2\cdot\mathrm{T}(\mathrm{N},\mathrm{IDELX})+\mathrm{T}(\mathrm{N}-1,\ \mathrm{IDELX})\ )}{\mathrm{THICK}\cdot\mathrm{DELTA}\ \ (\mathrm{AEL})^2}\end{aligned}$$

Solving for T(N, IDELX), which represents here the variable T_t, the relation for T(N, IDELX) in the program is obtained.

$$\begin{aligned}\mathrm{T}(\mathrm{N},\ \mathrm{IDELX}) = \frac{1}{\mathrm{CRV}}\ &(\mathrm{DAO}\cdot\mathrm{QINTO}+\mathrm{CON}\cdot(\mathrm{T}(\mathrm{N}-1,\mathrm{IDELX})-\mathrm{T}'(\mathrm{N},\ \mathrm{IDELX}))\\ &+\frac{\mathrm{CON}}{\mathrm{CRV}}\cdot(\mathrm{T}(\mathrm{N}+1,\mathrm{IDELX})-\mathrm{T}'(\mathrm{N},\mathrm{IDELX}))\\ &-\frac{\mathrm{QGT}}{\mathrm{CRV}}\cdot\mathrm{D}+\mathrm{T}'(\mathrm{N},\mathrm{IDELX})\end{aligned}$$

APPENDIX III

PROOF FOR TEMPERATURE PROFILE USED FOR SHELL

If a function, say f(x), is continuous on an interval $a \leq x \leq b$, then its average value, or mean value, is given by

$$\bar{f} = \frac{1}{b - a} \int_a^b f(x)\, dx$$

In particular, if $0 \leq x \leq \delta$ and the profile for T is the parabolic form:

$$T = \frac{\alpha t}{\delta^2} - \left(1 - \frac{X}{2\delta}\right) \frac{X}{\delta} + \frac{1}{3} \tag{1}$$

then

$$\bar{T} = \frac{1}{\delta} \int_0^\delta \left[\frac{\alpha t}{\delta^2} - \frac{(1 - X)}{\delta^2 \delta} \frac{X}{\delta} + \frac{1}{3}\right] dx$$

$$= \frac{1}{\delta} \left[\frac{\alpha t}{\delta^2} X - \frac{1}{\delta} \frac{X^2}{2} + \frac{1}{2\delta^2} \frac{X^3}{3} + \frac{X}{3}\right]_0^\delta$$

$$= \frac{t}{\delta^2}$$

Define $F_0 = \frac{\alpha t}{\delta 2}$. Then $\bar{T} = F_0$. Now, from the requirements that at $x = 0$, $T = T_0$, and at $X = \delta$, $T = T_i$, then substituting in Equation 1:

$$T_0 = \frac{\alpha t}{\delta^2} + \frac{1}{3} = \bar{T} + \frac{1}{3}$$

$$T_i = \frac{\alpha t}{\delta^2} - \frac{1}{6} = \bar{T} - \frac{1}{6}$$

Setting up $\bar{T}$ in terms of T_0 and T_i gives

$$\frac{1}{2} T_0 = \frac{1}{2} \bar{T} + \frac{1}{6}$$

$$T_i = \bar{T} - \frac{1}{6}$$

or

$$\frac{1}{2} T_0 + T_i = \frac{3}{2} \overline{T}$$

$$\overline{T} = \frac{1}{3} (T_0 + 2 T_i)$$

which are the desired formulae, as used in the program.

APPENDIX IV

A. DERIVATION OF EQUATIONS FOR MASS FLOW RATE OF VAPOR

The basic equation for conservation of mass in one dimension states that $\partial(A\rho u) / \partial x = 0$ at any point along a flow passage, i.e., that mass flow rate, $\dot{m} = A\rho u = Au/v$, where A is flow area, u is velocity, ρ is density, and v, specific volume, when the valve on a tank car is open only for pressures of magnitude greater than about 200 psi. This insures choked flow through the valve because the ratio of atmospheric pressure to tank pressure is less than the critical value. This means that at the point along the passage where its flow area is minimum the flow velocity will be sonic. The relation for sonic velocity in a gas of constant ratio of specific heats is $u = \sqrt{g\gamma RT_s}$, where g is the acceleration of gravity, γ is the ratio of specific heats, R is the universal gas constant, and T_s is the stream static temperature. T_s can be obtained from $T_s = (T_R)^{2/(\gamma+1)*}$ where T_R is a reservoir or total temperature and in the present case $T_R = T_L$, temperature of the vapor in the tank.

At this critical point where velocity is sonic, the specific volume is desired, also. From the perfect gas equation of state, $v_c = RT_s/P_s$.

In real flows the full value of Au/v is not realized, and a flow coefficient is defined as the ratio of actual to ideal flow rate or $C = \dot{m}/Au/v$. Thus, all the relations used in the program to compute MR, i.e., $\dot{m}$, are explained.

This method for computing mass flow rate of vapor is a simplified one inasmuch as it assumes the fluid to remain in the vapor phase during its expansion. A small amount of liquid actually forms although its effect is negligible. Flow of vapor could have been treated by the method described below for liquid.

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*See any good textbook on gasdynamics, e.g., Shapiro, A.H., Compressible Fluid Flow, Ronald Press, 1953.

B. DERIVATION OF EQUATIONS FOR LIQUID FLOW THROUGH THE VALVE

Flow of fluid through a relief valve is assumed to be isentropic, at constant total enthalpy. Total enthalpy is $u^2/2g + h$ where h is static enthalpy. Therefore, $u_1^2/2g + h_1 = u_2^2/2g + h_2$ where the subscripts refer to two different stations along the flow passage. Let 1 represent the inlet at tank conditions and 2 be the minimum area condition. But $u_1 = 0$ so that $u_2 = \sqrt{2g(h_1 - h_2)}$. The mass flow rate is $\dot{m} = CA_2 u_2/v_2$ (see Part A of Appendix IV). Combining these two relations,

$$\frac{\dot{m}}{CA_2} = \frac{\sqrt{2g(h_1 - h_2)}}{v_2}$$

Now the enthalpy at 1, h_1, is that of saturated liquid found in the thermodynamic table for the fluid. To find h_2 and v_2, use S_1, the entropy of saturated liquid (from the table), which is equal to S_2. At any given pressure, p_2, downstream in the valve, the fraction x_2, of liquid to total fluid mass (i.e., quality) can be determined from $x = S - S_f / S_g - S_f$ where f and g denote liquid and vapor (i.e., gas), respectively. Then enthalpy, h_2, and specific volume can be determined from the relations:

$$h_2 = x(h_g - h_f) + h_f$$

$$v_2 = x(v_g - v_f) + v_f$$

Calculations for various pressures, p_2, yield curves of $\dot{m}/CA_2$ versus p_1; each with a single maximum. A curve through these maximum points appears as shown in the following figure, which is for propane. (The maximum point is analogous to the choked condition.) The case for a departure from isentropic flow by 20 percent was also computed.

In general, relatively large changes in entropy would be expected in the valve, as well as significant loss of flow energy due to the momentum exchange with liquid droplets that are formed. Consequently, a flow coefficient C_D, should be used to account for the losses.

The program uses a constant value of 3200 lb/sec-ft^2 for $\dot{m}/C_DA_2$ because liquid relief of propane only occurs above 265 psia, and the curve in the figure does not vary much for higher pressures. (See Figure A-1.) When this value is multiplied by 3600 to convert the units to lb/hr-ft^2, the constant, 11, 520, 000, is obtained. This, in turn, must be divided by TLENTH to put MR1 on a lb/hr per foot of tank length basis.

