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3/17/65

b
A STUDY OF CONTROL SYSTEM DESIGN
AND HARDWARE SELECTION BY COMPUTER

A THESIS
Presented to
The Faculty of the Graduate Division
by
Baxter Lee Thorman

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Mechanical Engineering

Georgia Institute of Technology
November, 1965
A STUDY OF CONTROL SYSTEM DESIGN

AND HARDWARE SELECTION BY COMPUTER

Approved:

[Signature]

Date approved by Chairman: May 10, 1966
The author would like to express his gratitude to all those who have contributed to the completion of this study. Dr. Eugene Harrison, of the School of Mechanical Engineering, the faculty advisor, provided the problem and guidance throughout the study. Appreciation is extended to Dr. G. P. Francis, of the School of Mechanical Engineering, and Dr. R. P. Webb, of the School of Electrical Engineering, for their critical review and service on the reading committee, to Mr. J. E. Jones and Mr. V. S. Robyn of Honeywell, Incorporated for their unlimited cooperation in the furnishing of information on Honeywell components, and to Mr. Frank Speckhart for his aid in setting up the numerical integration procedure used in this study. Finally, the author would like to express his gratitude to his wife, without whose programming aid and moral support this work would not have been possible.
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SUMMARY

The objective of the reported study was to determine the feasibility of writing a digital computer program which will, given certain required parameters, select control system components, compute system cost, and analyze system performance with the selected hardware. This objective was achieved by writing a computer program which met the above requirements and comparing its cost (development cost plus cost per run) with the cost of a conventional design of the same control system. The term "conventional" refers to a method whereby the engineer achieves the system design using tabulated data and past experience. The control system selected for this study was a tank liquid level control system.

It was found that even if program development costs were neglected, some computer designs would cost more than equivalent conventional designs, depending on the amount of required run time (the time needed to determine the response of the control system). This result is brought about because the cost per unit run time on the computer is greater than ten times the cost per unit run time for the conventional design method.

If an experienced programmer had been assigned to develop the program, it is estimated that the development cost would be approximately $4,580. This cost is made up of two components, a cost corresponding to a programming time of 500 hours and a cost corresponding to a computer time of 250 minutes.
Because the computer design method cannot compete with the conventional design method on a cost per design basis and because of the high program development cost required, it is felt that computer design of liquid level control systems using a digital computer program of the type developed for this study is not economically feasible.

Even if the results of this study had indicated that a design program of this nature would be slightly profitable, the wisdom of putting such a program into production would be questionable, because of the conservatism of the customers who buy this type of control system.

Three possible means of reducing the required computer time are discussed. The first deals with the selection of a faster numerical integration method, the second is concerned with the use of analog computational units for determining the system response curve, and the third suggests the possibility of using approximate flow equations.
<table>
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<th>Description</th>
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<td>A₁</td>
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</tr>
<tr>
<td>A₃</td>
<td>Internal cross sectional area of pipe at D₃</td>
</tr>
<tr>
<td>A₈</td>
<td>Tank cross sectional area</td>
</tr>
<tr>
<td>CR</td>
<td>Control range</td>
</tr>
<tr>
<td>CV</td>
<td>Valve size coefficient</td>
</tr>
<tr>
<td>CVI</td>
<td>Inlet valve size coefficient</td>
</tr>
<tr>
<td>CVO</td>
<td>Outlet valve size coefficient</td>
</tr>
<tr>
<td>Cost&lt;sub&gt;c.d.&lt;/sub&gt;</td>
<td>Cost of computer design</td>
</tr>
<tr>
<td>Cost&lt;sub&gt;m.d.&lt;/sub&gt;</td>
<td>Cost of manual design</td>
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<tr>
<td>d</td>
<td>Nominal pipe diameter</td>
</tr>
<tr>
<td>D</td>
<td>Inside diameter of pipe</td>
</tr>
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<td>D₁</td>
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<td>D₃</td>
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<td>See Figure 1</td>
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<td>E</td>
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<tr>
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<td>External force</td>
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<td>F&lt;sub&gt;f&lt;/sub&gt;</td>
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<tr>
<td>F₂</td>
<td>Friction factor—L₂ section of pipe</td>
</tr>
<tr>
<td>F₃</td>
<td>Friction factor—L₃ section of pipe</td>
</tr>
<tr>
<td>F₄</td>
<td>Friction factor—L₄ section of pipe</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration due to gravity</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$g_c$</td>
<td>Gravitational constant</td>
</tr>
<tr>
<td>G</td>
<td>Specific weight</td>
</tr>
<tr>
<td>$h_f$</td>
<td>Head loss due to friction</td>
</tr>
<tr>
<td>$H_i$</td>
<td>Initial value of head</td>
</tr>
<tr>
<td>$H$</td>
<td>Head of liquid in tank</td>
</tr>
<tr>
<td>$H_l$</td>
<td>Required head</td>
</tr>
<tr>
<td>$H_2$</td>
<td>See Figure 1</td>
</tr>
<tr>
<td>$H_3$</td>
<td>See Figure 1</td>
</tr>
<tr>
<td>$K_1$</td>
<td>Constant $0.04$/sec.</td>
</tr>
<tr>
<td>$K_2$</td>
<td>Constant whose value is a function of the system type</td>
</tr>
<tr>
<td>$K_3$</td>
<td>Constant—Cost per second for keeping an engineer in the field</td>
</tr>
<tr>
<td>$K_4$</td>
<td>Constant whose value depends on the system type</td>
</tr>
<tr>
<td>$K_{10}$</td>
<td>Ratio of flow through inlet control valve to maximum flow through the same control valve</td>
</tr>
<tr>
<td>$K_{20}$</td>
<td>Ratio of flow through outlet control valve to maximum flow through the same control valve</td>
</tr>
<tr>
<td>L</td>
<td>Pipe length</td>
</tr>
<tr>
<td>$L_1$</td>
<td>Tank height</td>
</tr>
<tr>
<td>$L_2$</td>
<td></td>
</tr>
<tr>
<td>$L_3$</td>
<td>Equivalent pipe lengths (See Figure 1)</td>
</tr>
<tr>
<td>$L_4$</td>
<td></td>
</tr>
<tr>
<td>$L_5$</td>
<td></td>
</tr>
<tr>
<td>$L_{2T}$</td>
<td></td>
</tr>
<tr>
<td>$L_{3T}$</td>
<td></td>
</tr>
<tr>
<td>$L_{4T}$</td>
<td></td>
</tr>
<tr>
<td>$L_{5T}$</td>
<td>True pipe lengths</td>
</tr>
</tbody>
</table>
M  Mass of fluid in pipe
N  Number of moles of gas
P  Control pressure
P0  See Figure 1
P00  Initial tank charging pressure
P1  
P2  
P3  See Figure 1
P4  
P5  
P6  
P7  
P13  Constant pressure above liquid in tank
PB  Proportional band
P_m  See Figure 10
P_m  See Figure 10
Q  Flow rate
QI  Flow rate into tank
QM  Maximum flow rate
Qo  Flow rate from tank
QOT  Quick opening time
r  Radius of pipe bend
R  Valve rangeability
Re  Reynolds number
Ro  Universal gas content
RR  Repeat rate
S.G.  Specific gravity
T   Time
TI  Initial temperature
T1  Time interval
T7  Temperature at D7 section
TRR Required rise time
U   Fluid viscosity
Vl  See Figure 9
V   Velocity of fluid in pipe
Vm  Motor voltage
Vo  Tank volume
Vo1 Initial tank volume
Vr  Liquid velocity in control volume
w   Fluid specific weight
w_w Specific weight of water
x   Position of valve stem
X   Maximum position of valve stem
ΔH See Figure 8
ΔP Pressure drop across the control valve
ρr  Density of liquid in region R
ρs  Density of liquid at surface S
CHAPTER I

INTRODUCTION

The object of the study described in this thesis is to determine the feasibility of writing a digital computer program which will, given certain required parameters such as maximum allowable rise time, maximum overshoot, maximum settling time, and maximum allowable steady state error, select system components for a control system with a known block diagram, compute system cost, and analyze the system performance with the selected hardware.

Since the inception of modern high speed digital computers, attempts have been made to apply them to various engineering design problems. Computer programs have been written for finding thermal stresses in piping, for calculating pressure drops in piping systems, for calculating stresses in structures, and for calculating power plant heat balances.

In every case listed above, the digital computer was ideally suited to the problem because of the large number of repetitive calculations required for solution.

Recently, attempts have been made to enlarge the field of computer applications. The IBM "COMMEND" program is one such attempt (1). This program attacks design problems previously done by graphical or experimental methods, and short duration calculations performed occasionally by an engineer. The following mechanical design areas are included in
COMMEND I: kinematic synthesis, kinematic analysis, component design, physical properties calculations, dynamic analysis, detail drawings, numerical control machining instructions, and engineering information retrieval.

The computer-aided design project at the Massachusetts Institute of Technology is an example of work in another area of computer application (2). This effort centers around the use of a light pen and a cathode-ray oscilloscope. With this concept, the engineer draws his design on the oscilloscope and the computer analyzes the design almost concurrently.

During and after World War II, tremendous advances in automatic control design theory took place. Control design changed from an art to a science with the increased application of the mathematical approach to control problems.

The use of both analog and digital computers for determining the time response of automatic control systems is common today (3). Gain settings which will give the required system response are the end product of most present computer solutions. Most of these programs require frequent communication between the computer and the engineer during the design process. If the control system is to be made up of purchased hardware, as is often the case in process control work, the designer must still select components with the required parameters from various catalogs.

The objective of this study, outlined in the first paragraph of this section, will be achieved by writing a program meeting the above requirements and comparing its cost (computer cost plus programming
cost) with an estimated cost for a conventional design. This cost comparison must be augmented by consideration of the ability of the two methods to accomplish the design.

Some of the information obtained from the specific control system design study above can be extrapolated to provide information on the feasibility of computer-aided control system design in general.
CHAPTER II

PROCEDURE USED IN FEASIBILITY STUDY

Comparison Method

One method of studying the feasibility of control system design by digital computer would involve selecting a control system, writing a computer program capable of carrying out the specified design, determining the total cost (program development cost plus cost per run) and comparing this cost to an estimated cost for a conventional design of the same system. This was the method used in the reported study.

Assumptions

The above comparison method makes the following assumptions:

1. The control system requires design methods of sufficient complexity to warrant computer solution.

2. The results of the conventional design and the computer design are equivalent.

3. There is no advantage of one design method over the other that cannot be evaluated numerically.

Control System Considerations

Any control system that is eligible for complete design by computer must meet several requirements. The block diagrams for the various configurations of the system must be fairly well standardized.
The subject study is concerned with control systems having known block diagrams. The design consists of finding the right components and the correct gain adjustments, if applicable, for those components. As long as the forms of the block diagrams are known, several different forms can be tried sequentially until an acceptable design is found. No component design will be required. The dynamic equations representing the plant and the control system must be available. Finally, there must be a systematic procedure available for determining the required gain settings.

A partial list of systems for possible use in this study was compiled from the literature. This list is given in Table 1.

Table 1. Systems Considered for Study

<table>
<thead>
<tr>
<th>PROCESS</th>
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<tbody>
<tr>
<td>Distillate Column Control</td>
<td></td>
</tr>
<tr>
<td>Exothermic Reactor Temperature Control</td>
<td></td>
</tr>
<tr>
<td>Liquid Level Control</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SERVOMECHANISM</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Position Control</td>
<td></td>
</tr>
<tr>
<td>Speed Control</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>POWER GENERATION</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Combustion Control</td>
<td></td>
</tr>
<tr>
<td>Feedwater Flow Control</td>
<td></td>
</tr>
<tr>
<td>Superheater and Reheater Temperature Control</td>
<td></td>
</tr>
<tr>
<td>Air Heater Temperature Control</td>
<td></td>
</tr>
</tbody>
</table>

It was felt that the control system for this study should be selected from the industrial controls field rather than the military
or aerospace areas, primarily because of the larger market for industrial control systems. Other considerations included the special design requirements connected with most military applications and the uncertainty of the military market.

The power generation control systems and the distillate column control listed in Table 1 were eliminated from consideration in the study because of the lack of usable information on dynamic equations describing the systems and due to the general complexity of the systems. Position and speed controls were eliminated because no complete listing of components was available. A tremendous amount of research would have been required to compile such a list. The exothermic reactor temperature control system was given considerable serious thought, but was eliminated on the basis of discussions with local consulting engineers and representatives of control system component manufacturers. These discussions indicated that the market for exothermic reactor controls was fairly small.

These considerations resulted in the selection of the tank liquid level control system as the system to be used in this study. Liquid level control systems find application where a constant liquid level or head is required. They are widely used in the textile, chemical, petroleum, food, and metals industries. Because liquid level control systems are so widely used, it was felt that there might be enough demand for new liquid level control systems to warrant development of a computer program specifically for their design.

Level control systems require varying degrees of design sophistication. Level tolerances in industry range from fractions of an inch
to several feet. Therefore, component and system costs will vary widely. Overdesign of the system can be fairly expensive.

Another reason for the selection of the liquid level control system was the availability of the dynamic equations representing the response of the system components. Campbell (4), Buckley (5), and Eckman (6) concern themselves to varying degrees with liquid level control.

The amount of available information on components was another factor in the selection of the liquid level control system. One of the key components of a liquid level control system is the control valve; and most valve manufacturers supply publications on the characteristics of their particular product line. Another source is a paper by Forman and Oriolo (7) which contains a large amount of information on control valves.
CHAPTER III

COMPUTER PROGRAM DESCRIPTION

General Description

From a list of available components, the computer program written for this study selects the two most economical sets of components that will meet the given response requirements. This is accomplished by determining a trial CV (valve size coefficient) on the basis of the initial flow into the tank, setting the gain adjustments to predetermined values, and plotting a trial response curve. If the resulting response curve does not meet the design criteria satisfactorily, the trial system is adjusted, either by changing component gains or by changing the type of component used, and the data for the response curve is calculated again. If the response curve is satisfactory, control valves, level sensors, and controllers with approximately the same characteristics as those which resulted in the acceptable response curve found above are selected from a list of components stored on a tape. The characteristics of the two most economical sets of selected components are used in the response curve calculations to verify the acceptability of the resulting control system and, if the system is acceptable, cost, component ordering information, and gain settings are printed as the program output.

If one or both of the two selected sets of components fail to achieve the required response curve characteristics, gain adjustments
are made if possible, or the system or systems are discarded and other sets of components are selected. If no components with the required characteristics are available, a message to that effect is printed, and work on the program stops.