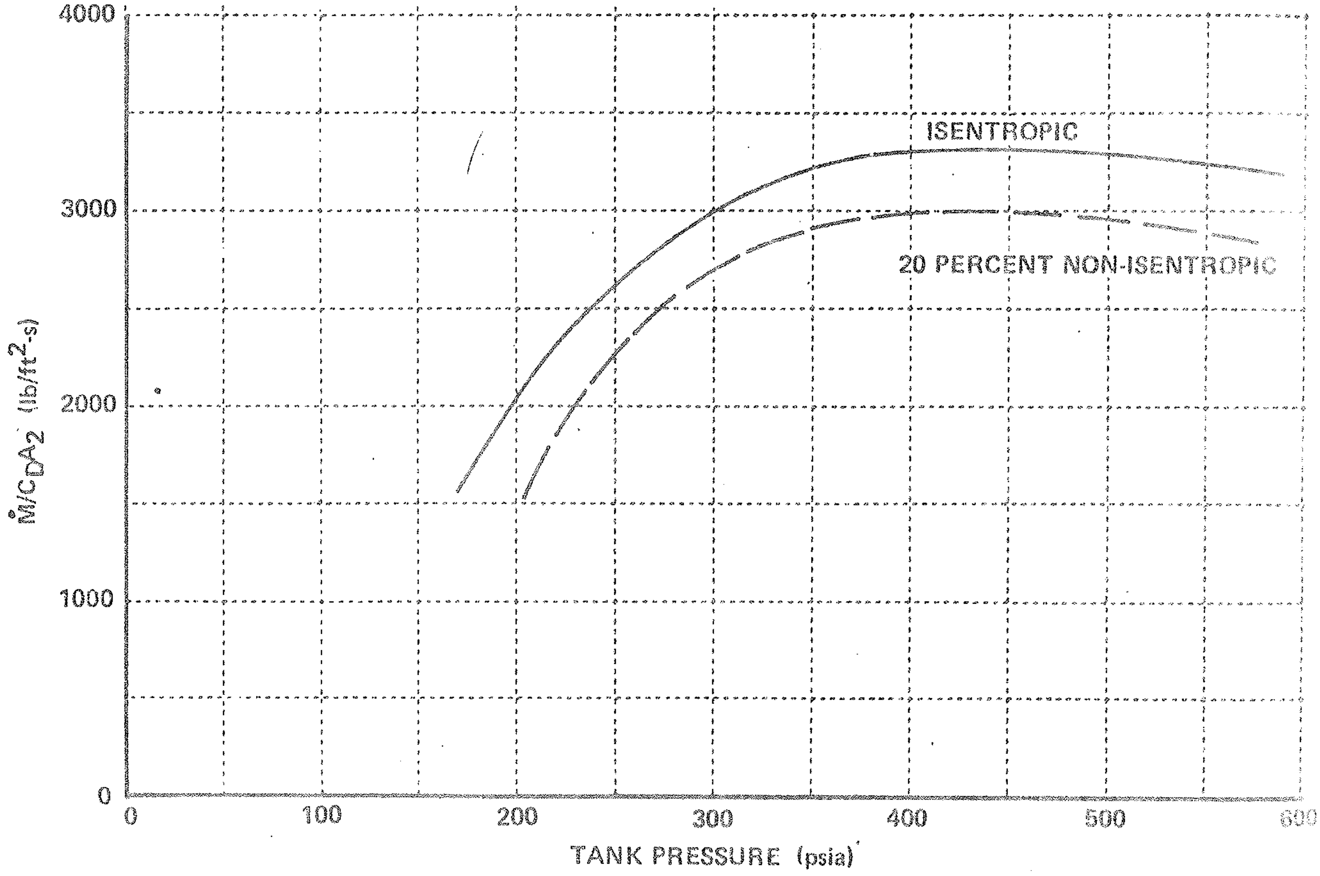

Figure A-1 MAXIMUM FLOW OF LIQUID PROPANE THROUGH AN ORIFICE

APPENDIX V

FORTRAN LISTING

```
                    C*      COMPUTATIONAL VARIABLES:
                    C*
                    C*    AEL      - CROSS SECTIONAL AREA OF EACH ELEMENT OF THE TANK CAR
                    C*       SHELL
                    C*    DANG     - INCLUDED ANGLE OF EACH TANK CAR ELEMENT
                    C*    FLG  -     IF 0., THE VALVE IS CLOSED , IF 1., IT IS OPEN
                    C*    FLIQ     - IFZERO IMPLIES GAS FLOW  THROUGH VALVES
                    C*             - IF 1. IMPLIES LIQUID FLOW THROUGH VALVES
                    C*    G        - GRAVITY
                    C*    HE       - COMBINED GAS/SHELL HEAT TRANSFER COEFFICIENT . BTU/FT**2
                    C*    HF       - SPECIFIC ENTHALPY OF LIQUID AT TIME T
                    C*    HG       - SPECIFIC ENTHALPY OF VAPOR AT THE TIME T
                    C*    QG       - GAS HEAT TRANSFER RATE PER UNIT AREA FOR ONE ELEMENT
                    C*       OF TANK CAR SHELL   ......  BTU/FT**2-HR
                    C*    QGSUM    - TOTAL HEAT INPUT TO THE INTERNAL GAS ENVIRONMENT FROM
                    C*       THE TANK CAR WALL ...... BTU
                    C*    QINTO    - HEAT TRANSFER RATE PER UNIT AREA APPLIED TO THE OUT-
                    C*       SIDE WALL OF THE TANK CAR ...... BTU/FT**2-HR
                    C*    QL       - LIQUID HEAT TRANSFER RATE PER UNIT AREA FOR ONE ELEMENT
                    C*       OF THE TANK CAR SHELL ...... BTU/FT**2-HR
                    C*    SIGC - CIRCUMFERENTIAL STRESS IN TANK CAR SHELL ... LB/IN**2
                    C*    SIGT     - TRANSVERSE STRESS IN TANK CAR SHELL .... LB/IN**2
                    C*    T        - AVERAGE TEMPERATURE OF TANK SHELL ELEMENT ... DEG. F.
                    C*    SIG      - BOLTZMAN'S CONSTANT
                    C*    TAU      - SHEAR STRESS AT 45-DEGREE PLANE IN TANK CAR SHELL ELE-
                    C*       MENT .... LB/IN**2
                    C*    TE       - FIRE TEMPERATURE .... DEG. F.
                    C*    TG       - TEMPERATURE OF GAS IN CAR ..... DEG. F.
                    C*    THET     - ANGLE FROM THETA =0 TO LIQUID-GAS INTERFACE AT TANK
                    C*       CAR SHELL .... DEG.
                    C*    THETA    - POSITION OF THE CENTROID OF EACH ELEMENT OF THE TANK
                    C*       CAR SHELL ... RADIANS
                    C*    TI       - TEMPERATURE OF INSIDE SURFACE OF TANK CAR SHELL ELEMENT
                    C*       ...... DEG. F.
                    C*    TL       - TEMPERATURE OF LIQUID IN TANK CAR ..... DEG. F.
                    C*    TO       - TEMPERATURE OF OUTSIDE OF TANK CAR SHELL .... DEG. F.
                    C*    TS       - SONIC TEMPERATURE FOR GAS FLOW THROUGH RELIEF VALVE
                    C*       ..... DEG. F.
                    C*    UC       CRITICAL VELOCITY ..... FT/SEC
                    C*    VF       - SPECIFIC VOLUME OF LIQUID IN TANK CAR .... LB**3/LB
                    C*    VG       - SPECIFIC VOLUME OF GAS IN TANK CAR ..... FT**3/LB
                    C*    VOLG     - VOLUME OF GAS IN TANK CAR PER UNIT LENGTH ... FT**3/FT
                    C*    VOLL     - VOLUME OF LIQUID IN TANK CAR PER UNIT LENGTH ...FT**3/FT
                    C*
                    C*
                    C*           TANK CAR MODEL PROGRAM
                    C*
  0001                    COMMON/OUTPUT/ TIME,HF,PL, TL,TI,VOLL, VOLG, MG,ML,MR,THE,
                         *DANG, TINT( 30,6), SIGC, SIGT, TAU, QINTO, QGSUM, QLSUM
  0002                    COMMON/COMP/C,EO,EM,G,KK,KP,RHO,RP,SIG,CG,GAMMA,GASCON,HGT
                         *,RHOSK,SKTHK
  0003                    REAL KK,KP,MTOT,L,MG,ML,LT,MGG,MR
  0004                    COMMON/TEMP/ T( 30,6), TT( 30,6),TSURF( 30,6),LT(25),
                         *                                 HFT(25),TLT(25),PLT(25),VFT(25),
                         *VGT(25),        TTT(30),PBT(30) ,          X(4,5),S(5)
  0005                    COMMON/MODIFY/ HEATX(30,10,6), TEMPX(30,10,6), ANG(30), TIMET(10),
                         1 TILT,PITCH,NX
  0006                    COMMON/VALVES/ VENPOS(6), VAREA(6)
```

```
 0007                COMMON/TO/ TO( 30,6)
 0008                REAL MR1, MR2,LAGTHK
 0009                REAL*4 LAGTH1, LAGTH2
 0010                REAL*4 KK1, KK2
 0011                COMMON/ON/HOFTIM(3), TOFTIM(3)
 0012                COMMON  /GENRL/ DELX,                 CPTNK, EI, EFIRE, FKS,
                    1 RHOTNK, CD, DELTA, HF1, MTOT, NEL, PR, THICK, RTANK, PRL, EMO,
                    2 TLENTH,TDCMP,                 CINS1, CINS2, TEM1, TEM2, LAGTH1,
                    3 LAGTH2, FK1, FK2
 0013                COMMON /PLOTS/ PLOT,TPLOT,NPT, NPP, TEMDAT(200, 25,1),TIMPDT(40
                    1          PDAT(400), TIMDAT(200), NRAD, NP
 0014                DATA DELQ1/100./
             C*
             C*
 0015                XLAGR(C0,C1,C2,CX,U0,U1,U2)=(CX-C1)*(CX-C2)/(C0-C1)/(C0-C2)*U0-
                    1(CX-C0)*(CX-C2)/(C0-C1)/(C1-C2)*U1+(CX-C0)*(CX-C1)/(C0-C2)/(C1-C
                    2*U2
 0016            102 FORMAT  (8F8.3,F16.12,F4.0)
 0017            113 FORMAT  ('   BURST TABLE LIMITS ELEMENT ',I6)
 0018            114 FORMAT  (' T ',F7.2,'(',I4,')  PL',F6.2,'  PB',F6.0,' TIME',F7.
 0019            123 FORMAT  (10F10.2)
 0020                CALL INPUT
 0021                GO TO 2
 0022              1 CONTINUE
 0023                NP = NP-1
 0024                IF(NP.LE.0) NP=1
 0025                NPT= NPT -1
 0026                IF(NPT.LT.2) NPT=2
 0027                NPP= NPP-1
 0028                IF(NPP.LT.1) NPP=2
 0029                IF(PLOT.EQ. 1.0) CALL PLOTR
 0030                CALLINPUT1
 0031              2 CONTINUE
 0032                TSAV = DELTA
 0033                LAGTH1 = LAGTH1/12.
 0034                LAGTH2 = LAGTH2/12.
 0035                TIME=0.
 0036              3 THICK=THICK/12.
 0037                DANG=3.1416/(NEL-1)
 0038                AEL  =(RTANK+.5*THICK)*DANG
 0039                DA   =DELTA/3600.*AEL
 0040                CRV  =C*RHO*THICK*AEL
 0041                VOL  =3.1416*RTANK*RTANK
 0042                CON  =KK*THICK*DELTA/(AEL*3600.)
 0043                QLSUM=C.
 0044                QGSUM=0.
 0045                FLAG=0.
 0046                FLG=0.
 0047                POP= 0.0
             C*
             C*        SEARCH ENTHALPY TABLES FOR HF1
             C*
 0048                DO  6  J=1,20
 0049                IF  (HFT(J)-HF1)  6,6,7
 0050              6 CONTINUE
 0051              7 H1=HFT(J-2)
 0052                H2=HFT(J-1)
 0053                H3=HFT(J)
```

```
      H4=HFT(J+1)
      J=J-2
      DO 10 I=1,4
      X(I,1)=TLT(J)
      X(I,2)=PLT(J)
      X(I,3)=VFT(J)
      X(I,4)=VGT(J)
      X(I,5)=LT(J)
   10 J= J+1
C*
C*         INTERPOLATE FOR THE INDEPENDENT VARIABLE HF1 THE SATURATION
C*         VALUES FOR;
C*              PLT   - PRESSURE
C*              TLT  - TEMPERATURE
C*              VFT  - SPECIFIC VOLUME OF SATURATED LIQUID
C*              VGT  - SPECIFIC VOLUME OF SATURATED VAPOR
C*              LT   - HEAT OF VAPORIZATION OF LADING
C*
      DO 15 J=1,5
      XV1=XLAGR(H1,H2,H3,HF1,X(1,J),X(2,J),X(3,J))
      XV2=XLAGR(H2,H3,H4,HF1,X(2,J),X(3,J),X(4,J))
   15 S(J) = (XV1+XV2)*.5
      TL=S(1)
      PL=S(2)
      VF=S(3)
      VG=S(4)
      VGS= VG
      VGS1  = VG
      VGS2 = VG
      L =S(5)
      HG=HF1+L
      HF=HF1
      TG = TL + 460.
      I=NEL+1
      NPRNT=40
      TK1 = TL
      TK2 = TL
      KK1=FK1
      KK2=FK2
      THK = LAGTH1 + LAGTH2
      DO 20 J=1,I
      DO 20 IDELX= 1,NX
      T(J,IDELX) = TL
      TSURF(J,IDELX)=TL+30.
   20 TT(J,IDELX)= TL
C*
C*         INITIALIZE PLOT PARAMS
C*
      NPT=1
      NPP= 1
      IF(TPLOT.EQ. 0.0) TPLOT= DELT
      IF(NRAD .EQ. 0) NRAD= 10
C                    GET MASS OF LIQUID
C             GET MASS OF VAPOR
   30 ML=(VOL-MTOT*VGS)/(VF-VGS)
      MG = MTOT - ML
      IF(MTOT-ML) 32,32,31
   31 IF(ML.LT.0.) ML= 0.
```

```
      VOLL=ML*VF
      VOLG=MG*VGS
      GO TO 50
   32 ML= MTOT
      VOLL=ML*VF
      IF(MG.LT.0.) MG=0.
      VOLG=0.
      VOLP=0.
      DO 40 IDELX= 1,NX
      A = VAREA(IDELX)
      IF(VENPOS(IDELX) -(IDELX-1)*DELX .LT. .75*DELX .AND.
     1   VENPOS(IDELX) -(IDELX-1)*DELX .GT. .25*DELX ) GO TO 35
      A= .5*A
   35 CONTINUE
   40 VOLP= VOLP+11520000./TLENTH*CG*A
      TOPM=VOLP*DELTA*VF/3600.
      POP= VOLL- VOL
      IF(POP.LE.TOPM) GO TO 45
      WRITE(6,171)
  171 FORMAT('  TANK RUPTURE DUE TO EXPANDING LIQUID')
      GO TO 1
   45 VOLL= VOL
      VOLG=0.
      ML=VOLL/VF
      MTOT=ML
C*          DETERMINE THE LIQUID/GAS INTER-FACE
   50 V= 6.28*VOLG/(VOLG+VOLL)
      IF(V.LE. .1) GO TO 60
      Y=V/3.
   55 W= Y-SIN(Y)
      IF(IFIX((V-W)*1000.))  57,65,57
 57   Y=Y+(V-W)*.2
      GO TO 55
   60 THET= 0.0
      Y= 0.0
      GO TO 70
   65 THET= .5*Y
   70 THE= .5*57.2958*Y
      DAO=DANG*(RTANK+THK+THICK/2.)*DELTA/3600.
      D=RTANK*DANG*DELTA/3600.
      M=1
      WEHT= MTOT
      PLIN= PL
      FLUID= ML
      GASIN = MG
      VF1= VF
      VG1= VGS
      HF1= HF
      HG1= HG
      EL1= L
      TL1= TL
      TG1 = TG
   75 CONTINUE
      DAO=DAO/(1.5**(M-1))
      CON=CON/(1.5**(M-1))
      D=D/(1.5**(M-1))
      MTOT= WEHT
      QLSUM=0.
```

```
  0154               QGSUM=0.
  0155               PL= PLIN
  0156               ML= FLUID
  0157               MG= GASIN
  0158               VF= VFI
  0159               VGS= VGI
  0160               HF= HFI
  0161               HG= HGI
  0162               TG = TGI
  0163               L= EL1
  0164               TL= TLI
             C*
             C*       START LOOP ON X STATIONS
             C*
  0165               IPLOT= 0
  0166               TG = TG-460.
  0167               DO 200 IDELX= 1,NX
  0168               DO 200 N=1,NEL
  0169               CALL HUNTEM(TIME, TIMET, 10, J)
             C*
             C*         J POINTS TO LEAD INDEX FOR LAGRANGIAN FIT FOR TIME
             C*
  0170               ANGLE = DANG*FLOAT(N) * 57.2958
  0171               CALL HUNTEM (ANGLE, ANG, 30, K)
             C*
             C*         K POINTS TO LEAD INDEX FOR LAGRANGIAN ON HEATX
             C*
             C*         NOW GENERATE THREE POINTS DEFINING HEATX AS FUNCTION OF TIME
             C*      AND TEMPX AS FUNCTION OF TIME
             C*
  0172               KSAV = K
  0173               DO 80 I=1,3
  0174               HOFTIM(I)  = XLAGR(TIMET(J),TIMET(J+1),TIMET(J+2),TIME,
                    1 HEATX(K,J,IDELX),HEATX(K,J+1,IDELX),HEATX(K,J+2,IDELX))
  0175               TOFTIM(I)  = XLAGR(TIMET(J),TIMET(J+1),TIMET(J+2),TIME,
                    1 TEMPX(K,J,IDELX), TEMPX(K,J+1,IDELX), TEMPX(K,J+2,IDELX))
  0176               K=K+1
  0177            80 CONTINUE
  0178               K = KSAV
  0179               HE = XLAGR(ANG(K),ANG(K+1),ANG(K+2),ANGLE,
                    1 HOFTIM(1),HOFTIM(2),HOFTIM(3))
  0180               TE = XLAGR(ANG(K),ANG(K+1),ANG(K+2),ANGLE,
                    1 TOFTIM(1),TOFTIM(2),TOFTIM(3))
  0181               IF(N-1) 81,81,82
             C*
             C*       COMPUTE HEATING RATES AND ELEMENT TEMPERATURES
             C*
  0182           81  XX = TT(2,IDELX)
  0183               GO TO 85
  0184            82 XX= TT(N-1,IDELX)
             C*
             C*       NG IDENTIFIES ELEMENT AT LIQUID SURFACE
             C*
  0185            85 NG= IFIX(1.5+THET/DANG)
  0186               QINTO=HE*(TE-TSURF(N,IDELX))
  0187               IF(N-NG) 90,100,100
  0188            90 CONTINUE
  0189               QG=HGT*(TT(N,IDELX)-TG)+SIG*EI*((TT(N,IDELX)+460.)**4-
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```
                    1 (TG+460.)**4)
  0190                QGSUM=QGSUM+2.*D*QG
  0191                QGT=QG+(SIG*EI*(TG+460.)**4)-(SIG*EI*(TL+460.)**4)
              C*       COMPUTE SHELL TEMPERATURES
  0192                T(N,IDELX)= (DAO*QINTO+CON*(XX-TT(N,IDELX))+CON*
                    1 (TT(N+1,IDELX)-TT(N,IDELX))-QGT*D+CRV*TT(N,IDELX))/CRV
  0193                TII=T(N,IDELX)
  0194                TI= T(N,IDELX)-QINTO*THICK/(6.*KK)
  0195                IF(TI.LT. TL) TI= TL
  0196                TO(N,IDELX)=3.*T(N,IDELX)-2.*TI
  0197                IF(KK1.EQ. 0.0 .OR. KK2.EQ.0.0) GO TO 95
  0198                COND=(FK2/FK1)*LAGTH1/LAGTH2
  0199                TNFE= (TSURF(N,IDELX)+COND*TO(N,IDELX))/(1.0+COND)
  0200                TK1= .5*(TSURF(N,IDELX)+TNFE)
  0201                TK2= .5*(TO(N,IDELX)+TNFE)
  0202                KK1=FK1+CINS1*(TK1-TEM1)
  0203                KK2=FK2+CINS2*(TK2-TEM2)
              C*       TEMPERATURE OF INSULATION SURFACE IS GREATER THAN SHELL OUTSIDE
  0204                TSURF(N, IDELX)=TO(N,IDELX)+QINTO*((LAGTH1/KK1)+(LAGTH2/KK2))
  0205             95 CONTINUE
  0206                QL=0.
  0207                IF(TSURF(N,IDELX).GT.TDCMP) GO TO 150
  0208                GO TO 150