The program simulates the types of control systems available (low cost proportional, general proportional, and proportional plus integral) in order of increasing cost. The first control system to be simulated (the low cost proportional system) requires a proportional band setting of 30 per cent. If the response curve corresponding to a representative low cost system is acceptable, the two most economical sets of hardware that are compatible with the low cost system are selected, and the response curves are run again to verify the acceptability of the two resulting low cost proportional control systems. If the low cost proportional system is not acceptable, the general proportional system (proportional band equal five per cent) is simulated and, if its response is adequate, two sets of components compatible with the general proportional control system are selected. The same procedure is used for the proportional plus integral control systems. In every case, after the response of a representative of one of the three types of control systems is acceptable, the two most economical sets of hardware (control valve, level sensor, and controller) compatible with that type control system are selected and checked in the response calculations. The coordinates of the response curves can be printed if desired.

Component Information

Honeywell components were used exclusively throughout the study.
as it was felt that program capability could be demonstrated adequately with only one manufacturer's components.

The following types of control valves are listed on the tape used with the program: angle, double seated, single seated, low flow, Saunders, split body, and cage. Two types of pneumatic actuators and one type of electric actuator are listed. The valve size range covered in the program is from three-fourths to four inches nominal diameter. Foreman (8) states that 96 per cent of all valves used in general chemical or petrochemical facilities are four inches or under. The same reference indicates that butterfly valves are not generally used in sizes less than four inches and none was considered in the study.

A positioner is sometimes used in connection with a valve actuator if the static friction forces which result when the valve is opened are large or when the actuator response is too slow. Basically, the positioner is a form of pilot valve. When a positioner is used, the control air pressure is not applied to the actuator diaphragm as it is when no positioner is used, but is used to vary a nozzle opening which controls the flow of supply air (at pressures of 20 to 100 psig) to the actuator diaphragm. A feedback linkage is required to re-position the flapper when the valve opening corresponding to the input pressure is reached.

Forman also states that positioners are used on all four inch and larger control valves. Therefore, the devised program was set up so that selection of a four inch valve automatically calls for the use of a positioner. Saunders valves used in throttling service require the use of a positioner on all sizes, and the program provides these posi-
tioners automatically. All valves fail shut.

Information on 81 full capacity and reduced capacity v-port and quick-opening control valves is stored on the tape.

Based on the Corrosion Table on pages 74 and 75 of reference (9), 161 possible flowing mediums can be handled by this program. A "Proceed with Caution" message can be seen on the program output (page 16 of this study) after the body material entry of the first system selected in the first example included in this study. Certain combinations of flowing fluids and body materials will cause this message to be printed. The "Proceed with Caution" message indicates that corrosion will result with this combination of fluid and body material, but that it is not dangerously rapid.

Cast iron, bronze, cast steel, and 316 stainless steel are the available body materials for valves included in the study. Available trim materials are stellite, 440C stainless steel, Hastelloy B and Hastelloy C, Durimet 20, Monel, and 316 stainless steel. Radiating fin, bellows seal, and extension column bonnets can be selected by this program.

Honeywell offers a wide range of level sensors, controllers, and displacer-controller combinations. Four types of displacer-controller combinations are available. Since the major difference in these four types of displacer-controllers is the method of mounting, only one type, the top mounted Series 1 unit was included on the component tape. Slight price increases must be added to the cost listed on the program output if one of the more expensive displacer-controllers is desired. Other types of level sensors included are static pressure sensors and a differential pressure-to-current transmitter.
Controllers with three types of control action are included in this study. These three types are on-off, proportional, and proportional plus integral.

The on-off controller, which is the least expensive of the three types, can only maintain a liquid level between two points; it cannot hold a given level. Furthermore, the on-off system must be used with an electrically conductive flowing medium.

The proportional systems used in the study can be divided into two types; a type in which a general controller is used which has an infinite number of gain settings, and a type called the low cost system. Two low cost systems are available from Honeywell: System A and System B. System A is made up of a static pressure transmitter, a positioner-controller which mounts on the control valve actuator, and the control valve. Only control valves with Honeywell 05 actuators can be used in System A. Three possible proportional band settings are available with System A. The value of these three settings is determined by the control valve travel. System B is slightly higher in price than System A, and is made up of a static pressure transmitter, a controller which mounts on the static pressure transmitter, and the control valve. Any Honeywell valve can be used in System B, but only three proportional band settings (30, 50, and 100 per cent) are available.

The most sophisticated controller used in this study is the proportional plus integral controller. Proportional plus integral control is available with a displacer-controller combination (72-25, Series 1) or a general purpose two mode controller used in conjunction with a static pressure transmitter.
Since controller selection is largely a matter of individual preference after the number of control modes required is determined, no attempt was made to list all available controllers on the component tape for this feasibility study. The controller prices listed in the program must be adjusted if special controller features are desired.

Two tank configurations, Configuration One and Configuration Two are used in this study. Configuration Two (Figure 1) requires that flow out of the tank be through a discharge pipe and is the more general configuration. Configuration One, which requires that flow out be from the top of the tank, would be used in a dipping or dyeing process in which material is placed in the tank. When this material leaves the tank, some of the liquid in the tank is removed with it.

The complete computer program is given in Appendix F.

Program Results for Two Examples

Input information and program results are given below for two examples.

Example One

It is desired to design a system having the following known physical characteristics. Configuration Two was selected because it illustrates more of the program capabilities. The tank used is a 125-lb., vented tank. Water is to be the system fluid, pneumatic control is desired, and a full capacity valve is needed. For the location of the following variables, see Figure 1.
Figure 1. Diagram of Configuration Two.
Pressures—psia
P0  15
P1  30
P7  17.25

Temperatures—F
T7  80

Dimensions—Inches
D1  4.0
D3  4.0
DV3 4.0
D8  36.0
H3  12.0
L1  200.0
L2T 150.0
L3T 100.0
L4T 100.0
L5T 150.0

Outlet Valve Size Coefficient—Inches⁴/Lb. Seconds
CVO  654

Pipe Roughness—Inches
E  0.00085

Fluid Characteristics

\[
\begin{align*}
U & = 1 \times 10^{-7} \text{lb sec/in}^2 \\
G & = 0.036 \text{ lb/in}^3
\end{align*}
\]

The following fittings are included in the indicated pipe sections:

L2 section—1 conventional swing check valve
L3 section—1 conventional disc gate valve, 2-90° pipe bends
(r/d = 4.0)
L4 section—1 in-line ball check valve
L5 section—1 conventional disc gate valve

This system is to meet the following criteria if the required head
H1 is changed by a step change from 100 inches to 125 inches with the
outlet valve fully opened, \((K20 = 1.00)\).

- Required rise time: 45 sec.
- Maximum overshoot: 2.0 in.
- Maximum settling time: 100 sec.
- Maximum steady state error: 0.500 in.

The initial conditions are:

\[
\begin{align*}
Q_I &= 768 \text{ in}^3/\text{sec.} \\
Q_0 &= 768 \text{ in}^3/\text{sec.} \\
H &= 100 \text{ in.} \\
X_T &= 0.82 \\
H_1 &= 125 \text{ in.}
\end{align*}
\]

The program output (excluding response curve points) for Example One is given below.

Proportional Band = 0.05

<table>
<thead>
<tr>
<th>System</th>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>ONE</td>
<td>Type 72-25 Series 1</td>
<td>$260.00</td>
</tr>
<tr>
<td></td>
<td>Valve Model No. 1101</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Size 3.00 in.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Type double seated</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CV 112.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Actuator No. 13</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Body Material cast iron</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Proceed with caution)</td>
<td></td>
</tr>
<tr>
<td>System</td>
<td>Component</td>
<td>Cost</td>
</tr>
<tr>
<td>---------------</td>
<td>------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>ONE (Continued)</td>
<td>Body rating 125 lb.</td>
<td>$326.00</td>
</tr>
<tr>
<td></td>
<td>(Flanged end)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plain bonnet</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trim material 316 S.S.</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>TOTAL COST $586.00</td>
<td></td>
</tr>
<tr>
<td>TWO</td>
<td>Type 72-25 Series 1</td>
<td>$260.00</td>
</tr>
<tr>
<td></td>
<td>Valve Model No. 1001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Size 3.00 in.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Type Angle</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CV 115.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Actuator No. 13</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Body Material 316 S.S.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Body Rating 150 lb.</td>
<td>914.00</td>
</tr>
<tr>
<td></td>
<td>(Flanged end)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plain bonnet</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trim material 316 S.S.</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>TOTAL COST $1,174.00</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2 shows plots of level versus time for a low cost system and the first of the systems selected by the program, a 72-25 Series 1 system using a Model 1101, three inch, double seated control valve.
Figure 2. Plot of Level Versus Time for a Low Cost System and a 72-25, Series 1 System.
The low cost system was eliminated by the program because it did not meet the settling time requirement. Inspection of Figure 2 indicates that the low cost system does meet this requirement if it is defined as the time required for the response to stay within a band, centered on the desired level, whose width equals 10 per cent of the initial error. The problem is caused by the fact that the program is set up so initiation of the settling time check must wait until the overshoot check is completed. Because of the response sluggishness caused by the high proportional band requirement for the low cost system, the overshoot check consumed so much time that the maximum allowable settling time was exceeded. It is felt that the program method of checking settling time is acceptable for program demonstration, but, for production use, the program should be changed to allow the overshoot and the settling time checks to run concurrently.

Had the low cost system been selected, an example of the program output would appear as shown below.

Proportional Band = 0.30

<table>
<thead>
<tr>
<th>System</th>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>ONE</td>
<td>System B</td>
<td>$147.00</td>
</tr>
<tr>
<td></td>
<td>Valve Model No. 1101</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Size 3.00 in.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Type double seated</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CV 112.00</td>
<td></td>
</tr>
</tbody>
</table>
System Component | Cost
--- | ---
Actuator No. 13 | 
Body Material cast iron | 
(Proceed with Caution) | 
Body Rating 125 lb. | $326.00 | 
( Flanged end) | 
Plain Bonnet | 
Trim Material 316 S.S. | 0 | 
TOTAL COST | $473.00

Figure 2 clearly illustrates the effect of CV and proportional band on the system response. The level of the low cost system, with a CV of 485.80 rises faster than that of the 72-25 system which used a CV of 431.00. Because of its smaller proportional band, 0.05 versus 0.30, the 72-25 system reached its final position much faster. Figure 2 shows that the larger the proportional band used, the more sluggish is the resulting response.

Example Two

It is desired to design a system having the same physical characteristics, initial conditions, desired level change, required rise time, overshoot, and settling time. However, the allowable steady state error is now 0.07 inches.

The program output is given below.
Proportional Band = 0.05  
Repeat Rate = 0.50

<table>
<thead>
<tr>
<th>System</th>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>ONE</td>
<td>Type 72-25 Series 1</td>
<td>$ 285.00</td>
</tr>
<tr>
<td></td>
<td>Valve Model No. 1101</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Size 3.00 in.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Type double seated</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CV 112.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Actuator No. 13</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Body Material cast iron</td>
<td>(Proceed with caution)</td>
</tr>
<tr>
<td></td>
<td>Body Rating 125 lb.</td>
<td>326.00</td>
</tr>
<tr>
<td></td>
<td>Body Rating 150 lb.</td>
<td>914.00</td>
</tr>
<tr>
<td></td>
<td>Body Rating 150 lb.</td>
<td>914.00</td>
</tr>
<tr>
<td></td>
<td>Trim Material 316 S.S.</td>
<td>0</td>
</tr>
</tbody>
</table>

TOTAL COST $ 611.00

| TWO    | Type 72-25 Series 1 | $ 285.00  |
|        | Valve Model No. 1001 |          |
|        | Size 3.00 in. |            |
|        | Type Angle |            |
|        | CV 115.00    |            |
|        | Actuator No. 13 | 0         |
|        | Body Material 316 S.S. |          |

TOTAL COST $ 611.00
Plots of level versus time for a proportional system and for the first proportional plus integral system selected by the program are given in Figure 3, which indicates that the addition of the integral mode makes the transient response less stable (the curve is now oscillatory) but it forces the steady state error to approach zero. As in Example One, the difference in slopes during the transient response for the two systems is caused by a difference in the CV used.
Overshoot O.K.  
Settling Time O.K.  
Proportional
Proportional Plus Integral

Proportional ESS = 0.08 in.
Proportional Plus Integral ESS < 0.07 in.

Figure 3. Plot of Level Versus Time for a Proportional System and for the First Proportional Plus Integral System Selected by the Program.
CHAPTER IV

RESULTS OF THE COMPARISON OF COST FOR THE TWO DESIGN METHODS

Neglecting development cost and any costs common to both conventional and computer designs, the cost per design completed on the computer and the cost per conventional design are made up of two quantities.

**Computer Design Cost Considerations**

The computer design cost consists of a constant cost which covers compilation time, component selection time, input time, and any other miscellaneous times that can be considered constant for all runs, and a variable cost which is a function of the type system used and the time required to test the system response on the computer. For this program, the constant time was found to be approximately 170 seconds.

The variable cost was determined as follows: The cost of problem time on the Burrough's B5500 computer was taken as $0.04 per problem second. This cost was obtained by dividing the computer cost per hour by 3600 since one problem second took approximately one real time second.

The present program requires that the system response curve coordinates be calculated several times. The number of times that the curve must be determined is a function of the type system necessary to meet the design requirements since the program always tries the different types of control systems in order of increasing cost.
Three calculations of the response curve are required if the low cost proportional system can be used; one general plot which determines the applicability of a representative low cost system, and one run through the response curve for each of the two low cost systems (sets of hardware) selected.

If the low cost system cannot meet any one of the required design criteria, a general proportional control system is simulated. If this general proportional system will satisfy the design criteria, the system response curve will have to be calculated four times; once for the low cost system which could not meet the design criteria, once for the general proportional system, and once for each of the specific sets of proportional system components selected by the program.

In both cases above, no time need be required for setting system gains. The response curve for most practical systems having proportional control is exponential and there is no problem with stability. The proportional band is set at a predetermined minimum and no further adjustment is possible. Gain adjustment is necessary only when simulating a proportional plus integral control system.

Finally, if a proportional plus integral system is required, and it is assumed that the system gains can be adjusted in two trials, seven plots of the system response curves are required. The first checks the response of the low cost proportional system, which is not acceptable. The second calculation of the response curve coordinates is made for a general proportional system which is also not acceptable. The third, fourth, and fifth determinations of the system's response are required to test a general proportional plus integral control system.
and to adjust its gains, and the sixth and seventh runs are made with
the specific sets of components to be used in the final systems.

It is assumed that the person in charge of installation of the
equipment can make the gain settings at the time of installation, since
these gains are given on the computer output. If this is true, very
little design time is required for tuning the system in the field.

The length of time required per run is assumed to be $M$, an
arbitrary constant found in the program by multiplying the required
rise time by four. Although the program is set up so that run time
does not reach $M$ in all cases because calculation of the response curve
points is stopped when the design requirements are met, no estimate of
the shorter time is possible and $M$ must be used. This fact will result
in calculated computer design costs slightly higher than true computer
design costs.