  0209            100 CONTINUE
  0210            110 CONTINUE
  0211                TI=TT(N,IDELX)-(.5*QINTO*THICK/KK)
  0212                HTCL=(15.+(.0642E-6)*PL**3.347)*((ABS(TI-TL))**1.55)
  0213                IF(HTCL .GT. 6000.) HTCL=6000.
  0214                IF(TI.LT. TL) TI= TL
  0215                QL=HTCL*(TI-TL)
  0216                IF(N .EQ. NG) QL = .5*QL
  0217            120 CONTINUE
  0218                T(N,IDELX)= (DAO*QINTO+CON*(XX-TT(N,IDELX))+CON*
                    1 (TT(N+1,IDELX)-TT(N,IDELX))-QL *D+CRV*TT(N,IDELX))/CRV
  0219                IF(N .EQ. NEL) QL=.5*QL
  0220                QLSUM=QLSUM+2.*D*QL
  0221                TO(N,IDELX)=T(N,IDELX)+(.5*QINTO*THICK/KK)
  0222                IF(KK1.EQ. 0.0 .OR. KK2.EQ.0.0) GO TO 130
  0223                COND=(FK2/FK1)*LAGTH1/LAGTH2
  0224                TNFE= (TSURF(N,IDELX)+COND*TO(N,IDELX))/(1.0+COND)
  0225                TK1= .5*(TSURF(N,IDELX)+TNFE)
  0226                TK2= .5*(TO(N,IDELX)+TNFE)
  0227                KK1=FK1+CINS1*(TK1-TEM1)
  0228                KK2=FK2+CINS2*(TK2-TEM2)
  0229                TSURF(N, IDELX)=TO(N,IDELX)+QINTO*((LAGTH1/KK1)+(LAGTH2/KK2))
  0230            130 CONTINUE
  0231                QG=0.
  0232                IF(TSURF(N,IDELX).GT.TDCMP) GO TO 150
  0233                GO TO 180
  0234            150 THK=(TDCMP-T(N,IDELX))*KK1/QINTO+LAGTH2
  0235                IF(THK.GT.LAGTH2) GO TO 160
  0236                THK = (TDCMP-T(N,IDELX))*KK2/QINTO
  0237                IF(THK.LE. 0.0) TSURF(N,IDELX)= TO(N,IDELX)
  0238                IF(THK.LE. 0.0) GO TO 180
  0239            160 TSURF(N,IDELX)= TDCMP
  0240            180 CONTINUE
  0241                TINT(N,IDELX)= TI
  0242            190 CONTINUE
```

```
  200 CONTINUE
      [illegible]
      DAO=DAO*(1.5**(M-1))
      CON=CON*(1.5**(M-1))
      D=D*(1.5**(M-1))
      FLIQ=0.0
      IF(THE-TILT .LT. 0.0) FLIQ = 1.0
      DO 220 IDELX= 1,NX
      T(NEL+1,IDELX) = T(NEL,IDELX)
  220 CONTINUE
      MR=0.
      MR1 = 0.0
      MR2 = 0.0
      ICOUNT= 0
      REAL*4 ML2, MG2
      PL1= PL
      PREV = QGSUM+QLSUM
      DO 300 IDELX= 1,NX
      A = VAREA(IDELX)
      IF(VENPOS(IDELX)-(IDELX-1)*DELX .LT. .75*DELX
     * .AND. (VENPOS(IDELX)-(IDELX-1)*DELX .GT. .25*DELX)) GO TO 230
      A = .5* VAREA(IDELX)
C*
C*         USE ONE HALF VALVE AREA IF VALVE IS "NEAR" AN ELEMENT BOUNDARY
C*
  230 IF(FLG) 245,245,235
  235 IF(PL-PRL) 240,260,260
  240 FLG= 0.0
C*
C        TEST FOR VALVE OPEN PRESSURE
C*
  245 IF(PL-PR) 350,250,250
  250 FLG= 1.0
  260 IF(FLIQ) 280,280,270
  270 MR1= MR1+ 11520000./TLENTH*CG*A
      GO TO 300
  280 CONTINUE
      PS=PL*(2./(KP+1.))**(KP/(KP-1.))
      TS=(TG+460.)*(2./(KP+1.))
      VC=RP*TS/(PS*144.)
      UBC=ABS(KP*G*RP*TS)
      UC=SQRT(UBC)
      MR2 = MR2 + (CG*A*UC)/VC*(3600./TLENTH)
  300 CONTINUE
      MR = MR1 + MR2
      MTOT= MTOT-MR*DELTA/3600.
C*
C*         TEST VALVE CLOSING PRESSURE
C*
      IF(PL-PRL) 350, 310,310
C*
C*        THE VALVE IS OPEN,ITERATE ON HEAT INPUT FOR PRESSURE
C*
  310 CONTINUE
      PL2= .95*PL1
  320 CONTINUE
      CALL FPLT(PL2, PLT,HFT,TLT,VFT,VGT,LT,TL,VG,VF,HF,L )
      ML2 = ML - MR1*DELTA/3600.
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```
      MG2 = MG - MR2*DELTA/3600.
      IF(MG2 .GT. 0.0) GO TO 322
      MG2 = 0.0
      GO TO 325
  322 CONTINUE
      HG= (QGSUM-MR2*HG1*DELTA/3600.+MG*HG1+(ML-ML2-MR1*DELTA/3600.)*L)
     */MG2
      CPG = .829 - .000298*HG - .00009*(PL2 - 50.)
      TG = HG/CPG
      VGS= (.243*TG+.05*PL2+1.15/VGS**2)/(PL2+23.)
      ML2=(VOL-MTOT*VGS)/(VF-VGS)
      MG2= MTOT-ML2
  325 CONTINUE
      QIN=ML2*HF+MG2*HG-ML*HF1-MG*HG1
     * +(MR1*HF1+MR2*HG1)*DELTA/3600.
      TEST= QIN
      DELQ2= PREV-TEST
      IF(ABS(DELQ2) .LE.  .1*(ABS(PREV)+10. )) GO TO 330
      PL= PL2-DELQ2*(PL1-PL2)/(DELQ1-DELQ2)
      PL= ABS(PL)
      PL1= PL2
      PL2= PL
      DELQ1 = DELQ2
      ICOUNT = ICOUNT+1
      IF(ICOUNT .GT. 30) GO TO 400
      GO TO 320
  330 PL= PL2
      IF(PL.LT. .99*PRL) GO TO 340
      FLG=0.
      IF(PL.GT. 1.02*PRL) FLG= 1.0
      GO TO 410
  340 M= M+1
      DELTA= DELTA/1.5
      GO TO 75
  350 CONTINUE
      PL2= 1.05*PL1
C*
C*     THE VALVE IS CLOSED, ITERATE ON HEAT INPUT FOR PRESSURE
C*
  360 CONTINUE
      CALL FPLT(PL2, PL1,HF1,TL1,VF1,VG1,L1,TL,VG,VF,HF,L )
      ML2 = ML
      MG2 = MG
      IF(MG2 .GT. 0.0) GO TO 362
      MG2 = 0.0
      GO TO 365
  362 CONTINUE
      HG= (QGSUM+(ML-ML2)*L+MG*HG1+.1851*(PL2*MG2*VGS2-PL1*MG*VGS1))/MG2
      CPG = .829 - .000298*HG-.00009*(PL2-50.)
      TG = HG/CPG
      VGS= (.243*TG+.05*PL2+1.15/VGS**2)/(PL2+23.)
      ML2=(VOL-MTOT*VGS)/(VF-VGS)
      MG2= MTOT-ML2
  365 CONTINUE
      QIN=ML2*HF+MG2*HG-ML*HF1-MG*HG1
     * -(.1851*(PL2*(ML2*VF+MG2*VGS)-(PL1*(ML*VF1+MG*VG1))))
      TEST= QIN
      DELQ2= PREV-TEST
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      IF(ABS(DELQ2) .LE. .1*(ABS(PREV)+10. )) GO TO 370
      PL= PL2-DELQ2*(PL1-PL2)/(DELQ1-DELQ2)
      PL= ABS(PL)
      PL1= PL2
      PL2= PL
      DELQ1 = DELQ2
      ICOUNT = ICOUNT+1
      IF(ICOUNT .GT. 20) GO TO 400
      GO TO 360
  370 PL= PL2
      VGS1= VGS2
      VGS2= VGS
      IF( PL.GT. 1.03*PR) GO TO 340
      GO TO 410
  400 PRINT 3334
 3334 FORMAT('   ITERATION EXCEEDED')
      GO TO 1
  410 CONTINUE
C*
C*      PRESSURE SATISFACTORY FOR VALVE ACTION AND HEAT IS BALANCED
C*
      DO 450 IDELX= 1,NX
      DO 450 K=1,NEL
      DO 420 J=2,25
      IF(TTT(J) -T(K,IDELX)) 420,420,430
  420 CONTINUE
      WRITE  (6,113)  K
  430 Z= (T(K,IDELX)-TTT(J-1))/(TTT(J)-TTT(J-1))
      PB=Z*(PBT(J)-PBT(J-1))+PBT(J-1)
      THSTRS= 128.0*(TO(I,IDELX)-TINT(I,IDELX))
      PALL=(THSTRS* THICK/RTANK+PL-14.7)*RTANK/5.0
      IF(PALL-PB) 460, 440, 440
  440 CONTINUE
      WRITE(6,114) T(K,IDELX),K,PL,PB,TIME
      WRITE(6,1000)
 1000 FORMAT (1H1)
      GO TO 1
  450 CONTINUE
  460 CONTINUE
      SIGC= (PL-14.7)*RTANK/THICK+THSTRS
      SIGT=.5*SIGC
      TAU=.25*SIGC
      TIME=TIME+DELTA
      TSAV = TSAV + DELTA
      CALL OUTPUT
      IF(TIME .GT. 480.) GO TO 1
      IF(PLOT .NE. 1.0) GO TO 4000
C*      BYPASS PLOT SETUP
C*
      IF(TSAV .LT. TPLOT) GO TO 3980
      TSAV = DELTA
      IPLOT= 1
      NP= 1
      TIMDAT(NPT) = TIME
      DO 3960 N=1,NEL,NRAD
C*
C*    PLOT ONLY ONE AXIAL STATION.... IF ALL ARE DESIRED UP THE DIMENSION
C*    ON TEMDAT AND LOOP THROUGH NX STATIONS.
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C*
      TEMDAT(NPT,NP,1) = TO(N,1)
      NP= NP+1
      IF(NP.GT.25) NP= 25