Mathematically, the above information can be expressed by the
following equation:

$$\text{Cost}_{c.d.} = K_1(\text{Constant time}) + K_1K_2M$$  \hspace{1cm} (1)

where

$M = 4(\text{TRR})$

$K_1 = \$0.04/\text{second}$

$K_2 = \begin{cases} 
3 & \text{Low cost system} \\
4 & \text{Proportional system} \\
7 & \text{Proportional plus integral system} 
\end{cases}$
Conventional Design Cost Considerations

Conventional design cost is made up of a constant component selection cost and a variable cost due to the time spent tuning the completed control system in the field.

The component selection cost was arrived at as follows: It is assumed that the designer's salary works out to $4.00 per hour, that the overhead per hour in the office is 100 per cent, and that two hours are required to complete the design using the outline given in Table 2. Therefore the constant design cost will be

\[
\text{Cost}_{c.d.} = 6.80 + 0.04 K M
\]

Table 2. Outline of Conventional Design Method for Liquid Level Control System

I. Find Maximum Flow into Tank, \( Q_1 \)
   A. Use maximum flow from tank plus safety factor
   B. Find the flow rate required to fill the tank in a specified time

II. Find Pressure Drop Across the Control Valve
   A. Assume \( \Delta P = P_1 - P_0 \) (\( P_1, P_0 \) are both known)

III. Find CV
Table 2. Outline of Conventional Design Method for Liquid Level Control System (Continued)

| A. CV = \frac{QI}{\sqrt{\frac{\Delta P}{S.G.}}}

| IV. Select Control Valves on the Basis of |
| A. CV |
| B. Body material |
| C. Trim material |
| D. Maximum allowable pressure drop across the control valve |
| E. Maximum allowable static pressure |
| F. Bonnet required |
| G. Body strength |
| H. Availability of Positioner |

| V. Select Level Sensor on the Basis of |
| A. Tank configuration |
| 1. Open |
| 2. Closed |
| B. Required control range |

| VI. Select Controller |
| A. Allowable steady state error |

System tuning cost is estimated as follows: It is assumed that the field engineer's salary is equivalent to $4.00 per hour, that the
overhead cost per hour in the field is 200 per cent of the engineer's salary, that the field engineer can tune the system in the same number of trials as used in the computer program, and that the average time required for the field engineer to travel to and from the equipment location is one hour. In contrast to the computer simulation of the control system, on-site calibration must take into consideration the time for the tank to return to its initial condition between trials. This time is taken as \( M \). Therefore, one trial takes \( M \) seconds, two trials take \( 3M \) seconds, and three trials take \( 5M \) seconds. The coefficients of \( M \) just found are called \( K_4 \) and are listed below as a function of the system used.

<table>
<thead>
<tr>
<th>System</th>
<th>( K_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low cost</td>
<td>1</td>
</tr>
<tr>
<td>Proportional</td>
<td>1</td>
</tr>
<tr>
<td>Proportional plus integral</td>
<td>5</td>
</tr>
</tbody>
</table>

The cost per second of keeping the field engineer on the job is a constant called \( K_3 \). This constant equals \((\$4.00/\text{hour})(3.0)(1/3600 \text{ sec.})\).

The above information can be summarized by the following equation for conventional design cost.
Cost_{m.d.} = $16.00 + K_3(K_4M + 3600) \quad (3)

where \( K_4 \) and \( M \) are as previously defined.

A plot of Design Cost versus \( M \) for the three types of control systems used in this study is shown in Figure 4.

**Determination of Program Development Cost**

The engineering time required for writing the computer program included here was 1041 hours. The computer time used was 495.82 minutes. It is felt that both the time required for writing the program and the computer time could be cut in half if an experienced person had done the work. This would result in a programming time of approximately 500 hours and a computer time of 250 minutes. If computer time cost $140 per hour, the engineer's salary was equivalent to $4.00 per hour, and overhead per hour is 100 per cent of the engineer's salary, the program development cost would be $4,583.

It is obvious from Figure 4 that even neglecting program development costs, using the present numerical integration technique will result in some computer designs costing more than equivalent conventional designs, since many practical systems will require run times of several hundred seconds. This is due to the fact that the cost per unit of run time (which is one component of the slope of the lines in Figure 4) for the computer design is greater than ten times the cost per unit time for the conventional design.

Since almost all of the run time is spent in performing the numerical integration necessary for solution of the system of differ-
Figure 4. Plot of Design Cost Versus Run Time.
ential equations, the use of any numerical method which requires less computer time than the Runge-Kutta method will make the computer design more competitive.

Because of the lack of clear cut savings in design cost and because of the high program development cost, any justification for computer design of tank liquid level control system must come from consideration of advantages of the computer design not available with the conventional design. That there are several of these advantages will be brought out in Chapter V. Unfortunately, it is extremely difficult to place these advantages on a numerical basis.
CHAPTER V

CONCLUSIONS

Based only on comparative values of cost per design for the two design methods, the computer design cannot compete with the conventional design if the numerical integration method in the present program is used.

This conclusion must be tempered by consideration of other information. Although a large number of levels of design sophistication are possible, all liquid level control systems can be divided into three categories. The first category contains control systems that are only required to maintain a liquid level within a fairly wide band. On-off and proportional controllers are used in this category. The second category is made up of systems that maintain the liquid level fairly accurately, say within a band of one inch or less. The third and most sophisticated of the level control design categories contains control systems for which the transient response as well as close maintenance of the required liquid level is important. Proportional and proportional plus integral controllers are used for the last two categories.

The conventional design method is much less sophisticated than the computer design method. Liquid level control systems are not considered as systems when designed conventionally. The control valve is sized on the basis of the estimated flow necessary to maintain the
desired liquid level. The assumptions of steady flow and constant CV are made.

Controller selection is made strictly on the basis of past experience. If no stand-off error is allowable, it is known that a proportional plus integral controller must be used. If some stand-off error is allowable, the applications engineer must decide whether to use a low cost proportional system, with its limited proportional band range, or a general proportional system.

The average applications engineer is not concerned with determining rise time, amount of overshoot, or settling time. He hopes that the system can be tuned to meet the desired criteria after it is installed in the field.

The computer solution considers the level control system as a system; the group of differential equations representing the control system are solved simultaneously. The control valve is sized on the basis of required rise time and the computer solution takes unsteady flow and the variation of CV with Reynolds number into consideration. The system response is simulated on the computer. Therefore, a system can be selected that will meet any reasonable rise time, overshoot, settling time, and/or steady state error requirements. Since potential systems are tested in order of increasing system cost, the customer is guaranteed that he isn’t buying more control system than he needs. Very little time is required to select gains after the system is installed, since approximate gains are obtained from the computer simulation.

Comparison of the three levels of design sophistication mentioned
earlier with the level of sophistication available from the two design methods covered here reveals that the conventional design is all that is required for the first category. Customers interested in control systems in this category are not the least bit interested in rise time and overshoot and there is generally little question about what type of controller to use. The computer design method becomes more attractive if the level of design sophistication is that of category two; not because of any need to find approximate gain settings or any interest in rise time, overshoot, or settling time, but because the computer design guarantees that the least expensive system will be selected. If there is any question at all in the applications engineer's mind about whether to use a proportional or a proportional plus integral system because of a small allowable steady-state error, he will call for a proportional plus integral controller. This is because he never knows exactly what steady-state error the proportional system will have until the system is installed. The customer would be extremely unhappy if the control system had been installed and it could not meet his steady-state error requirements. No problem like this would arise if the system were simulated on the computer. The proper controller can be selected with a high degree of accuracy. System cost for a low cost proportional system can be as much as $100 less than the cost of a proportional plus integral system.

If the level of design sophistication required corresponds to Category Three, there is no guarantee that the conventional design method will be entirely satisfactory in many cases. If the level control system is part of a large process, the prospect of tuning the
level control system after installation is not pleasant, particularly when adjusting the level control system's gains might necessitate recalibration of the rest of the process. Total system characteristics cannot be determined until the system is installed if the conventional design method is used.

There has been considerable interest generated recently about computer control of processes. Conventional design of control systems included in larger systems controlled by computer is out of the question. Accurate data on system response is necessary for the design of the computer control circuits.

It appears that computer design can only compete with conventional design if the level of sophistication required is that of Category Two or Three. Discussions with manufacturer's representatives indicate that the bulk of the liquid level control system market is in the first category. Although the demand for systems of the second and third level of design sophistication is increasing, it is felt that this demand will fall far short of the number of systems required to justify the large development cost for a program of this nature.

Reference to an on-off control system can be found throughout this study. The original study outline called for the inclusion of an on-off, a proportional, and a proportional plus integral control system in the computer program.

When an example problem using the on-off control system was introduced into the program, the Runge-Kutta method of solution of the equation representing flow into the tank required a time increment of 0.001 seconds for stability when the control valve was in the closed
position. Calculation of response curve points for any normal liquid level control system would be extremely expensive with this small time increment. Since the comparison of available levels of sophistication for the computer and the conventional design methods and the required level of design sophistication for the three categories listed above indicates that on-off control system design by computer is not feasible, it was decided to discontinue development of the on-off control section of the computer program.

Weighing these considerations with the original conclusion, that on a cost per design basis the computer design cannot compete with the conventional design, can only lead to the conclusion that computer design of liquid level control systems using a digital computer program of the type developed for this study is not economically feasible.

If the computer run time could have been reduced by a factor of ten, use of such a computer program might become feasible on a cost per run basis. Three possible methods of decreasing the time required to obtain system response are discussed in Chapter VI.

Based on the results of this study, component selection by computer for certain classes of components can be profitable. Honeywell's method of selecting components and finding their cost involves searching through two different sets of books, one listing the components and their characteristics and the other giving their cost. It is estimated that component selection for the program included in this study took approximately one minute of computer time. Equivalent manual selection would have taken approximately one hour. Only classes of components which can be selected on a logical basis would yield such savings. Con-
Control valves are excellent examples of this type of component.

Control system design by computer requires a knowledge of the process dynamic equations. The number of assumptions required in developing the flow equations for the simple system used in this study brought out the lack of basic knowledge about transient flow through valves and fittings.

A systematic method of gain adjustment must be available if the computer is to determine acceptable system response for the simulated control system without adjustment between runs by the system designer. Gain adjustment for the liquid level system used in this study was no problem, but had a control system which included a rate mode been selected, a fairly elaborate trial and error method of gain variation would have been required in the computer program.

Even if the results of this study had indicated that a design program of this nature would have been slightly profitable, it might not be a wise idea to develop such a program for production. Customers for control systems of the type used as an example in this study are extremely conservative. An interview with an instrument engineer for a local consulting engineering firm revealed that his company's policy is to never incorporate any new design features into their designs until these new features have been proven in someone else's installation. Any cost advantage due to computer design can be lost if upon completion of the design, the customer wanted to increase the control valve diameter one size to insure that he will have adequate flow capacity.

Many control systems are sold on the strength of considerations which cannot be evaluated on a numerical basis. One such consideration
is the availability of maintenance and replacement parts. The sales ability of the applications engineer and the personal preference of the customer or his representative are two large considerations since purchases in the price range of most of the control systems considered here ($1,000 or less) do not have to be justified on a comparative cost basis to management.
CHAPTER VI

RECOMMENDATIONS

It has been found (see Chapter V) that if the time required for the computer to make the calculations necessary to plot the system response curve could be cut by a factor of ten, the computer design would be competitive with the conventional design on a cost per run basis. Three alternate approaches to reducing the computer time required per design are presented here and are recommended as areas in which further profitable research might be done.

The first approach concerns using a faster numerical integration technique for the response curve determination. One candidate for this application would be the modified Euler method. If the modified Euler method were substituted for the Runge-Kutta method, and only two cycles were required per point on the curve, the computer time required would be one half that required for the Runge-Kutta method, which requires four cycles per point.

It is believed that a second approach, concerned with utilization of analog computational techniques, promises greater reductions in computer time required for control system design. In general, the digital computer is slower and more accurate than the analog computer. The value of this increased accuracy is questionable in determination of control system response in many cases. On the other hand, component selection and involved decision making is impossible on the analog
computer. These facts lead one to consider the possible applications of a hybrid digital-analog computer.

A large amount of research is now being directed toward determination of optimization methods. One approach to the determination of optimum gain settings for control systems involves trial and error methods of gain adjustment. The systematic method of gain variation used in the trial and error approach could be programmed into the digital part of a hybrid computer. The digital section would then control the gain settings of the analog part of the hybrid computer on which a large number of trial response curves could be run in a much shorter time than on a digital computer alone.

The third method of attempting to reduce the required computer time is suggested by the results of the tests of the system equations in Appendix B. It can be seen that for the chosen example and the short run time, the approximate method in which pipe friction is ignored resulted in values within 5 per cent of those found by the more rigorous computer solution. Further research could be directed toward determining the applicability of approximate expressions for fluid flow that could be solved in less computer time than the expressions used in this study.