 3960 CONTINUE
      IF(IPLOT .EQ. 1) NPT= NPT+1
      IF(NPT.GT. 200) NPT= 200
 3980 CONTINUE
      PDAT(NPP) = PL
      TIMPDT(NPP)= TIME
      NPP= NPP+1
      IF(NPP.GT.400) NPP= 400
 4000 CONTINUE
      DELTA=DELTA*(1.5**(M-1))
      IF(ML.LE.0.0) GO TO 1
      QLSUM=0.
      QGSUM=0.
      DO 4010 IDELX= 1,NX
      DO 4010 J=1,NEL
 4010 TT(J,IDELX)= T(J,IDELX)
      GO TO 30
      END
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FORTRAN IV G LEVEL  20                  INPUT                  DATE = 73009            18/04/3

 0001                SUBROUTINE INPUT
 0002                COMMON IPRNT(5)
 0003                COMMON YLAB(41),XLAB(30), PLAB(41)
 0004                COMMON SPACE(41,121)
 0005                COMMON ISYM(21)
 0006                COMMON XAXIS(13), YAXIS(41)
 0007                COMMON/COMP/C,EO,EM,G,KK,KP,RHO,RP,SIG,CG,GAMMA,GASCON,HGT
                    *,RHOSK,SKTHK
 0008                REAL KK,KP,MTOT,L,MG,ML,LT,MGG,MR
 0009                COMMON/TEMP/ T( 30,6), TT( 30,6),TSURF( 30,6),LT(25),
                    *                                 HFT(25),TLT(25),PLT(25),VFT(25),
                    *VGT(25),       TTT(30),PBT(30) ,            X(4,5),S(5)
 0010                COMMON/MODIFY/ HEATX(30,10,6), TEMPX(30,10,6), ANG(30), TIMET(10),
                    1 TILT,PITCH,NX
 0011                COMMON/VALVES/ VENPOS(6), VAREA(6)
 0012                REAL MR1, MR2,LAGTHK
 0013                COMMON/ON/HOFTIM(3), TOFTIM(3)
 0014                COMMON  /GENRL/ DELX,                     CPTNK, EI, EFIRE, FKS,
                    1 RHOTNK, CD, DELTA, HF1, MTOT, NEL, PR, THICK, RTANK, PRL, EMO,
                    2 TLENTH,TDCMP,                  CINS1, CINS2, TEM1, TEM2, LAGTH1,
                    3 LAGTH2, FK1, FK2
 0015                COMMON /PLOTS/ PLOT,TPLOT,NPT, NPP, TEMDAT(200, 25,1),TIMPDT(400),
                    1          PDAT(400), TIMDAT(200), NRAD, NP
 0016                CALL CLEAR(VENPOS(1), VAREA(6))
 0017                CALL CLEAR(DELX, FK2)
 0018                REAL*4 LAGTH1, LAGTH2
 0019                READ(5,3000) XLAB
 0020                READ(5,3050) YLAB
 0021                READ(5,3050) PLAB
 0022           3000 FORMAT(20A4/10A4)
 0023           3050 FORMAT(41A1)
 0024                NAMELIST/INPUT/ HEATX,TEMPX,TIMET,TILT,ANG,NX,PITCH
 0025                ENTRY INPUT1
 0026                READ(5,INPUT,END=50)
               C*
               C*        CARD INPUTS:
               C*
               C*     DATA SET "INPUT"
               C*
               C*     HEATX    - HEAT DISTRIBUTIONON CIRCUMFERENTIAL ELEMENTS PER LENGTH
               C*     TEMPX    - FIRE TEMPS CIRCUMFERENTIALLY DISTRIBUTED PER LENGTH
               C*     ANG      - RADIAL LOCATIONS FOR HEATX AND TEMPX
               C*     TIMET    - TIME TABLE FOR DURATION OF FIRE
               C*     TILT     - ROLL ANGLE OF THE VENT VALVE FROM UPRIGHT POSITION
               C*     PITCH    - PITCH ANGLE OF THE TANK CAR
               C*
 0027                NAMELIST /LADING/ HFT, LT, TLT, PLT, VGT, VFT, GAMMA, GASCON, HGT
 0028                READ(5,LADING)
               C*
               C*        CARD INPUTS:
               C*
               C*     DATA SET "LADING"
               C*
               C*     HFT       - SPECIFIC ENTHALPY OF SATURATED LIQUID LADING
               C*     LT        - HEAT OF VAPORIZATION OF LADING
               C*     TLT       - TEMPERATURE VALUES FOR ENTHALPY AND VOLUME DATA
               C*     PLT       - PRESSURE VALUES FOR ENTHALPY AND VOLUME DATA
               C*     VGT       - SPECIFIC VOLUME OF SATURATED VAPORIZED LADING
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                   C*     VFT      - SPECIFIC VOLUME OF SATURATED LIQUID LADING
                   C*     HGT      - GAS HEAT TRANSFER COEFFICIENT  ...... BTU/FT**2-HR
                   C*     GASCON   - GAS CONSTANT
                   C*     GAMMA    - RATIO OF SPECIFIC HEATS
                   C*
 0029                     NAMELIST /BURST/ TTT, PBT
 0030                     READ(5,BURST)
                   C*
                   C*        CARD INPUTS:
                   C*
                   C*     DATA SET 'BURST'
                   C*
                   C*     TTT      - TANK BURST TEMPERATURES
                   C*     PBT      - TANK BURST PRESSURES
                   C*
 0031                     WRITE(6,2300) (HFT(K), LT(K), TLT(K), PLT(K), VGT(K), VFT(K),
                         * K=1,25)
 0032                2300 FORMAT(                                                     '
                         *1   HFT         LT         TLT        PLT        VGT        VFT  '//,
                         * 6(1X,1PE9.3))
 0033                     WRITE(6,2100) (TTT(K),PBT(K),K=1,30)
 0034                2100 FORMAT                                                    (/'
                         *     TTT       PBT   '//,
                         * (2(1X,1PE9.3)))
 0035                     WRITE(6,2200) (((HEATX(I,J,K),TEMPX(I,J,K),I=1,30),J=1,10),
                         * K=1,NX)
 0036                2200 FORMAT                                                    (/'
                         *    HEAT X    TEMP  X   '/(2(1X,1PE9.3)))
 0037                     WRITE(6,2310) ANG
 0038                2310 FORMAT(/'  RADIAL ANGLE DISTRIBUTION'/(10(F12.2)))
 0039                     WRITE(6,2320) TIMET
 0040                2320 FORMAT(/'  HEATING TIME '/(10(F12.2)))
 0041                     NAMELIST/GENRL/ DELX, VENPOS, VAREA, CPTNK, EI, EFIRE, FKS,
                         1 RHOTNK, CD, DELTA, HF1, MTOT, NEL, PR, THICK, RTANK, PRL, EMO,
                         2 TLENTH,TDCMP,                CINS1, CINS2, TEM1, TEM2, LAGTH1,
                         3 LAGTH2, FK1, FK2, PLOT, TPLOT, NRAD
 0042                     READ(5,GENRL)
                   C*
                   C*        CARD INPUTS:
                   C*
                   C*     DATA SET 'GENRL'
                   C*
                   C*     CPTNK    - SPECIFIC HEAT OF TANK CAR SHELL MATERIAL .... BTU/LB-DEG
                   C*     RTANK    - RADIUS OF TANK CAR ...  FT
                   C*     EI       EMISSIVITY OF INSIDE OF TANK SHELL
                   C*     EFIRE    - EMISSIVITY OF FIRE
                   C*     FKS      - THERMAL CONDUCTIVITY OF TANK SHELL
                   C*     RHOTNK   - DENSITY OF TANK CAR SHELL
                   C*     VAREA    - AREA OF RELIEF VALVE      ..... FT**2