The need for a large amount of experimental work in the field of transient fluid flow, particularly in connection with flow through valves and fittings was demonstrated by the number of assumptions required in the development of the flow equations used in this study. Several articles have been written on control valve selection, but none is satisfactory from an unsteady flow standpoint. Each of the flow assumptions mentioned above must be justified if the computer solution is to
have any practical value. The use of system engineering concepts in process work requires much stronger definitions of some of the basic flow processes than are now available.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Number of fluid as read from compatibility table on input tape</td>
</tr>
<tr>
<td>A8</td>
<td>Area of tank</td>
</tr>
<tr>
<td>CAPCTY</td>
<td>Code indicating whether capacity is full or reduced (1—full; zero—reduced)</td>
</tr>
<tr>
<td>CHANGE</td>
<td>Value of sign of ( \frac{dH}{dT} ) at ( T-\Delta T )</td>
</tr>
<tr>
<td>COMPAT</td>
<td>Number of control valves which meet system requirements</td>
</tr>
<tr>
<td>COMPONENT</td>
<td>Type of low-cost system (A or B)</td>
</tr>
<tr>
<td>CONFIG</td>
<td>Code indicating whether system is of configuration 1 or 2 (1—flow out of top of tank; 2—flow out of discharge pipe)</td>
</tr>
<tr>
<td>COST</td>
<td>Temporary storage for cost of an item used during printing</td>
</tr>
<tr>
<td>CR</td>
<td>Control range</td>
</tr>
<tr>
<td>CV1</td>
<td>Value of valve size coefficient at a given Reynolds number (inlet side)</td>
</tr>
<tr>
<td>CV3</td>
<td>Value of valve size coefficient at a given Reynolds number (outlet side)</td>
</tr>
<tr>
<td>CVCN1</td>
<td>Catalog valve size coefficient (inlet side)</td>
</tr>
<tr>
<td>CVCN3</td>
<td>Catalog valve size coefficient (outlet side)</td>
</tr>
<tr>
<td>CVMAX</td>
<td>Maximum allowable ( C_v ) of control valve</td>
</tr>
<tr>
<td>CVMIN</td>
<td>Minimum allowable ( C_v ) of control valve</td>
</tr>
<tr>
<td>CVO</td>
<td>Outlet valve size coefficient</td>
</tr>
<tr>
<td>D1</td>
<td>Pipe diameter on inlet side</td>
</tr>
<tr>
<td>D3</td>
<td>Pipe diameter on outlet side</td>
</tr>
<tr>
<td>D8</td>
<td>Diameter of circular tank</td>
</tr>
</tbody>
</table>
P  Pressure drop
DELTP1  ΔP required by system
DELT2  Time increment used in checking system response
ΔH  Desired band width x (1/2)
DH  
DIFF  HI-initial value of H
DIAP1  Parameter used in Runge-Kutta routine to represent Dl
DIAP3  Parameter used in Runge-Kutta routine to represent D3
DIAV1  Parameter used in Runge-Kutta routine to represent diameter of control valve
DIAV3  Parameter used in Runge-Kutta routine to represent diameter of valve on outlet side
DT  ΔT used in Runge-Kutta
DUM  Dummy variable used to store absolute values
DV1  Control valve diameter
DV3  Valve diameter on outlet side
DX1  Used as an index
E  A measure of pipe roughness
ESS  Allowable steady state error
EXT  Code indicating whether extension column is required or not (1—yes; zero—no)
F2  Inlet pipe friction factor
F4  Outlet pipe friction factor
FAC0
FAC1
FAC10
FAC2
FAC20  Constant factors used in Runge-Kutta routine
FAC3 \quad \text{Constant factors used in Runge-Kutta routine}

FAC30

FAC300

FAC33

FAC4\quad \text{Constant flow out}

FAC40

FAC5

FAC50

FAC6

FLOUT

FMAX \quad \text{Factor by which catalog valve size coefficient (inlet) is multiplied to get CVMAX}

FMIN \quad \text{Factor by which catalog valve size coefficient (inlet) is multiplied to get CVMIN}

G \quad \text{Specific weight of fluid}

H1 \quad \text{Desired level in tank}

H1X2 \quad H1-H(t) \text{ at a given time}

H2 \quad \text{See Figure 3}

H3 \quad \text{See Figure 3}

I \quad \text{Used as an index}

IND \quad \text{Used as an index}

INITL \quad \text{Initial value of an index used in a program loop}

IFINAL \quad \text{Final value of an index used in a program loop}

J \quad \text{Used as an index}

JL \quad \text{Used as an index}

K \quad \text{Used as an index}

KL \quad \text{Used as an index}

K20 \quad \text{Measure of degree of opening of outlet valve}

L \quad \text{Used as an index}

L1 \quad \text{Height of tank}

M \quad \text{Used as an index}
MEDM  Number of fluid desired by customer

MONEL  Code indicating whether a monel bellows seal can be used by the system (1--yes; zero--no)

N  Number of differential equations being solved in Runge-Kutta routine

NEXTV  Code indicating whether next cheapest valve is to be checked for response characteristics or not (1--yes; zero--no)

NMRTR  Storage for numerator of initial CV equation

NVALVS  Total number of valves in valve table on input tape

ONOFF  Code indicating whether system is on-off or not (1--yes; zero--no)

OP  Code indicating whether manual operator is desired or not (1--yes; zero--no)

OS  Maximum allowable overshoot

OSCK  Code indicating whether overshoot has been checked or not (1--yes; zero--no)

P  Used as a factor in Runge-Kutta routine

P0  See Figure 1

P1  See Figure 1

P1MAX  Maximum value of P1

P4MIN  Minimum value of P4

P7  See Figure 1

P8  See Figure 1

P13  Pressure for regulated tank

P15  Allowable system pressure

P30  Allowable system pressure

P40  Allowable system pressure

P60  Allowable system pressure
PB  Proportional band
PBMAX  Limit on proportional band
PLAIN  Code indicating whether plain bonnet is required or not (1—yes; zero—no)
PNEU  Code indicating whether system is pneumatic or not (1—yes; zero—no)
QI  Flow in
QO  Flow out
QOM  Maximum flow out
QOTIM  Parameter used in Runge-Kutta to represent closing time of a quick-opening valve
QOT  Quick opening time
R  Valve rangeability
   Maximum controllable flow/Minimum controllable flow
RADFIN  Code indicating whether radiating fin is required or not (1—yes; zero—no)
RD  r/d for elbows
REl  Storage for inlet pipe Reynolds number or control valve Reynolds number, depending upon whether valve has been chosen or not
RESTART  Parameter used in Runge-Kutta to indicate if next cheapest valve is to be checked for adequate response
RP1  Inlet pipe Reynolds number
RP3  Outlet pipe Reynolds number
RUNGKUTTA  Name of Runge-Kutta subroutine
RR  Integral gain, repeats per second
RV1  Control valve Reynolds number
RV3  Outlet valve Reynolds number
SAUNDERS  Code indicating whether Saunders valve is to be considered or not (1—yes; zero—no)
SEALI Code indicating whether bellows seal is required or not (1—yes; zero—no)

SETTLNG Code in Runge-Kutta indicating if settling time has been checked (1—yes; zero—no)

SLURRY Code indicating whether fluid is a slurry or not (1—yes; zero—no)

SPECIAL Code indicating whether special transducer is to be ordered or not (1—yes; zero—no)

STATIC Code indicating if static pressure sensor is desired (1—yes; zero—no)

STEEL Code indicating whether 316 stainless steel bellows seal can be used or not (1—yes; zero—no)

STOPX Code indicating whether program is to be stopped at this point (1—yes; zero—no)

SUML Sum of equivalent lengths of fittings in a length of pipe

T Accumulated time (seconds) in Runge-Kutta

T1 Time accumulated during calculation of on-off XT in Runge-Kutta

T3 Time accumulated during checking of settling time during the Runge-Kutta

T4 Time accumulated during checking of steady state error in Runge-Kutta

T7 Temperature of fluid

TANK Code indicating whether tank is vented, regulated, or trapped (1—vented; 2—regulated; 3—trapped)

TLAST Time which is equal to present time minus DT in the Runge-Kutta

TNKRATNG Tank rating

TOP Code indicating whether a manual operator is mounted in top or side position (1—top; zero—side)

TOTAL Total cost of a system in printing routine

TRO Rise time or difference between TR(2) and TR(1) in Runge-Kutta
TRR  Required rise time
TSETR  Required settling time
U  Fluid viscosity
V1  Motor voltage used computing XT for on-off system
VLAST  Previous motor voltage
W1  See Figure 1
W2  See Figure 2
XLM  Design flow in
XT  x/X, per cent opening for control valve used in program
Z  Computer time stored at the beginning of the program

ARRAYS:
ACTCOST  Valve actuator or motor cost
ACTNO  Valve actuator or motor number
AIR  Air-to-diaphragm value of a valve
AVAIL  Number of a valve that is usable in the system so far
AVAIL  Temporary storage for AVAIL
B  Number of material that is compatible with fluid
BCOST  Cost of valve body material
BODY  Number of available body materials for a valve
BONCOST  Valve bonnet costs
CHEAP  Number of a valve that has been inserted in the list of
valves in order of cost
COL  Location of the applicable CV of a valve
COSTX  Temperature storage for cost of valve body material
CV  Valve CV
CX  Factor used in computing rise time in Runge-Kutta
D Derivative used in Runge-Kutta
DELTP AP of valve
DISCOST Level sensor cost
DISPL Control range of level sensor
EXT Code indicating whether valve has extension column or not
INDX1 Row location of least expensive body material and rating of a valve
INDX2 Column location of least expensive body rating of a valve
LD Equivalent length of a fitting
LE Equivalent length of a length of pipe
LIMVFC Location of last available v-port CV of a full capacity valve
LIMVRC Location of last available v-port CV of a reduced capacity valve
LT True length
MAN Row location of applicable valve manual operator cost
MCOST Cost of a valve manual operator
MODEL Model number of a valve
NAME Alphanumeric name of a body or trim material
NE Valve body material
NEI Required body material
NBNI Body material corresponding to a valve bonnet cost
NBX Temporary storage for cheapest valve body material
NFIT Number of a type of fitting in one length of pipe
NT Valve trim material
NTI Required trim material
NTX Trim material compatible with fluid
NUMCVS Total number of available CV's of a valve
OMIT  Number of valves omitted from list of usable valves
ORIGX Initial value of an element in the X array
POS Location of a positioner on a valve
POSCOST Cost of a positioner on a valve
QO Code indicating whether valve is quick-opening or not
QOLINK Linkage number of a quick-opening valve
QOTIME Closing time for a quick-opening valve
RAD Code indicating whether valve has radiating fin available
RATNG Body rating of valve
RATNGX Temporary storage for rating of cheapest body material
SEAL Code indicating whether valve has bellows seal or not
SIZE Diameter of a valve
SPRMAX Maximum pressure to be balanced by valve actuator spring
SPRMIN Minimum pressure to be balanced by valve actuator spring
TMAX Maximum allowable ambient temperature for valve
TMCOL Location of cheapest trim material of valve
TMCOST Cost of a valve trim material
TMIN Minimum allowable ambient temperature for valve
TOTCOST Total cost of a useable valve
TR Time stored for use in calculating rise time in Runge-Kutta
TRAVL Valve travel
TSET Time stored for use in calculating settling time
TYPE Valve type
VPFV Number of CVs available with v-port characteristics in a full capacity valve
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>VPLINK</td>
<td>Linkage number of a valve with v-port characteristics</td>
</tr>
<tr>
<td>VPORT</td>
<td>Code indicating that valve has v-port characteristics</td>
</tr>
<tr>
<td>VPRC</td>
<td>Number of CVs available with a reduced capacity valve with v-port characteristics</td>
</tr>
<tr>
<td>VPTIME</td>
<td>Closing time of a valve with v-port characteristics</td>
</tr>
<tr>
<td>X</td>
<td>Solution of differential equation in Runge-Kutta</td>
</tr>
<tr>
<td>XLAST</td>
<td>Solution at T-ΔT of differential equations in Runge-Kutta</td>
</tr>
</tbody>
</table>
APPENDIX B

DERIVATION OF SYSTEM FLOW EQUATIONS

Two tank configurations are utilized in this study. The first, Configuration One, represents a system containing a tank discharging from the top. Configuration Two, shown in Figure 1 which is repeated here for convenience, contains a tank which discharges thru an outlet pipe. Configuration Two is illustrated because it is the more general of the two. For the same reason equations of motion will be developed for Configuration Two. Flow into the tank and the liquid level in the tank of Configuration One can be represented by the corresponding equations for Configuration Two if flow from the tank, \( Q_o \), is assumed constant or varies only by step changes.

The tank shown in Figure 1 is typical of those found in industry. It has vertical sides and a round or a rectangular cross section. All pipes are assumed level, and \( L_2, L_3, L_4, \) and \( L_5 \) are equivalent lengths made up of the true pipe length and the equivalent length of any bends or fittings included in that run of piping. It is assumed that flow will never reverse direction in the systems covered by this derivation. To insure fully developed flow, all sections of pipe must have an L/D ratio greater than 20, where \( L \) is the pipe length and \( D \) is the inside diameter of the pipe.

The definitions of the symbols used in the following derivations are found in the Nomenclature Table.
Figure 1. Diagram of Configuration Two.
According to Eckman (10), the flow rate of a liquid through a fully opened control valve is given by

\[ Q = CV \sqrt{\frac{\Delta P}{S.G.}} \]  \hspace{1cm} (4)

The specific gravity uses the specific weight of water at 60°F as the reference specific weight.

\[ S.G. = \frac{w}{w_w} \]  \hspace{1cm} (5)

The valve size coefficient \( CV \) is defined as the flow rate of water in gallons per minute provided by a pressure differential of one pound per square inch through a fully opened control valve.

Forman (11) recommends the equal-percentage spool characteristic for control valves used in most process situations, primarily on the basis of its good rangeability. Therefore, only control valves with equal-percentage characteristics will be used in the throttling systems of this study. With an equal-percentage spool characteristic, each increment of plug movement produces a change in flow which is proportional to the amount flowing before the change occurred. Rangeability is the ratio of maximum controllable flow to minimum controllable flow. The flow through a sliding stem equal-percentage control valve is given by Eckman (12) as

\[ \frac{Q}{Q_m} = R^{(x/X-1)} \]  \hspace{1cm} (6)
A plot of flow versus valve lift for an equal-percentage valve is given in Figure 5.

The flow-lift characteristic for Honeywell quick-opening control valves was not available at the time of this writing. For lack of better information, the quick-opening valves were assumed to have approximately linear characteristics described by Eckman (13) as

\[ \frac{Q}{Q_m} = \frac{1}{R} \left[ 1 + \frac{(R-1)x}{X} \right] \]  

Let \( \frac{Q}{Q_m} = K_I \). Combining \( K_I \), Equation (4), and Equation (5) results in the following expression for flow through a control valve at any stem position.

\[ Q = (K_I)C \sqrt{\frac{w \Delta P}{\frac{w}{w} - 1}} \]  

Applying this equation to the control valve on the inlet side of the tank in Figure 1 yields

\[ Q_I = (K_I)C \sqrt{\frac{w \Delta P}{\frac{w}{w} - 1}} \]  

Forman (14) states that control valves are sometimes one pipe size larger or smaller than the pipe in which they are connected. In these cases, reducers are used between the pipe and the control valve. If the friction loss in the reducers is neglected,
Figure 5. Flow Versus Valve Lift for an Equal-Percentage Control Valve.
AP = P2 - P3  (10)

It can be shown (15) that the momentum equation for fluid flow applied to a control volume R, bounded by a surface S, is

\[ \Sigma F = \frac{1}{g_c} \left[ \frac{d}{dt} \int_R p_R \mathbf{v}_R \ d\mathbf{R} + \int_S (p_S \mathbf{v}_S) \mathbf{v}_S \cdot d\mathbf{s} \right] \quad (11) \]

where \( \frac{d}{dt} \int_R p_R \mathbf{v}_R \ d\mathbf{R} \) is the time rate of change of momentum of the fluid within R and bounded by S and \( \int_S (p_S \mathbf{v}_S) \mathbf{v}_S \cdot d\mathbf{s} \) is the net rate of efflux of momentum across the control surface S. Since the flow is uniform and since \( \mathbf{v}_1 \) equals \( \mathbf{v}_2 \) which equals \( \mathbf{v}_R \) (the velocity in the region) if \( \mathbf{v}_R \) is set equal to \( \mathbf{v}_1 \),

\[ \Sigma F = \frac{1}{g_c} \left[ \frac{d}{dt} \int_R p_R \mathbf{v}_R \ d\mathbf{R} + \mathbf{m}_2 \mathbf{v}_2 - \mathbf{m}_1 \mathbf{v}_1 \right] \quad (12) \]

Since \( \mathbf{v}_1 = \mathbf{v}_2 = \mathbf{v}_R \),

\[ \Sigma F = \frac{1}{g_c} \left[ \frac{d}{dt} (M \mathbf{v}_R) \right] \quad (13) \]

Because the flow is incompressible,

\[ \Sigma F = M \frac{d\mathbf{v}}{dt} \quad (14) \]

Three external forces act on the fluid flowing in the "L2" section of
the pipe as shown in Figure 6. Since all the forces act along the same axis, the vector notation can be dropped and

$$\Sigma F_E = M \frac{dV}{dt}$$  \hspace{1cm} (15)

![Free-Body Diagram](image)

Figure 6. Free-Body of Fluid in Pipe "L2."

The friction force, $F_f$, is shown in Figure 6. Assuming that resistance to flow in unsteady flow is equal to steady flow resistance at the same velocity (16), the head loss due to resistance is

$$h_f = \frac{FLV^2}{2gD}$$  \hspace{1cm} (16)

For the case in Figure 6,

$$V = \frac{Q_I}{A_I}$$  \hspace{1cm} (17)

where $A_I = \frac{\pi}{4} D_I^2$.

The friction force $F_f$ is the product of the head loss, the fluid specific weight, and the cross sectional area of the pipe as expressed by the equation
Substituting Equation (16) and Equation (17) into Equation (18) yields

\[ F_f = \frac{wF2(L2)Q_1^2}{2gD_1A_1} \]  \hspace{1cm} (19)

for the pipe in Figure 6.

The mass of the fluid in the pipe, \( M \), is given by

\[ M = \frac{w(L2)A_1}{g} \]  \hspace{1cm} (20)

Since

\[ V = \frac{Q_1}{A_1} \]

\[ \frac{dV}{dt} = \frac{1}{A_1} \frac{dQ_1}{dt} \]  \hspace{1cm} (21)

Substituting Equations (19), (20), and (21) into Equation (15) and rearranging results in

\[ F_2 = P_1 - \frac{wF2(L2)}{2gD_1A_1} Q_1^2 - \frac{w(L2T)}{gA_1} \frac{dQ_1}{dt} \]  \hspace{1cm} (22)
Likewise, for pipe length L3,

\[ P_3 = P_4 + \frac{wF_3(L_3)}{2gD_1A_1} \int Q_1^2 \, dQ + \frac{w(L_3T)dQ_1}{A_1g \, dt} \]  

(23)

Combining Equations (22) and (23) and assuming the friction factor in L2 is equal to the friction factor in L3,

\[ P_2 - P_3 = P_1 - P_4 - \frac{wF_2}{2D_1gA_1} [L_2 + L_3]Q_1^2 - \frac{w}{gA_1} [L_2T + L_3T] \frac{dQ_1}{dt} \]  

(24)

As can be seen from Figure 1, P4 may be made up of two components: the pressure due to a head of liquid above the pipe inlet in the tank, and the pressure of the gas above the liquid level. Three conditions are covered here. The tank can be vented, i.e., the pressure above the liquid level is taken as 15 psia; the pressure above the liquid in the tank is regulated or maintained at a constant pressure P13; or, the gas above the liquid level is trapped so that the pressure above the liquid is a function of the level. Representing P4 mathematically results in

\[ P_4 = P_0 + (H_2)w \]  

(25)

where

\[
\begin{align*}
P_0 &= 15 \text{ psi} \quad \text{Vented} \\
&= P_{13} \quad \text{Regulated} \\
&= \frac{(P_0)l_1}{l_1 - H} \quad \text{Trapped}
\end{align*}
\]
\( H_2 \) is defined as follows.

\[
H_2 = \begin{cases} 
0 & H \leq H_3 \\
H - H_3 & H > H_3 
\end{cases}
\]  

(26)

The expression for \( P_0 \) for the trapped tank is found as follows. It is assumed that the empty tank is charged to a pressure, \( P_{00} \). Using the perfect gas law,

\[
(P_{00}) V_i = N R_c T_i
\]

(27)

where \( i \) subscripts indicate initial conditions, and

\[
(P_0) V_o = N R_c T
\]

(28)

Since the tanks covered by this derivation will generally not be insulated, it is assumed that the gas above the liquid will not experience any appreciable temperature change during level changes and the expansion and contraction of this gas will therefore be assumed isothermal. Therefore,

\[
(P_0) V_o = (P_{00}) V_{oi}
\]

(29)

where
\[ V_0 = A_8[L_1 - H] \]  
(30)

and

\[ V_{oi} = A_8(L_1) \]  
(31)

Substituting Equation (30) and (31) into Equation (29) yields

\[ P_0 = \frac{(P_{00})L_1}{L_1 - H} \]  
(32)

Substituting Equation (24) into Equation (9) and rearranging yields the following equation for flow into the tank,

\[ \frac{dQ_I}{dt} = \frac{gA_1}{(L_2T + L_3T)} \left( \frac{P_L - P_4}{w} - \frac{1}{((KI)CV)^2_w} + \frac{F_2(L_2 + L_3)}{2gD_1(A_1)^2}Q_I^2 \right) \]  
(33)

The equation to be used for the friction factor, \( F_2 \), depends on the Reynolds number for flow in the pipe where

\[ \text{Re} = \frac{4Q_I w}{D_1 |g|} \]

For \( \text{Re} \leq 2000 \),

\[ F = \frac{64}{\text{Re}} \]  
(34)

Therefore,
From Potter (17), if the Reynolds number is greater than 4000, the friction factor $F$ can be found from the equation,

$$ F = 0.0055 \left[ 1 + \left( \frac{20,000}{D} + \frac{10^6}{Re} \right)^{\frac{1}{3}} \right] $$

(36)

Assuming that the friction factor corresponding to Reynolds numbers in the range between 2000 and 4000 can be found by Equation (35).

For $Re > 2000$,

$$ F_2 = 0.0055 \left[ 1 + \left( \frac{20000}{D_1} + \frac{10^6}{Re_1} \right)^{\frac{1}{3}} \right] $$

(37)

As shown in Chapter IV, control valve selection is based in part on a valve size coefficient, $CV$. This size coefficient is a measure of the flow rate through a control valve as a function of the fluid and pressure drop across the valve. The $CV$ is determined for the flow system under consideration by the following relationship

$$ CV = \frac{Q}{\sqrt{\Delta P}} $$

The size and type of control valve required to meet a specific
application can be selected on the basis of a comparison of this calculated CV and the tabulated CV's found in the valve manufacturer's literature. The valve size coefficients given in the manufacturer's literature have been determined experimentally for each type and size valve.

Although the valve size coefficient is generally given as a constant in the manufacturer's catalogs, in reality, its value varies somewhat with Reynolds number. Even though manufacturer's information on this variation was not available at the time of this writing, a correction to be applied to the manufacturer's constant CV values is included in the computer program for demonstration purposes. The variation of CV with Reynolds number was assumed to be that of a 200 x 400 Venturi meter as given by the curve in the 4th edition of "Fluid Meters: Their Theory and Application" published by the American Society of Mechanical Engineers in 1937. This curve should be replaced with the manufacturer's curves of CV versus Reynolds number for various valves when they are available if the computer program is to be used in practice. The 200 x 400 Venturi meter curve is approximated by straight line segments as shown in Figure 7. In Figure 7, CV is the manufacturer's published valve size coefficient, CVI is the valve size coefficient corrected for the effect of the Reynolds number, and the Reynolds number is the Reynolds number for flow through the valve.

From Figure 7, the following relationships were found. (The program is not applicable for RE < 200). For,
Figure 7. Straight-Line Approximation of Assumed Variation of CVI with Reynolds Number.
The pipe lengths used in the terms containing the friction factors in Equation (33) correspond to the true length of the pipe plus the equivalent length of any bends or fittings included in that length of pipe. For the purpose of the described study, it is assumed that the head loss effect of various fittings is the same in transient flow as in steady flow. It is felt that this assumption is justified for a feasibility study of this sort, but, in practical usage, the error caused by making this assumption should be determined. Table 4 contains a list of various valves and fittings covered by the program along with their equivalent lengths in pipe diameters. This list is taken from Crane (18). The equivalent length for a run of pipe is found by summing up the equivalent lengths in pipe diameters for all the fittings included in that run of pipe and multiplying that sum by the nominal pipe diameter. The equivalent length of a 90° pipe bend must be found from a "Chart for Resistance of 90 Degree Bends" on page A-27 in Crane. Assuming \( r/d \) will be greater than or equal to 3.0, but less than 20, the curve has been approximated by a polynomial curve fit computer program which resulted in the following equation,
If the tank is set up as in Configuration Two, the equation for flow from the tank is found in much the same way as that found for flow into the tank. This study assumes that $K_2$, the opening of the outlet valve is a known constant greater than or equal to zero, but less than or equal to one. Then from Equation (8),

$$Q_w = \frac{CVO}{(K_0)CV_0} \frac{\Delta P}{W}$$

(40)

It is also assumed that the outlet valve $CV$ varies with Reynolds number as shown in Figure 7, and that friction in the reducers can be neglected.

$$\Delta P_0 = P_5 - P_6$$

(41)

Substituting values in Equation (15) yields the following equations for $P_5$ and $P_6$,
Combining Equations (40), (41), (42), and (43) results in

\[ \frac{dQ_0}{dt} = \frac{gA_3}{(L_4T+L_5T)w} \left[ \frac{P_0-P_7}{w} + H - \frac{1}{w_{W((K_0)CVO)^2}} \frac{F_4(L_4+L_5)-[Q_0-z]^2}{2D_3(A_3)g^2} \right] \]  

(44)

where \( F_4, L_4, L_5, \) and \( CV_0 \) are found as on the inlet side.

The change in level in the tank is found by the following equation,

\[ \frac{dH}{dt} = \frac{1}{A_8}(Q_I-Q_0) \]  

(45)

Tests for the validity of the system flow equations derived above for use in the computer program were developed and are described on page 72.

Certain simplifying assumptions can be made to obtain approximate expressions for the time rate of change in head in the tank, for flow into the tank, and for flow from the tank. If the tank outlet valve is shut, \( Q_0 = 0 \) and the control valve is held open \( (K_1 = 1.0) \), an
Table 4. Equivalent Lengths of Valves and Fittings

<table>
<thead>
<tr>
<th>Type</th>
<th>Sub-Type</th>
<th>Description</th>
<th>Equival L/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Globe Valves</td>
<td>Conventional</td>
<td>With no obstruction in flat, bevel, or plug type seat.</td>
<td>Fully open 340</td>
</tr>
<tr>
<td></td>
<td></td>
<td>With wing or pin guided disc.</td>
<td>Fully open 450</td>
</tr>
<tr>
<td></td>
<td>Y-Pattern</td>
<td>(No obstruction in flat, bevel, or plug type seat.)</td>
<td>Fully open 175</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stem 60 degrees from run of pipe line.</td>
<td>Fully open 145</td>
</tr>
<tr>
<td>Angle Valves</td>
<td>Conventional</td>
<td>With no obstruction in flat, bevel, or plug type seat.</td>
<td>Fully open 145</td>
</tr>
<tr>
<td></td>
<td></td>
<td>With wing or pin guided disc.</td>
<td>Fully open 200</td>
</tr>
<tr>
<td>Gate Valves</td>
<td>Conventional</td>
<td></td>
<td>Fully open 13</td>
</tr>
<tr>
<td>Check Valves</td>
<td></td>
<td>Conventional swing.</td>
<td>Fully open 135</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Clearway swing.</td>
<td>Fully open 50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Globe lift or stop.</td>
<td>Fully open 450</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Angle lift or stop.</td>
<td>Fully open 200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In-line ball.</td>
<td>Fully open 150</td>
</tr>
<tr>
<td>Fittings</td>
<td>Standard Tee</td>
<td>90 Degree standard elbow.</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45 Degree standard elbow.</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90 Degree long radius elbow.</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90 Degree street elbow.</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45 Degree street elbow.</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Square corner elbow.</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td></td>
<td>With flow through run.</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>With flow through branch.</td>
<td>60</td>
</tr>
<tr>
<td>Pipe</td>
<td>90 Degree pipe bends.</td>
<td>See Equation</td>
<td></td>
</tr>
</tbody>
</table>

approximate expression for head in the tank as a function of time can be found as follows:
For steady flow, neglecting friction, with the control valve open,

\[ Q_I = (1.0)CVI \sqrt{\frac{(P_I - P_O)w}{w}} \]

For water,

\[ \frac{w}{w} = 1.0 \]

Therefore,

\[ \frac{dH}{dT} = \frac{CVI}{A_B} \sqrt{P_I - P_O} \]

\[ dH = \left[ \frac{CVI}{A_B} \sqrt{P_I - P_O} \right]dT \]

Integrating,

\[ H^H_0 = \left[ \frac{CVI}{A_B} \sqrt{P_I - P_O} \right]^T_0 T \]

If the tank is empty at \( T = 0 \),

\[ H = \frac{CVI}{A_B} \sqrt{P_I - P_O} T \]
Setting

\[ P_0 = 15.0 \]

\[ P_I = 16.6 \]

\[ A_8 = 1000 \]

\[ CVI = 654 \]

results in

\[ H = (0.827) T \]

Table 5 shows the results obtained from the above expression and the corresponding computer solution and the per cent deviation for a five-second run. The per cent deviation uses the computer values as base.

Table 5. Results of the First Flow Equation Test

<table>
<thead>
<tr>
<th>T</th>
<th>( H ) Hand</th>
<th>( H ) Computer</th>
<th>Per Cent Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.0</td>
<td>0.827</td>
<td>0.801578</td>
<td>3.12</td>
</tr>
<tr>
<td>1.5</td>
<td>1.240</td>
<td>1.20259</td>
<td>3.08</td>
</tr>
<tr>
<td>2.0</td>
<td>1.654</td>
<td>1.60360</td>
<td>3.11</td>
</tr>
<tr>
<td>2.5</td>
<td>2.070</td>
<td>2.00461</td>
<td>3.14</td>
</tr>
<tr>
<td>3.0</td>
<td>2.480</td>
<td>2.40563</td>
<td>3.08</td>
</tr>
<tr>
<td>4.0</td>
<td>3.310</td>
<td>3.02766</td>
<td>3.18</td>
</tr>
<tr>
<td>5.0</td>
<td>4.130</td>
<td>4.00968</td>
<td>3.00</td>
</tr>
</tbody>
</table>
Table 5 demonstrates the fairly close agreement between the results of the two methods of solution for the short time interval used. It can be seen that $H_{\text{hand}}$ is consistently larger than $H_{\text{computer}}$. It is felt that this is due to the inclusion of the effects of pipe friction in the computer solution. This pipe friction is a retarding factor which reduces the flow rate into the tank. Therefore, the tank fills slower than when the pipe friction is ignored.

An approximate expression for the complete set of equations can be found for certain specific cases.