                   C*     CD       - RELIEF VALVE FLOW COEFFICIENT
                   C*     DELX     - LENGTH OF EACH TANK CAR ELEMENT
                   C*     DELTA    - TIME INCREMENT IN CALCULATION .... SECONDS
                   C*     HF1      - INITIAL SPECIFIC HEAT OF LADING
                   C*     MTOT     - INITIAL TOTAL MASS OF LIQUID AT LADING    .... LB/FT
                   C*     NEL      - NUMBER OF TANK CAR RADIAL STATIONS
                   C*     PR       - PRESSURE TO OPEN RELIEF VALVE  ..... PSF
                   C*     THICK    - THICKNESS OF TANK CAR SHELL  .... INCHES
                   C*     PRL      - LOW PRESSURE VALVE LIMIT
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                 C*     EMO      - EMISSIVITY OF TANK CAR OUTSIDE
                 C*     VENPOS   - LOCATIONS OF VALVES
 0043                   CONTINUE
                 C*     LAGTH1   - THICKNESS OF OUTER LAYER OF INSULATION.... INCH
                 C*     LAGTH2   - THICKNESS OF INNER LAYER OF INSULATION.... INCH
                 C*     FK1      - THERMAL CONDUCTIVITY OF OUTER INSULATION AT REFERENCE
                 C*                TEMPERATURE .... BTU/FT-DEGF-HR
                 C*     FK2      - THERMAL CONDUCTIVITY OF INNER INSULATION AT REFERENCE
                 C*                TEMPERATURE .... BTU/FT-DEGF-HR
                 C*     CINS1    - SLOPE OF LINEAR TEMPATURE VARIATION OF THERMAL
                 C*                CONDUCTIVITY FOR OUTER INSULATION
                 C*     CINS2    - SLOPE OF LINEAR TEMPERATURE VARATION OF THERMAL
                 C*                CONDUCTIVITY FOR INNER INSULATION
                 C*     TEM1     - REFERENCE TEMPERATURE FOR FK1 .... DEG F
                 C*     TEM2     - REFERENCE TEMPERATURE FOR FK2 ....DEG F
                 C*     PLOT     - IF 1.0, PLOTS REQUESTED
                 C*     TPLOT    - TIME INTERNAL AT WHICH TO PRODUCE TEMPERATURE PLOT
                 C*     NRAD     - RADIAL STATION INCREMENT FOR TEMPERATURE PLOT
                 C*                (25 DISTINCT PLOT SYMBOLS AVAILABLE)
                 C*
 0044                 2 G = 32.16
 0045                   CG = CD
 0046                   RHO = RHOTNK
 0047                   KP= GAMMA
 0048                   RP= GASCON
 0049                   KK = FKS
 0050                   C  = CPTNK
 0051                   SIG = .173E-8
 0052                   EM= EMO
 0053                   EO= EFIRE
 0054                   WRITE(6,GENRL)
 0055                   WRITE  (6,105)
 0056                   WRITE(6,102) C,EI,EO,G,KK,KP,RHO,RP,SIG
 0057                   WRITE  (6,106)
 0058                   WRITE  (6,103) A,CG,DELTA,HGT,HF1,MTOT,NEL,PR,RTANK,THICK,TE,HE,
                       *PRL,EM
 0059                   WRITE  (6,104)
 0060               100 FORMAT  (10F8.0)
 0061               101 FORMAT  (6F8.0,I8,3F8.0)
 0062               102 FORMAT  (8F8.3,F16.12,F4.0)
 0063               103 FORMAT  (2F8.4,F8.1,3F8.2,I8,2F8.3,F8.4,F8.0,F8.2,F8.3,F8.4)
 0064               104 FORMAT  (1H )
 0065               105 FORMAT ('        C        EI        EO        G        K        KP       RHO
                       *      RP                SIG FLQ')
 0066               106 FORMAT ('        A        CG    DELTA      HGT      HF1     MTOT       NEL
                       *      PRL  RTANK    THICK        TE        HE       PR        EM')
 0067               110 FORMAT (1H1)
 0068               111 FORMAT ('   NEL  TIME     HF      MG        ML      PL      QINTO       QGSU
                       *M       QLSUM        T  THET    NG      TL   VOLL   VOLG      TI      TO')
 0069               112 FORMAT  (I5,F7.2,2F7.2,F8.2,F6.1, F10.0,F10.5,F10.2,F6.1,F6.2,I4,
                       *F7.2,2F6.2,2F6.0)
 0070               113 FORMAT  ('   BURST TABLE LIMITS ELEMENT ',I6)
 0071               114 FORMAT  (' T ',F7.2,'(',I4,')  PL',F6.2,'  PB',F6.0,' TIME',F7.0)
 0072               120 FORMAT(1H ,  ' TIME        MR      PS        SIGC        SIGT         TAU
                       *      TG      PL         ML        MG    T(1) THETA  QINTO   QGSUM  DMG    L
                       *')
 0073               121 FORMAT  (F6.0,F8.2,F6.2,4F10.0,F6.1,2F8.2,F7.1,F6.2,F7.0,F6.2,
                       *F7.0,F5.0)
```

```
 0074            122 FORMAT  ('  LIQUID ZERO, ML= ',F8.2)
 0075            123 FORMAT  (10F10.2)
 0076            124 FORMAT  ('        DAO        CON     T(N-1)          QG          QL
                   *   D    T(N+1)          TT          TL')
 0077                RETURN
 0078             50 CONTINUE
 0079                CALL EFPLOT
 0080                STOP
 0081                END
```

```
FORTRAN IV G LEVEL  20                 HUNTEM              DATE = 73005          09/21/3

 0001                  SUBROUTINE HUNTEM (V,X,N,J)
 0002                  DIMENSION X(N)
               C*         V     - THE INDEPENDENT VARIABLE
               C*         X     - TABLE OF INCEPENDENT VARIABLES
               C*
 0003                  L = N-1
 0004                  DO 20 I=2,L
 0005                  IF(X(I-1) .LE. V .AND. V.LE. X(I) .OR.
                      * X(I-1) .GE. V .AND. V .GE. X(I)) GO TO 30
 0006               20 CONTINUE
               C*
               C*         ARRIVAL HERE IMPLIES THE USE OF THE LAST VARIABLE
               C*
 0007                  I=L
 0008               30 CONTINUE
 0009                  J = I-1
               C*
               C*        J POINTS TO X ARRAY FOR 3 POINT FIT INDEXING
 0010                  RETURN
 0011                  END
```

```
0001                 SUBROUTINE FPLT(PL, PLT,HFT,TLT,VFT,VGT,LT, TL,VG, VF,HF, L)
0002                 DIMENSION PLT(1),HFT(1),TLT(1),VFT(1),VGT(1),LT(1)
0003                 REAL*4 LT,L
0004                 XLAGR(C0,C1,C2,CX,U0,U1,U2)=(CX-C1)*(CX-C2)/(C0-C1)/(C0-C2)*U0-
                    1(CX-C0)*(CX-C2)/(C0-C1)/(C1-C2)*U1+(CX-C0)*(CX-C1)/(C0-C2)/(C1-C2)
                    2*U2
0005                 DO 6 J=2,20
0006                 IF(PLT(J)-PL) 6,6,7
0007               6 CONTINUE
0008                 J= 20
0009               7 H1=PLT(J-2)
0010                 H2= PLT(J-1)
0011                  H3=PLT(J)
0012                 H4= PLT(J+1)
0013                 TL= XLAGR(H2,H3,H4,PL, TLT(J-1), TLT(J), TLT(J+1))
0014                 VG= XLAGR(H2,H3,H4,PL, VGT(J-1), VGT(J), VGT(J+1))
0015                 VF= XLAGR(H2,H3,H4,PL, VFT(J-1), VFT(J), VFT(J+1))
0016                 HF= XLAGR(H2,H3,H4,PL, HFT(J-1), HFT(J), HFT(J+1))