Using the head equation,

$$\frac{dH}{dT} = \frac{1}{A_b} (Q_I - Q_o)$$

If $Q_I$ is held constant and

$$Q_o = (K20)CVO \sqrt{wH}$$

$$\frac{dH}{dT} = \frac{Q_I}{A_b} - \frac{(K20)CVO}{A_b} \frac{1}{\sqrt{w}} \frac{1}{\sqrt{H}}$$

Making the following substitutions,

$$u = \sqrt{H}$$

$$K = (K20)CVO \sqrt{w}$$
\[
\frac{dH}{dT} = 2u \frac{du}{dT}
\]

results in

\[
2A_g u \frac{du}{dT} = Q_I - ku
\]

Separating the variables,

\[
2A_g \left[ \frac{u}{Q_I - ku} \right] = dT
\]

Integrating the above equation and replacing \( u \) with \( H \) results in

\[
T = 2A_g \left[ \frac{\sqrt{H} - \sqrt{H_I}}{k} + \frac{Q_I}{k^2} \ln \left( \frac{\sqrt{H} - Q_I/k}{\sqrt{H_I} - Q_I/k} \right) \right]
\]

Table 6 shows comparative values of head and flow out, and lists per cent deviation for the two methods of solution. As before, per cent deviation uses the computer values as base.

It can be seen that there is a very small per cent deviation in head resulting from the two methods of solution. Since the hand calculation neglects pipe friction and the computer solution does not, it can be assumed, that for the specific example used, the effect of the pipe friction on the inlet side of the tank is virtually cancelled by the effect of the pipe friction on the outlet side of the tank. Table 6 also indicates that \( Q_{\text{Hand}} \) is consistently larger than \( Q_{\text{Computer}} \). This can also be explained as the effect of the inclusion of the friction factor in the computer solution.
Table 6. Results of Second Flow Equation Test

<table>
<thead>
<tr>
<th>T</th>
<th>H&lt;sub&gt;Hand&lt;/sub&gt;</th>
<th>H&lt;sub&gt;Computer&lt;/sub&gt;</th>
<th>Q&lt;sub&gt;oHand&lt;/sub&gt;</th>
<th>Q&lt;sub&gt;oComputer&lt;/sub&gt;</th>
<th>Per Cent Deviation</th>
<th>Per Cent Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>200</td>
<td>200.000</td>
<td>1755</td>
<td>1755.00</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.459</td>
<td>199</td>
<td>199.265</td>
<td>1750</td>
<td>1677.20</td>
<td>0.133</td>
<td>4.34</td>
</tr>
<tr>
<td>1.048</td>
<td>198</td>
<td>198.338</td>
<td>1745</td>
<td>1667.88</td>
<td>0.170</td>
<td>4.63</td>
</tr>
<tr>
<td>2.416</td>
<td>196</td>
<td>196.196</td>
<td>1735</td>
<td>1658.65</td>
<td>0.100</td>
<td>4.60</td>
</tr>
<tr>
<td>3.192</td>
<td>194</td>
<td>194.998</td>
<td>1728</td>
<td>1653.57</td>
<td>0.200</td>
<td>4.50</td>
</tr>
<tr>
<td>4.240</td>
<td>192</td>
<td>193.370</td>
<td>1718</td>
<td>1646.64</td>
<td>0.713</td>
<td>4.33</td>
</tr>
</tbody>
</table>
APPENDIX C

DEVELOPMENT OF CONTROL EQUATIONS

Based on information obtained from Honeywell catalogs and discussions with local Honeywell engineers, the following Table of System Types was prepared.

Table 7. System Types

<table>
<thead>
<tr>
<th>Control</th>
<th>Pneumatic</th>
<th>Electric</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-Off</td>
<td></td>
<td>Open or Closed Tank</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Versa-Tran (Controller)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Probes (Sensor)</td>
</tr>
<tr>
<td>Proportional</td>
<td>Open Tank</td>
<td>Open or Closed Tank</td>
</tr>
<tr>
<td></td>
<td>Low Cost System A</td>
<td>R7165A Proportioning</td>
</tr>
<tr>
<td></td>
<td>Low Cost System B</td>
<td>Relay (Controller)</td>
</tr>
<tr>
<td></td>
<td>Type 71-06 Level Control (Displacer)</td>
<td>P/I Transmitter (Sensor)</td>
</tr>
<tr>
<td></td>
<td>Closed Tank</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Type 71-06 Level Control (Displacer)</td>
<td></td>
</tr>
<tr>
<td>Proportional</td>
<td>Open Tank</td>
<td></td>
</tr>
<tr>
<td>Plus Integral</td>
<td>Type 71-06 Level Control (Displacer)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2-Mode Indicating Controller,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Statis Pressure Transmitter (Sensor)</td>
<td></td>
</tr>
<tr>
<td>Proportional</td>
<td>Closed Tank</td>
<td></td>
</tr>
<tr>
<td>Plus Integral</td>
<td>Type 71-06 Level Control (Displacer)</td>
<td></td>
</tr>
</tbody>
</table>
It should be noted that no systems containing three mode controllers are included. Eckman (19), Buckley (20), and Honeywell (21) indicate that the rate mode is rarely used in liquid level control.

It can be seen from Table 7 that only proportional systems have both electric and pneumatic components. This does not mean that Honeywell cannot provide components from which an electric proportional plus integral control system, for example, could be made. It does indicate that the frequency of demand for such a system is so low that applications engineers at the local level do not have full information on the system and considerable correspondence with the factory would be required for the purchase of such a system.

The set of equations governing the valve opening for an on-off control system is obtained as follows. Figure 8 is a diagram of the on-off control system used in this study. It can be seen that this type of liquid level control can only maintain a level between two points; it cannot hold the level at a specified location. Honeywell on-off liquid level control systems require that the liquid used be an electrical conductor. The relationship of motor voltage V versus the error (H1-H), in the liquid level is given in Figure 9.

A design requirement for the systems of this study was that all control valves fail shut. This means that all valves must be of the spring return type for which closing time is assumed negligible. On the other hand, opening time is a linear function of time. The motor-operated valves used in the study have opening times of 30 and 60 seconds.
Figure 8. On-Off Control System Diagram.
As shown in Figure 9, the voltage $V$, to the valve motor is not only a function of the error in the head $(H_l - H)$, but is also a function of the voltage past history. In addition, the opening of the valve is a function of the voltage applied to the valve and a function of the time elapsed since the voltage was applied. With this in mind, the following set of equations can be written.

For $(H_l - H) \leq -\Delta H$,

$$V = 0$$

and

$$\frac{X}{X} = 0 \quad \text{(46)}$$

For $-\Delta H < (H_l - H) < \Delta H$, 

...
and \( V(T-\Delta T) = 0 \),

\[
V = 0
\]

and

\[
\frac{x}{X} = 0 \quad (47)
\]

For \(- \Delta H < (H_l - H) < \Delta H\)

and \( V(T-\Delta T) = V_1 \),

\[
V = V_1
\]

and if \( T_l \leq QOT \),

\[
\frac{x}{X} = \frac{T_l}{QOT} \quad (48)
\]

if \( T_l > QOT \),

\[
\frac{x}{X} = 1.0 \quad (49)
\]

For \((H_l - H) \geq \Delta H\),

\[
V = V_1
\]
and if $T_1 \leq QOT$,

$$\frac{X}{X} = \frac{T_1}{QOT} \quad (50)$$

or if $T_1 > QOT$,

$$\frac{X}{X} = 1.0 \quad (51)$$

The control equation used for the proportional systems of this study is derived for a pneumatic system but can be used for an electric system.

According to Buckley (22), the natural frequency of a displacer type level sensor is one to three cycles per second. Since this frequency is much higher than the frequency of the tank level changes for any practical liquid level system, the transfer function for the displacer is represented by a constant. This same reasoning also holds for the other level sensors included in the study. For the purpose of the study, the system is assumed to be set up so that a zero error signal corresponds to flow through the control valve equal to one half the maximum flow for a given pressure drop across the valve.

From Figure 5 in Appendix B, when $Q/Q_m = \frac{1}{2}$, $x/X = 0.82$ for an equal-percentage control valve. The relationship between $x/X$ and $P$ is shown in Figure 10. From Figure 10,

$$P = P_{mi} + (P_{ma} - P_{mi}) \frac{X}{X} \quad (52)$$
The relationship between $P$ and $(H_1-H)$ is shown in Figure 11. Point $P_c$ can be found by setting $x/X$ equal to 0.82 in Equation (52). In Figure 11,

$$P = \frac{P_{ma} - P_{mi}}{PB(CR)} (H_1-H) + P_c \quad (53)$$

Eliminating $P$ between Equation (52) and Equation (53) yields

$$\frac{x}{X} = \frac{(H_1-H)}{PB(CR)} + 0.82 \quad (54)$$

Because of the limiting nonlinearities in Figure 11, the expression for $x/X$ for the entire range of allowable values is

$$\frac{x}{X} = \begin{cases} 
\frac{(H_1-H)}{PB(CR)} + 0.82 & 0 \leq \frac{(H_1-H)}{PB(CR)} + 0.82 < 1 \\
1 & \frac{(H_1-H)}{PB(CR)} + 0.82 \geq 1 
\end{cases} \quad (55)$$

The most sophisticated control system used in this study uses a two mode controller incorporating a proportional mode and an integral or reset mode. The addition of the integral mode to the proportional controller results in the following control equation,

$$\frac{x}{X} = \frac{1}{PB(CR)} \left[ PB \int_0^t (H_1-H)dt + (H_1-H) \right] + 0.82 \quad (56)$$
Figure 10. Plot of Valve Opening Versus Control Pressure.

Figure 11. Plot of Control Pressure Versus Error in Level.
Again, the range of \( x/X \) is limited and, if

\[
\frac{1}{PB(CR)} \left[ \int_{0}^{t} (H_l-H)dt + (H_l-H) \right] + 0.82 = A,
\]

the complete proportional plus integral control equation is

\[
\frac{x}{X} = \begin{cases} 
0 & A \leq 0 \\
\frac{1}{PB(CR)} \left[ \int_{0}^{t} (H_l-H)dt + (H_l-H) \right] + 0.82 & 0 < A < 1 \\
1.0 & 1 \leq A
\end{cases}
\]
APPENDIX D

THEORY OF DIFFERENTIAL EQUATION SOLUTION

Determination of the time response of the tank liquid level requires the simultaneous solution of a system of first order nonlinear differential equations. The number of differential equations making up the system depends on the tank configuration and on the type of control system used.

The Runge-Kutta method of numerical integration is used to obtain the required solutions. A brief explanation of this method follows (23). Given $y' = f(x,y)$ and $(x_0,y_0)$, additional points $(x_1,y_1)$ on the integral curve are desired. Let $\Delta x = h$ and $\Delta y = k$ so that

$$y_1 = y_0 + k \quad (58)$$

and

$$x_1 = x_0 + h \quad (59)$$

The problem is now reduced to finding values of $k$ to the required degree of accuracy. There have been several methods presented for finding $k$ based on the Taylor series expansion

$$k = y'_0 h + y''_0 \frac{h^2}{2!} + y'''_0 \frac{h^3}{3!} + y''''_0 \frac{h^4}{4!} + \cdots \quad (60)$$
The easiest to calculate are the formulas of Runge, which have been
modified by Heun and Kutta. The chief advantage of these formulas is
that they can be written with the functional values only. Let \( k_1, k_2, \)
\( k_3, \ldots \), be the successive approximations of \( k \), which will be weighted
and averaged as indicated by Equation (65) below. The formulas as
modified by Kutta are

\[
k_1 = f(x_0, y_0)h \tag{61}
\]
\[
k_2 = f(x_0 + \frac{h}{2}, y_0 + \frac{k_1}{2})h \tag{62}
\]
\[
k_3 = f(x_0 + \frac{h}{2}, y_0 + \frac{k_2}{2})h \tag{63}
\]
\[
k_4 = f(x_0 + h, y_0 + k_3)h \tag{64}
\]

and

\[
k = \frac{1}{6} (k_1 + 2k_2 + 2k_3 + k_4) \tag{65}
\]

If \( y \) does not appear on the right side of the differential equa-
tion, the problem reduces to simple quadrature and Kutta's equations
take the form of Simpson's rule.

The method can be extended to systems of simultaneous differential equations. For example, consider two simultaneous equations

\[
y' = f(x, y, z) \tag{66}
\]
and

\[ z' = g(x, y, z) \]  \hspace{1cm} (67)

By defining \( q \) such that

\[ z_1 = z_o + q \]  \hspace{1cm} (68)

\( k \) and \( q \) can be written as follows:

\[ k_1 = f(x_o, y_o, z_o)h \]  \hspace{1cm} (69)

\[ q_1 = g(x_o, y_o, z_o)h \]  \hspace{1cm} (70)

\[ k_2 = f(x_o + \frac{h}{2}, y_o + \frac{k_1}{2}, z_o + \frac{q_1}{2})h \]  \hspace{1cm} (71)

\[ q_2 = g(x_o + \frac{h}{2}, y_o + \frac{k_1}{2}, z_o + \frac{q_1}{2})h \]  \hspace{1cm} (72)

\[ k_3 = f(x_o + \frac{h}{2}, y_o + \frac{k_2}{2}, z_o + \frac{q_2}{2})h \]  \hspace{1cm} (73)

\[ q_3 = g(x_o + \frac{h}{2}, y_o + \frac{k_2}{2}, z_o + \frac{q_2}{2})h \]  \hspace{1cm} (74)

\[ k_4 = f(x_o + h, y_o + k_3, z_o + q_3)h \]  \hspace{1cm} (75)

\[ q_4 = g(x_o + h, y_o + k_3, z_o + q_3)h \]  \hspace{1cm} (76)
and

\[ k = \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4) \quad (77) \]

\[ q = \frac{1}{6}(q_1 + 2q_2 + 2q_3 + q_4) \quad (78) \]

It can be shown that the error in these approximations is proportional to \( h \) to the fifth power (24). A simpler but less sophisticated method of determining the error involves re-running the calculation for a short interval of \( x \) at half the increment \( h \). The number of significant figures found in agreement is an indication of the accuracy of the results.
APPENDIX E

PROGRAM FLOW CHARTS

The Computer Program Flow Charts are given on the following pages. The Main Program Flow Chart starts on page 90 and the Flow Chart for the Runge-Kutta numerical integration method starts on page 103.
READ DATA CARDS AND PRINT CONTENTS

COMPUTE A8 AND SET REPEAT RATE EQUAL TO ZERO

COMPUTE EQUIVALENT LENGTHS OF L2, L3, L4, AND L5

IS SYSTEM ON-OFF?

No

DESIGN FLOW IN = INITIAL FLOW IN (FOUND ON DATA CARD)

Yes

DESIGN FLOW IN = (1.1)(QOM)

 COMPUTE INLET PIPE REYNOLDS NUMBER

IS REYNOLDS NUMBER < 200?