0017                 L = XLAGR(H2,H3,H4,PL,  LT(J-1),  LT(J),  LT(J+1))
0018                 RETURN
0019                 END
```

```
      SUBROUTINE OUTPUT
      COMMON/MODIFY/ HEATX(30,10,6), TEMPX(30,10,6), ANG(30), TIMET(10),
     1 TILT,PITCH,NX
      COMMON/OUTPU1/ TIME,HF,PL, TL,TI,VOLL, VOLG, MG,ML,MR,THE,
     *DANG, TINT( 30,6), SIGC, SIGT, TAU, QINTO, QGSUM, QLSUM
      COMMON/TEMP/ T( 30,6), TT( 30,6),TSURF( 30,6),LT(25),
     *                                    HFT(25),TLT(25),PLT(25),VFT(25),
     *VGT(25),          TTT(30),PBT(30) ,          X(4,5),S(5)
      COMMON/VALVES/ VENPOS(6), VAREA(6)
      COMMON  /GENRL/ DELX,                  CPTNK, EI, EFIRE, FKS,
     1 RHOTNK, CD, DELTA, HF1, MTOT, NEL, PR, THICK, RTANK, PRL, EMO,
     2 TLENTH,TDCMP,                        CINS1, CINS2, TEM1, TEM2, LAGTH1,
     3 LAGTH2, FK1, FK2
      COMMON/TO/ TO( 30,6)
      REAL KK,KP,MTOT,L,MG,ML,LT,MGG,MR
      DIMENSION  LSET(6), STA(10)
      DO 30  K= 1,NX
      IF(TIME.EQ.DELTA) LSET(K)=0
      IUNIT =  K+7
C***********************************************************************
C*
C*        IF NX = 1, IUNIT MAY BE SET TO 6 FOR SYSOUT
C*
C***********************************************************************
      IF( MOD (LSET, 3) .EQ.0) WRITE(IUNIT,1000)  K
 1000 FORMAT(1H1,50X,'AXIAL STATION NO. ', I5)
      WRITE(IUNIT,1010)  TIME
 1010 FORMAT(/'   TIME   ',F10.2,' SECONDS' /,
     *35X,'INTERNAL SURFACE TEMPFRATURES OF STEEL SHELL'/)
      DO 20   I= 1,200
      LIM = NEL - 10* (I-1)
      IF(LIM .LE. 0)  GO TO  25
      L1 = (I-1)*10+1
      L2 =  L1 + 9
      L3 =  10
      IF(LIM .LT. 10)  L3=LIM
      IF(LIM .LT. 10)  L2 = L1+ LIM-1
      LL= 1
      DO 10 J= L1, L2
      STA(LL) = (J-1)*DANG* 57.2958
      LL= LL+1
   10 CONTINUE
      WRITE (IUNIT, 1020)     (STA(J),J=1,L3)
 1020 FORMAT (1X,'AT', 10(3X,F8.2))
      WRITE (IUNIT,1030)  ( TINT (J,K), J=L1,L2)
 1030 FORMAT( 3X,10(3X,F8.2)/)
   20 CONTINUE
   25 WRITE (IUNIT,1040)    PL, TL, HF, ML, VOLL, MR, TSURF(1,K)
 1040 FORMAT                                                        (/1X,
     *'TANK PRESSURE  LIQUID TEMPERATURE  LIQUID ENTHALPY  MASS OF LIQUI
     *D  VOL OF LIQUID  VALVE FLOW RATE  TSURF(N=1)'/,
     *3X,F10.2,4X,F10.2, 11X,F10.2,5X,F10.2,5X,F10.2,5X,F10.2,5X,F10.2/)
      WRITE (IUNIT,1050)   THE  ,SIGC, SIGT  , TAU , QINTO, QGSUM ,
     * QLSUM, T(1,K)
 1050 FORMAT                                                        (1X,
     *'ANGLE TO LIQUID  CIRCUM. STRESS  LONG. STRESS  SHEAR STRESS      Q
     *INTO        QGSUM          QLSUM       T(N=1) '/,
     *3X,F10.2, 7X, F10.2, 4X, F10.2, 4X, F10.2 ,4X,F10.2,2X,F10.2,
```

```
FORTRAN IV G LEVEL  20                    OUTPUT              DATE = 73010         [illegible]
                         *2X,F10.2,2X,F10.2/)
 0039                     LSET(K) = LSET(K) +1
 0040                  30 CONTINUE
 0041                     RETURN
 0042                     END
```

```
            SUBROUTINE PLOTTR (XDATA,YDATA,NPT)
C
C           REQUIRED INPUTS;
C            Y-LABEL CARD (1)
C            X-LABEL CARDS (2)
C
C           INPUT PARAMETERS REQUIRED;
C            XDATA --- X
C            YDATA ---- Y
C            NPT - NUMBER OF X,Y PAIRS IN ENITE PLOT INCLUDING OVERLAYS
C            ISYM(I) - ENTER NUMBER OF X,Y PAIRS FOR WHICH SYMBOL I APPLIES
C            ISYM(I+1) =0 TERMINATES PLOTS
C
C
C            SUBROUTINES REQUIRED;
C            GRID
C            NORMAL
C            AXSCAL SCALES TO 2,5, OR 10 DELX
C            CALLING SEQUENCE;
C              CALL PLOTTR(XDATA,YDATA,NPTS)
C
C
           COMMON IPRNT(5)
           COMMON YLAB(41),XLAB(30), PLAB(41)
           COMMON PLOT(41,121)
           COMMON ISYM(21)
           COMMON XAXIS(13),YAXIS(41)
           DIMENSION  SYMBOL(20)
           DIMENSION XDATA (1), YDATA(1)
           DATA PLUS/1H+/
           DATA SYMBOL/1H*,1H-,1H.,1H,,1HY,1H#,1H$,1H@,1H%,1H&,1H=,1H>,
          1 1H<,1H?,1H(,1H),1HA,1HX,1HZ,1H0/
           CALL GRID
           XMIN = XDATA(1)
           YMIN = YDATA(1)
           XMAX = XDATA(1)
           YMAX = YDATA(1)
           DO 5 I = 1,NPT
           IF ( YDATA(I) .LT. YMIN)  YMIN = YDATA(I)
           IF ( XDATA(I) .LT. XMIN) XMIN = XDATA(I)
           IF (XDATA(I) .GT. XMAX) XMAX = XDATA(I)
           IF (YDATA(I) .GT. YMAX) YMAX = YDATA(I)
         5 CONTINUE
           DATA SYSMAX/Z7F7F7F7F/
           IF(XMIN.EQ. SYSMAX .OR. YMIN.EQ. SYSMAX) GO TO 200
C
C             CALCULATE SCALE FACTORS BASED ON 35 SKIP INTERVALS IN THE Y-
C          DIRECTION AND 115 TYPE BAR INTERVALS IN THE X- DIRECTION.
C          NOTE THAT THERE ARE ACTUALLY 5 MORE INTERVALS SERVUNG AS "BUFFER"
C          SPACE.
C
           DELX = (XMAX-XMIN)/116.
           DELY   = (YMAX-YMIN)/35.
           IF(DELX.EQ. 0.0) DELX=1.0
           IF(DELY.EQ. 0.0) DELY= 1.0
           CALL NORMAL (DELX,IXPNT)
           CALL NORMAL(DELY,IYPNT)
C    C PRINT 9999, DELX, DELY, IXPNT, IYPNT
```

```
 0030          9999 FORMAT('  DELX, DELY, IXPNT, IYPNT =',2F10.2, 2I10)
              C
              C         "NORMAL" RETURNS DELX,DELY NORMALIZED TO X.XXXXXX
              C         "NORMAL" RETURNS A "NORMALIZED NUMBER IN POWER OF 10 NOTATION.
              C      NOW SELECT A SCALE FOR THE NORMALIZED NUMBER SUCH THAT IT IS,
              C      NEAREST TO 2, 4, 5, 6, 8, OR 10.
              C
              C
 0031                CALL AXSCAL(DELX)
 0032                CALL AXSCAL(DELY)
              C      PRINT 1234, XMIN,YMIN
 0033                XSCALE = DELX*(10.**IXPNT)
 0034                YSCALE= DELY*(10.**IYPNT)
 0035                IDELX = DELX
 0036                IDELY = DELY
              C*
              C*   ESTABLISH PLOTTER ORIGIN AT IXIN, IYMIN
              C*
 0037                XK = 0.0
 0038                IF(XMIN .GT. 0.) GO TO 106
 0039            100 IF(XSCALE *XK .LE. XMIN) GO TO 105
 0040                XK = XK - 10.
 0041                GO TO 100
 0042            105 IXMIN = DELX*XK - .5
 0043                GO TO 109
 0044            106 IF(XSCALE*XK .GT. XMIN) GO TO 107
 0045                XK = XK + 10.
 0046                GO TO 106
 0047            107 IXMIN = DELX*(XK-10.0)
 0048            109 XK = 0.0
 0049                IF(YMIN .GT. 0.) GO TC 121
 0050            110 IF(YSCALE*XK .LE. YMIN) GO TO 120
 0051                XK = XK - 5.0
 0052                GO TO 110
 0053            120 IYMIN = DELY*XK - .5
 0054                GO TO 125
 0055            121 IF(YSCALE*XK .GT. YMIN) GO TO 122