Yes

EXIT

No

PRINT VALUE OF REYNOLDS NUMBER

Go to end of program

 COMPUTE INLET PIPE FRICTION FACTOR

IS H1 > H3?

No

H2 = ZERO

Yes

H2 = H1 - H3

 COMPUTE P0
COMPUTE $C_v$ OF CONTROL VALVE AS A FUNCTION OF REYNOLDS NUMBER

PRINT VALUE OF $C_v$

ENTER RUNGKUTTA SUB-Routine WITH ABOVE $C_v$

DOES FINAL CURVE IN RUNGKUTTA MEET DESIGN REQUIREMENTS?

- No → Go to end of program
- Yes → COMPUTE REQUIRED $\Delta P$

COMPUTE RANGE IN WHICH CONTROL VALVE $C_v$ MUST FALL (CVMAX AND CVMIN)

READ COMPATIBILITY TABLE FROM INPUT TAPE, PICKING UP ALL MATERIALS WHICH ARE COMPATIBLE WITH DESIRED FLUID

READ AND STORE LEVEL SENSOR TABLE

DID CUSTOMER CHOOSE A VALVE BODY MATERIAL AND TRIM MATERIAL?

- No → FILL NBI ARRAY WITH ALL POSSIBLE BODY MATERIALS WHICH ARE COMPATIBLE WITH FLUID AND NTX ARRAY WITH ALL POSSIBLE TRIM MATERIALS WHICH ARE COMPATIBLE WITH FLUID
- Yes
FILL ALL BUT FIRST ELEMENT OF NBI AND NTX ARRAYS WITH_ZEROES

READ VALVE TABLE FROM_INPUT TAPE AND STORE ALL DATA FOR EACH VALVE

USING P1MAX AND T7, DETERMINE REQUIRED BODY RATING OR RATINGS FOR EACH POSSIBLE BODY MATERIAL. SCREWED END CONNECTIONS ARE CONSIDERED NEGATIVE; FLANGED END CONNECTIONS ARE CONSIDERED POSITIVE.

DO ANY OF THE POSSIBLE BODY MATERIALS HAVE A USABLE RATING?

PRINT "INVESTIGATE POSSIBILITY OF LINED SAUNDERS VALVES"

Go to end of program

IS A BELLOWS SEAL REQUIRED?

IS T7>750?

IS T7>-450 AND ≤32?

IS T7>32 AND ≤450?

IS T7>450 AND ≤1200?

PRINT "NO BONNET AVAILABLE?"

EXTCOL=1

PLAIN BONNET IS REQUIRED

RADFIN=1

Go to end of program
IS PIMAX > 150?

MONEL=1

IS FLUID COMPATIBLE WITH MONEL?

STEEL=1

IS FLUID COMPATIBLE WITH 316 STEEL?

IS EITHER STEEL=1 OR MONEL=1?

PRINT "FLUID NOT COMPATIBLE W/MONEL OR 316 STEEL"

PRINT "NO BONNET AVAILABLE"

PRINT "FLUID NOT COMPATIBLE W/316 STEEL"

SAUNDERS VALVE IS REQUIRED

IS P>50?

POSSIBLE TRIM MATERIAL IS 316 STEEL

IS P>50?

IS FLUID A SLURRY?

POSSIBLE TRIM MATERIAL IS BRONZE
SAUNDERS
VALVE IS
REQUIRED

IS 316
STEEL
COMPATIBLE
WITH FLUID?

Yes
STORE
316
STEEL
IN NTI
ARRAY

No
Go to L33

IS P
>300?

No

STORE
316
STEEL
IN NTI
ARRAY

IS P
>600?

No
PRINT
"DELT P
BEYOND
RANGE"

Go to end of
program

POSSIBLE TRIM
MATERIAL IS MONEL

Yes
STORE
MONEL IN
TRIM ARRAY

No

IS SYSTEM
ON-OFF?

No

POSSIBLE TRIM
MATERIAL IS HASTELLOY B

Is 316
STEEL
COMPATIBLE
WITH FLUID?

No

STORE
316
STEEL
IN NTI
ARRAY

IS BRONZE
COMPATIBLE
WITH FLUID?

No

POSSIBLE TRIM MATERIAL
IS 316 STEEL

Yes

Has either
BRONZE OR
316 STEEL
been stored
in NTI
ARRAY?

Yes
Go to L33

STORE
BRONZE IN NTI
ARRAY

No

STORE
316
STEEL
IN NTI
ARRAY

Hastelloy
B

Yes

STELLITE
IN NTI
ARRAY

No

Is 316
STEEL
COMPATIBLE
WITH FLUID?

No

STORE
316
STEEL
IN NTI
ARRAY

No

STORE
STELLITE
IN NTI
ARRAY
STORE HASTELLOY B IN NTI ARRAY
YES

IS HASTELLOY B COMPATIBLE WITH FLUID?
NO

POSSIBLE TRIM MATERIAL IS HASTELLOY C

STORE HASTELLOY C IN NTI ARRAY
YES

IS HASTELLOY C COMPATIBLE WITH FLUID?
NO

POSSIBLE TRIM MATERIAL IS 440C STEEL

STORE 440C STEEL IN NTI ARRAY
YES

IS 440C STEEL COMPATIBLE WITH FLUID?
NO

HAS MONEL, HASTELLOY B, HASTELLOY C, OR 440C STEEL BEEN STORED IN NTI ARRAY?
NO

SAUNDERS=1

L33:

IS SYSTEM ON-OFF?
YES

COMPARE Cₐ OF QUICK-OPENING VALVES IN VALVE TABLE WITH REQUIRED Cₐ RANGE AND ELIMINATE ANY VALVE WHOSE Cₐ DOES NOT FALL WITHIN REQUIRED RANGE
NO
COMPARE CvS OF REDUCED CAPACITY VALVES WITH V-PORT CHARACTERISTICS WITH REQUIRED Cv RANGE AND ELIMINATE ANY VALVE THAT DOES NOT HAVE A Cv IN THE REQUIRED RANGE

IS CAPACITY FULL?

Yes

COMPARE CvS OF FULL CAPACITY VALVES WITH V-PORT CHARACTERISTICS WITH REQUIRED Cv RANGE AND ELIMINATE ANY VALVE THAT DOES NOT HAVE A Cv IN THE REQUIRED RANGE

HAVE ALL VALVES IN VALVE TABLE BEEN ELIMINATED?

Yes

PRINT "NO CV AVAILABLE"

Go to end of program

No

COMPARE AVAILABLE BODY MATERIALS OF REMAINING VALVES WITH REQUIRED BODY MATERIALS AND ELIMINATE ALL VALVES WHICH DO NOT HAVE ANY OF THE REQUIRED BODY MATERIALS

HAVE ALL REMAINING VALVES BEEN ELIMINATED?

Yes

PRINT "NO BODY MATERIAL AVAILABLE"

Go to end of program

No

COMPARE BODY RATINGS OF REMAINING VALVES WITH REQUIRED BODY RATINGS AND ELIMINATE ALL VALVES WHICH DO NOT HAVE ANY OF THE REQUIRED BODY RATINGS
HAVE ALL REMAINING VALVES BEEN ELIMINATED?

Yes

PRINT "NO FLANGE RATINGS AVAILABLE"

No

IS SYSTEM ON-OFF?

Yes

COMPARE REQUIRED ΔP WITH ΔPs OF QUICK-OPENING VALVES AND ELIMINATE ANY VALVE THAT DOES NOT HAVE A ΔP GREATER THAN OR EQUAL TO THE REQUIRED ΔP

No

Go to end of program

No

HAVE ALL REMAINING VALVES BEEN ELIMINATED?

Yes

PRINT "NO VALVE W/ ALLOWABLE DELT P AVAILABLE"

No

COMPARE AVAILABLE BONNETS OF REMAINING VALVES (UNLESS VALVE IS SAUNDERS) WITH REQUIRED BONNET AND ELIMINATE ANY VALVE WHICH DOES NOT HAVE REQUIRED BONNET

Go to end of program

No

HAVE ALL REMAINING VALVES BEEN ELIMINATED?

Yes

PRINT "NO BONNET AVAILABLE?"

No

Go to end of program
ELIMINATE ANY I

VALVES THAT ARE ELECTRIC

COMPARE AVAILABLE TRIM MATERIALS OF REMAINING VALVES WITH TRIMS IN NTI ARRAY AND ELIMINATE ANY VALVES THAT DO NOT HAVE ANY OF THE REQUIRED TRIM MATERIALS

HAVE ALL REMAINING VALVES BEEN ELIMINATED?

IS A MANUAL OPERATOR REQUIRED?

ELIMINATE ANY REMAINING VALVES THAT DO NOT HAVE A MANUAL OPERATOR MOUNTED IN THE REQUIRED POSITION (TOP OR SIDE)

HAVE ALL REMAINING VALVES BEEN ELIMINATED?

IS SYSTEM ON-OFF?

IS SYSTEM PROPORTIONAL PLUS INTEGRAL?

ELIMINATE ANY VALVES THAT ARE ELECTRIC

IS SYSTEM PNEUMATIC?

PRINT "NO TRIM AVAILABLE"

Go to end of program

PRINT "NO MANUAL OPERATOR AVAILABLE"
Eliminate any valves that are not electric.

Have all remaining valves been eliminated?

Find total cost of each remaining valve.

Arrange valves in order of cost.

Is system electric or proportional plus integral?

Take each valve, in order of cost, and enter Runge-Kutta with applicable valve $C_v$ until two valves have been found which have adequate response or until list of valves is exhausted.

Is tank vented?

Is $H_1 < 7.2/g$ and $0.25 < P_b < 0.35$?

Have any valves met design requirements?

Print "No valves have adequate response."

Go to end of program.
IS SYSTEM ON-OFF?  
Yes  
PRINT DH AND PROPER CONTROLLER AND PROBES WITH EACH OF TWO HALVES  
No  
Go to end of program

IS SYSTEM PROPORTIONAL PLUS INTEGRAL?  
Yes  
No  

IS SYSTEM PNEUMATIC?  
Yes  
No  
IS H₁≤14.4/G?  
Yes  
PRINT "NO TRANSmitter AVAILABLE"  
No  
Go to end of program

IS FLUID COMPATIBLE WITH CARBON STEEL OR 316 STAINLESS STEEL?  
Yes  
PRINT PB AND PROPER LEVEL SENSOR, CONTROLLER, AND POWER SUPPLY WITH EACH OF TWO VALVES  
No  

L11:  
IS FLUID COMPATIBLE WITH CAST IRON?  
Yes  
No  
IS TANK RATING ≤125 or ≤250?  
PRINT "WARNING-SPECIAL DISPLACER REQUIRED"  
No  
IS FLUID COMPATIBLE WITH CARBON STEEL?  
Yes  
PRINT "ORDER SPECIAL DISPLACER"  
No  
IS TANK RATING ≤300 OR ≤600?  
PRINT "ORDER SPECIAL DISPLACER"
PICK PROPER LEVEL SENSOR COST FROM LEVEL SENSOR TABLE

PRINT PB AND PROPER LEVEL SENSOR-CONTROLLER COMBINATION WITH EACH OF TWO VALVES

Go to end of program

IS SYSTEM PROPORTIONAL PLUS INTEGRAL?

Yes, IS STATIC PRESSURE SENSOR DESIRED?

No, Go to L11

PRINT PB AND LOW-COST SYSTEM B WITH EACH OF TWO VALVES

Go to end of program

IS 0.25<PB<0.35?

Yes, PRINT PB, RR, AND PROPER LEVEL SENSOR AND VERTICAL SCALE CONTROL WITH EACH OF TWO VALVES

No, Go to L11

HAS MODEL 1405, 4705, 9105, OR 9205 BEEN SELECTED AS ONE OR BOTH OF THE CHEAPEST VALVES?

Yes, ENTER RUNGEKUTTA WITH PROPER CV OF VALVE OR VALVES

Does at least one valve have adequate response?

Yes, PRINT PB AND LOW-COST SYSTEM A WITH EACH OF TWO VALVES (OR ONE VALVE IF ONLY ONE HAD ADEQUATE RESPONSE)

END
SET M EQUAL TO \( (i + K_{TRR}) \)

IS RESPONSE OF A VALVE BEING CHECKED? No \( PB = 0.30 \) (LOW-COST SYSTEM)

Yes

SET ALL TIMES TO ZERO AND DT TO 0.01

IS SYSTEM PROPORTIONAL PLUS INTEGRAL? No

IS CONFIG = 1? Yes

Yes

No

N = 4

N = 3

N = 2

IS CONFIG = 1? Yes

No

COMPUTE ALL CONSTANTS THAT WILL BE USED IN EQUATIONS FOR REYNOLDS NUMBERS AND IN DIFFERENTIAL EQUATIONS

STORE PREVIOUS SOLUTIONS (\( X[1] \) THROUGH \( X[N] \)) OF DIFFERENTIAL EQUATIONS

STORE SIGN OF PREVIOUS \( dH/dT \)
Begin:

COMPUTE INLET PIPE REYNOLDS NUMBER (RP1) AND CONTROL VALVE REYNOLDS NUMBER (RV1). (RV1 0 IF VALVE HAS NOT BEEN SELECTED YET)

IS RP1 < 200?

Yes
Print value of RP1

No

COMPUTE F2

IS X[2]-H3?

No

H2=ZERO

Yes

H2=X[2]-H3

COMPUTE P0 IF TANK IS VENTED: OTHERWISE RETAIN PREVIOUS P0

IS RESPONSE OF A VALVE BEING CHECKED?

Yes

RE1=RV1

No

RE1=RP1

COMPUTE VALVE SIZE COEFFICIENT AT RE1 USING CVCN1

Go to end of program
IS NEW X[1](O1) STABLE?  
Yes  
K=K+1  

IS K>4?  
No  
Go to Begin  
Yes  
End:

COMPUTE FINAL SOLUTIONS AT  
T=TLAST+DT  

IS NEW X[1] STABLE?  
Yes  
STORE INITIAL VALUES IN X ARRAY  
Go to L0  

SET T TO ZERO AND DT TO DT/10  

IS K>4?  
No  
Go to Begin  
Yes  

HAS RISE TIME BEEN CHECKED?  
Yes  

HAS TR[1] BEEN STORED?  
Yes  
TR[1]=T  

IS X[2]=0.1(H1  
-Ηt=0+Ηt=0?)  
Yes  
TR[1]=T  

No  

No  

No  

No  

No  

No  

No
IS $X[2] > 0.1(H_1 - H_t = 0) + H_t = 0$?  