 0056                XK = XK+ 5.0
 0057                GO TO 121
 0058            122 IYMIN = DELY*(XK-5.0)
 0059            125 CONTINUE
              C
              C
              C         NOW RE-ESTABLISH XMIN, YMIN AS THE LEFT HAND CORNER OF THE
              C      GRID.
              C
              C
              C
 0060                 XMIN = IXMIN*10.**IXFNT
 0061                 YMIN = IYMIN*10.0**IYPNT
              C*     PRINT 1234, XMIN, YMIN, DELX, DELY, IDELX, IDELY, IXMIN, IYMIN
 0062           1234 FORMAT(1X, 4F15.4,4I10)
              C         NOW PREPARE TO DRAW A YAXIS AT JXX ON THE X- AXIS
              C
 0063                JXX = (-IXMIN/IDELX)+1
 0064                IF(JXX .LE. 1 .OR. JXX .GE. 121) GO TO 7
 0065                DO 6 K = 1,41
 0066                PLOT(K,JXX) = PLUS
```

```
              6 CONTINUE
              7 CONTINUE
                JYY = 42-(-IYMIN/IDELY +1)
                IF(JYY .LE. 1 .OR. JYY .GE. 41) GO TO 8
                DO 70 K =1,121
                PLOT(JYY,K) = PLUS
             70 CONTINUE
              8 CONTINUE
                XSCAL = IDELX*10.**IXPNT
                YSCAL = IDELY*10.**IYPNT
                LO = 1
                LHI = 0
                DO 15 K = 1,20
                IF(ISYM(K) .EQ. 0) GO TO 16
                LHI = ISYM(K) + LHI
                DO 10 J = LO,LHI
                JXX = (XDATA(J)-XMIN)/XSCAL +  1.5
                JYY = (YDATA(J) - YMIN)/YSCAL +  1.5
                IYY = 42 - JYY
                IF(IYY .LT. 1 .OR. IYY .GT. 41) GO TO 10
                IF (JXX .LT. 1 .OR. JXX .GT. 121) GO TO 10
                PLOT(IYY,JXX) = SYMBOL(K)
             10 CONTINUE
                LO = LHI + 1
             15 CONTINUE
             16 CONTINUE
                DO 21 I=1,13
                XAXIS(I) = IXMIN +(I-1)*10*IDELX
             21 CONTINUE
                DO 22 J = 1,41,5
                K = 42-J
                YAXIS(K) = IYMIN+(J-1)*IDELY
             22 CONTINUE
             25 WRITE(6,2000) IYPNT,IXPNT
           2000 FORMAT(1H1,  50X,11HYSCALE=10**,I2,5X,11HXSCALE=10**,I2,///)
                DO 30 J = 1,41,5
                K = J+1
                L = J+4
                WRITE(6,2005) YLAB(J),YAXIS(J),(PLOT(J,I), I=1,121)
           2005 FORMAT(1X,A1,F10.0,121A1)
                IF(J .EQ. 41) GO TO 30
                DO 29 M = K,L
                WRITE(6,2010) YLAB(M),(PLOT(M,I),I=1,121)
           2010 FORMAT(1X,A1,10X,121A1)
             29 CONTINUE
             30 CONTINUE
                WRITE(6,1010) XAXIS
           1010 FORMAT(/3X,13(F10.0)/)
                WRITE(6,1015) XLAB
           1015 FORMAT (30A4)
                RETURN
            200 WRITE(6,1050)
           1050 FORMAT('   PLOT DIAGNOSTIC **** PLOTTER ORIGIN AT SYSTEM MAXIMUM
               * *** CHECK INPUT TO PLOT.')
                RETURN
                END
```

```
FORTRAN IV G LEVEL  20                    NORMAL              DATE = 73005          09/21

 0001               SUBROUTINE NORMAL (XN,IPNT)
 0002               K = 0
 0003               XIN = XN
 0004             1 IF(ABS(XN) .LT. 1.0) GO TO 10
 0005               IF(ABS(XN) .GE. 10.0) GO TO 20
              C
              C
              C    FALL THROUGH IMPLIES 1.0 .LE. ABS(XN) .LT. 10.0
 0006               IPNT = -K
 0007               IF(K .EQ. -0) IPNT=0
 0008               RETURN
 0009            10 K = K+1
 0010               XN = 10.0**K*XIN
 0011               GO TO 1
 0012            20 K = K-1
 0013               XN = 10.0**K*XIN
 0014               GO TO 1
 0015               END
```

```
FORTRAN IV G LEVEL  20                    AXSCAL              DATE = 73005            09/21/

                      SUBROUTINE AXSCAL(X)
                      IF( 8.0 .LT. X .AND. X.LT.10.0) X=10.0
                      IF(6.0.LT.X.AND. X.LT. 8.0) X= 8.0
                      IF(5.0 .LT. X .AND. X.LT. 6.0) X=6.0
                      IF(4.0 .LT.X .AND. X .LT. 5.0) X=5.0
                      IF(2.0 .LT. X .AND. X.LT.4.0) X= 4.0
                      IF(X.LT. 2.0) X=2.0
                      RETURN
                      END
```

```
      SUBROUTINE GRID
      COMMON IPRNT(5)
      COMMON YLAB(41),XLAB(30), PLAB(41)
      COMMON PLOT(41,121)
      COMMON ISYM(21)
      COMMON XAXIS(13),YAXIS(41)
      DATA BLANK/1H /
      DATA PLUS/1H+/
      DO 5 I = 1,41
      DO 5 J = 2,120
      PLOT(I,J)= BLANK
    5 CONTINUE
      DO 16 J = 1,41,5
      K = 42 - J
      DO 15 I = 1,121,5
      PLOT(K,I) = PLUS
   15 CONTINUE
   16 CONTINUE
      DO 18 I = 1,41
      PLOT(I,1) = PLUS
      PLOT(I,121) = PLUS
   18 CONTINUE
C     INSERT GRID
      RETURN
      END
```

```
0001               SUBROUTINE PLOTR
0002               COMMON IPRNT(5)
0003               COMMON YLAB(41),XLAB(30), PLAB(41)
0004               COMMON PLOT(41,121)
0005               COMMON ISYM(21)
0006               COMMON XAXIS(13),YAXIS(41)
0007               COMMON /PLOTS/ DUMM,TPLOT,NPT, NPP, TEMDAT(200, 25,1),TIMPDT(400),
                  1         PDAT(400), TIMDAT(200), NRAD, NP
0008               COMMON/MODIFY/ HEATX(30,10,6), TEMPX(30,10,6), ANG(30), TIMET(10),
                  1 TILT,PITCH,NX
0009               COMMON  /GENRL/ DELX,                    CPTNK, EI, EFIRE, FKS,
                  1 RHOTNK, CD, DELTA, HF1, MTOT, NEL, PR, THICK, RTANK, PRL, [illegible],
                  2 TLENTH,TDCMP,               CINS1, CINS2, TEM1, TEM2, LAGTH1,
                  3 LAGTH2, FK1, FK2
             C*
             C*       NOTE THAT NX MUST BE 1 FOR COMPATIBILITY WITH SIZE OF TEMDAT
             C*
0010               NX= 1
0011               DO 20 M=1,NX
0012               ISYM(1) = NPT
0013               ISYM(2) = 0
             C*
             C*
             C*           SINGLE PLOTS ONLY REQUIRED
0014               DO 10 L=1,NP
0015               CALL PLOTTR(TIMDAT,TEMDAT(1,L,M),NPT)
0016               LEVEL= 1+ NRAD*(L-1)
0017               WRITE(6,1000) M, LEVEL
0018          1000 FORMAT(//10X,'AXIAL STATION NO. ',I5,10X,'CIRCUMFERENTIAL STATION
                  *NO.',I5)
0019            10 CONTINUE
0020               PRINT 6666,(N,TIMDAT(N),TEMDAT(N ,L,M),N=1,NPT)
0021          6666 FORMAT(1X,I5,2F10.3)
0022            20 CONTINUE
             C*
             C*      NOW PLOT PRESSURES
             C*
0023               ISYM(1) = NPP
0024               DO 30 I=1,41
0025            30 YLAB(I)= PLAB(I)
0026               CALL PLOTTR(TIMPDT,PDAT,NPP)
0027               RETURN
0028               END
```