- **Yes**:  
  - IS $X_{LAST}[2] < 0.1(H_1 - H_t = 0) + H_t = 0$?  
    - **Yes**:  
      - $T[1] = T_{LAST} + DT/2$  
      - Go to L4  
    - **No**:  
      - Go to L4

- **No**:  
  - IS $X[2] = 0.9(H_1 - H_t = 0) + H_t = 0$?  
    - **Yes**:  
      - $T[2] = T$  
      - Go to L4  
    - **No**:  
      - IS $X[2] > 0.9(H_1 - H_t = 0) + H_t = 0$?  
        - **Yes**:  
          - $T[2] = T_{LAST} + DT/2$  
          - IS $T[R] < T[R]$?  
            - **Yes**:  
              - PRINT "RISE TIME O.K."  
              - IS RESPONSE OF A VALVE BEING CHECKED?  
                - **Yes**:  
                  - RESTART = 1  
                  - Go to L4  
                - **No**:  
                  - Go to end of RUNGKUTTA
IS LOW-COST SYSTEM BEING CHECKED?  
• No  

CVCN1=CVCN1x1.25  

IS CVCN1>500?  
• No  

PRINT NEW CVCN1  
STORE INITIAL VALUES IN X ARRAY  

SET PB TO 0.05 AND STORE INITIAL VALUES IN X ARRAY  
PRINT "LOW-COST SYSTEM NOT AVAILABLE"  
Go to Start  
PRINT "CANNOT MEET RISE TIME REQUIREMENTS"  
Go to end of program  

Go to start  

HAS OVERSHOOT BEEN CHECKED?  
• No  

HAS dH/dT UNDERGONE A SIGN CHANGE?  
• No  

IS dH/dT > .0001?  
• Yes  
Go to L4  

No  

No  

Yes
IS \( \frac{|H_1 - X[2]|}{X[2]} \) REQUIRED OVERSHOOT? Yes \( \text{OSOK} = 1 \)
No PRINT "OVERSHOOT O.K." Go to L4

IS RESPONSE OF A VALVE BEING CHECKED? Yes \( \text{RESTART} = 1 \)
No Go to end of RUNGKUTTA

IS LOW-COST SYSTEM BEING CHECKED? Yes SET PB TO 0.05 AND STORE INITIAL VALUES IN X ARRAY
No PRINT "LOW-COST SYSTEM NOT AVAILABLE"
Go to Start

IS PROPORTIONAL PLUS INTEGRAL SYSTEM BEING CHECKED? Yes \( \text{DECREASE RR BY 0.25} \)
No IS RR \( \geq 0.25 \)?
Yes No PRINT "RR < 0.25"

Go to end of program
INCREASE PB BY 0.1

IS PB < PBMAX?

STORE INITIAL VALUES IN X ARRAY

PRINT "CANNOT MEET OVERSHOOT REQUIREMENTS"

Go to end of Program

HAS SETTLING TIME BEEN CHECKED?

IS (H1-X[2]) < 0.05(H1-H_t = 0)?

T3 = T3 + DT

HAS (H1-X[2]) UNDERGONE A SIGN CHANGE?

IS (H1-X[2]) = 0?

HAS TSET[2] BEEN STORED?
TSET[2] = T


IS T3 < DELT2?

HAS TSET[1] BEEN STORED?

TSET[1] = T

IS T3 < TRR/2?

DELT2 = TRR/2

SETTLING = 1

PRINT "SETTLING TIME O.K."

IS T > TSETR?

IS LOW-COST SYSTEM BEING CHECKED?

SET PB TO 0.05 AND STORE INITIAL VALUES IN X ARRAY

PRINT "LOW-COST SYSTEM NOT AVAILABLE"

Go to Start
IS RESPONSE OF A VALVE BEING CHECKED?

Yes → RESTART = 1

No → Go to end of RUNGKUTTA

IS PROPORTIONAL PLUS INTEGRAL SYSTEM BEING CHECKED?

Yes → DECREASE RR BY 0.25

No → INCREASE PB BY 0.1

IS PB > PBMAX?

Yes → PRINT "RR < 0.25?"

No → STORE INITIAL VALUES IN X ARRAY

Go to Start

PRINT "CANNOT MEET SETTLING TIME REQUIREMENTS"

Go to end of program

STORE INITIAL VALUES IN X ARRAY

Go to Start

L20:

IS T > TSETR?

No → Go to L4

Yes → Print "RR < 0.25?"
Go to Start

RR=1.0

No

Is proportional plus integral system being checked?

Yes

Initialize \(X[3]\) to 0.82

Store initial values in \(X\) array

Print "Proportional + Reset"

Go to Start

Print "No proportional + Reset system available"

End

Go to Start
APPENDIX F

COMPLETE COMPUTER PROGRAM

The complete computer program is given on the following pages.
PROCEDURE TO KEPT

BEGIN

INTEGER I, TEMP

LABEL L1
I = 1

TEMPCOMPAT

START OF SEGMENT ******** 0004

0003 IS 0247 LONG, NEXT SEG 0002

0001
**PROCEDURE MKMK**

**BEGIN**

**INTEGER** J;

**LABEL** LJKL:

FOR J=1 STEP 1 UNTIL 10 DO BEGIN

IF MKMK(J,J,J) THEN GO TO L21

END;

L21 INCREASE

**END**

**PROCEDURE CWSLIMIT**

**VALUE LIMIT** INTEGER LIMIT;
CUST=CUST(J,J)+CUST(J,J) TOTAL=TOTAL+CUST
*NB(J,J)*
WRITE(PRINT,FL1)+NAME1(N)+NAME2(J)
FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)>=ABS(NB(J,J)) THEN GO TO L3
L3: IF NB(J,J)=0 THEN WRITE(PRINT,FL1)
WRITE(PRINT,FL2)+NAME11(J)+NAME2(J)+COST
IF RATIO(N,J)>=1.0 THEN WRITE(PRINT,FL9) ELSE WRITE(PRINT,FL1)
IF PLAN(J,J) THEN WRITE(PRINT,FL0) GO TO L4 ENDS
IF SB(J,J)=0 THEN GO TO L3
IF STEEL=0 THEN FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
END ELSE BEGIN FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
TOTAL=TOTAL+COST
WRITE(PRINT,FL4)+NAME1(N)+NAME2(J)+COST
END IF STEEL=0 THEN NAME1(N)+NAME2(J)
END ELSE WRITE(PRINT,FL4)
GO TO L4
L4: FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
CUST=CUST(J,J)+NAME2(J)
WRITE(PRINT,FL4)+NAME1(N)+NAME2(J)+COST
FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
L5: IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
IF STEEL=0 THEN WRITE(PRINT,FL4)
FOR 1=1 STEP 1 UNTIL COMPAT DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
L6: IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
CUST=CUST(J,J)+CUST(J,J)
WRITE(PRINT,FL1)+NAME1(N)+NAME2(J)+COST
FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
L7: IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
IF STEEL=0 THEN WRITE(PRINT,FL4)
CUST=CUST(J,J)
COST=CUST(J,J)
TOTAL=TOTAL+COST
WRITE(PRINT,FL1)+NAME2(J)+NAME2(J)+COST
FOR 1=1 STEP 1 UNTIL COMPAT DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
END ELSE WRITE(PRINT,FL4)
TOTAL=TOTAL+COST
WRITE(PRINT,FL4)+NAME1(N)+NAME2(J)+COST
FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
L8: IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
IF STEEL=0 THEN WRITE(PRINT,FL4)
FOR 1=1 STEP 1 UNTIL COMPAT DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
CUST=CUST(J,J)+CUST(J,J)
WRITE(PRINT,FL4)+NAME1(N)+NAME2(J)+COST
FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
L9: IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
IF STEEL=0 THEN WRITE(PRINT,FL4)
CUST=CUST(J,J)
TOTAL=TOTAL+COST
WRITE(PRINT,FL4)+NAME1(N)+NAME2(J)+COST
FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
L10: IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
IF STEEL=0 THEN WRITE(PRINT,FL4)
CUST=CUST(J,J)
TOTAL=TOTAL+COST
WRITE(PRINT,FL4)+NAME1(N)+NAME2(J)+COST
FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
L11: IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
IF STEEL=0 THEN WRITE(PRINT,FL4)
CUST=CUST(J,J)
COST=CUST(J,J)
TOTAL=TOTAL+COST
WRITE(PRINT,FL4)+NAME1(N)+NAME2(J)+COST
FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
L12: IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
IF STEEL=0 THEN WRITE(PRINT,FL4)
CUST=CUST(J,J)
TOTAL=TOTAL+COST
WRITE(PRINT,FL4)+NAME1(N)+NAME2(J)+COST
FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
L13: IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
IF STEEL=0 THEN WRITE(PRINT,FL4)
CUST=CUST(J,J)
TOTAL=TOTAL+COST
WRITE(PRINT,FL4)+NAME1(N)+NAME2(J)+COST
FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
L14: IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
IF STEEL=0 THEN WRITE(PRINT,FL4)
CUST=CUST(J,J)
TOTAL=TOTAL+COST
WRITE(PRINT,FL4)+NAME1(N)+NAME2(J)+COST
FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
L15: IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
IF STEEL=0 THEN WRITE(PRINT,FL4)
CUST=CUST(J,J)
TOTAL=TOTAL+COST
WRITE(PRINT,FL4)+NAME1(N)+NAME2(J)+COST
FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
L16: IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
IF STEEL=0 THEN WRITE(PRINT,FL4)
CUST=CUST(J,J)
TOTAL=TOTAL+COST
WRITE(PRINT,FL4)+NAME1(N)+NAME2(J)+COST
FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
L17: IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
IF STEEL=0 THEN WRITE(PRINT,FL4)
CUST=CUST(J,J)
TOTAL=TOTAL+COST
WRITE(PRINT,FL4)+NAME1(N)+NAME2(J)+COST
FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
L18: IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
IF STEEL=0 THEN WRITE(PRINT,FL4)
CUST=CUST(J,J)
TOTAL=TOTAL+COST
WRITE(PRINT,FL4)+NAME1(N)+NAME2(J)+COST
FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
L19: IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
IF STEEL=0 THEN WRITE(PRINT,FL4)
CUST=CUST(J,J)
TOTAL=TOTAL+COST
WRITE(PRINT,FL4)+NAME1(N)+NAME2(J)+COST
FOR 1=1 STEP 1 UNTIL 10 DO IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
L20: IF NB(J,J)=0 THEN WRITE(PRINT,FL4)
IF STEEL=0 THEN WRITE(PRINT,FL4)
CUST=CUST(J,J)
DIM X1
GO TO L9
IF 0 = X1 THEN WRITE PRINT*FL25+PUS(J,X1)+COST) ELSE WRITE PRINT*FL25+PUS(J,X1)+COST)
END PRINTZ

PROCEDURE HUNGKUTTA(DIAP1+DIAP)+USY=(DIAV3+DUT1+RU[N])
VALUE DIAP1+DIAP+DIAV1+DIAV2
REAL DIAP1+DIAP+DIAV1+DIAV2,USY(N)
INTEGER RESTART
BEGIN
INTEGER I,K,V,N,CHANGE,USOK,SETTLING
REAL T,DT,T1,FAC0,FACn,FAC10,FAC20,FAC30,FAC40,FAC50,FAC60,FAC70,FAC80,FAC90,FAC100
FAC5=FAC50*FAC60,FAC6=FAC60*FAC70,FAC7=FAC70*FAC80,FAC8=FAC80*FAC90,FAC9=FAC90*FAC100,FAC10=FAC100*FAC20,FAC2=FAC20*FAC30,FAC3=FAC30*FAC40,FAC4=FAC40*FAC50,FAC5=FAC50*FAC60,FAC6=FAC60*FAC70,FAC7=FAC70*FAC80,FAC8=FAC80*FAC90,FAC9=FAC90*FAC100
DEL(T,FAC,H,G)
ARRAY THEO123(T),THEO123(1),THEO123(2),THEO123(3)
FORMAT FMTC6E20.5)

FORMAT FL3("Rise Time O.K.")
FL3("Rise CV = "E15.5")
FL3("Cannot Meet Rise Time Requirements")
FL3("Missing O.K.")
FL3("Cannot Meet Overshoot Requirements")
FL3("Cannot Meet Settling Time Requirements")

START OF SEGMENT ************ 0002
0002 IS 0004 LONG> NEXT SEG 0004

START OF SEGMENT ************ 0010
0010 IS 0004 LONG> NEXT SEG 0004

START OF SEGMENT ************ 0013
0013 IS 0004 LONG> NEXT SEG 0004
FL1("SETTLING TIME U.K."), 0010
FL1("STABLE STAIL EMUH U.K."), 0010
FL1("CANNOT MEET OVERSHOOT REQUIREMENTS(RH>0.25")", 0010
FL1("CANNOT MEET SETTLING TIME REQUIREMENTS(RH>0.25")", 0010
FL1("PROPORTIONAL+RESET")
FL1("CUST SYSTEM NOT AVAILABLE"), 0010
FL1("(T1+A)"x17+"(T2)"x16+"(T3)"x15+"(T4)"x14+"(T5)"x13+"(T6)"x12+"(T7)"x11+(T8)")
FL1("NO PHANTOMAL+RESET SYSTEM AVAILABLE")

031 IS 0133 LONG NEXT SET DOWN

LABEL L0,L1,L2,L3,L4,L5,L6,L7,L8,L9,L10,L11,L12,L13,L14
L15,L16,L17,L18,L19,L20,L21,L22
DIFF=1=ORIGIN(21)
H=1(41)

IF RESTART=1 THEN PH=0,30
G1(1)=0,1 F1(1)=0,00)
IF RH=0.0 THEN H4=PH=PRINT(FL14) ELSE H4=PRINT(FL15)
START#1=11
VLEST=0
T3×0.07
OSBK=0
SETTLNG=0
T=0.07
DT×0.3
FOR I=1 TO BEGIN TRE=0.01 TSETIL=0.0 FND
IF RH×0.0 THEN H4=H4
O4×4033×133×1K(13)
IF CONFIRM THEN N+2 ELSE M+1
GU TO L27
END
IF CONFIRM THEN N+3 ELSE M+4
L21 END

FAC1 = 3.3 * XU / (HAP1 + HAP3 + HAP5)
FAC2 = LE1 + LE5 / (HAP3 * HAP5)
FAC3 = 3.3 * XU / HAP3
IF DIAV >= 0.0 THEN FAC3 = 3.3 * XU / HAP3
FAC4 = 1.94 * XU / HAP3
FAC5 = -2 * XU / HAP1
IF CONFIG = 2 THEN BEGIN
  FAC10 = 3.3 * XU / (HAP3 + HAP5)
  FAC20 = (LE4 + LE5) / HAP3 * 5;
  FAC30 = 3.3 * XU / HAP3
  FAC30 = 3.3 * XU / HAP3
  FAC40 = 1.94 * XU / HAP3
  FAC50 = -2 * XU / HAP1
END

LDZ FUR #1 STEP 1 UNTIL 4 DO KLASIE1 = KE(1)
KLASIE + 1
CHANGE = SIGN(0124)
FUR #1 STEP 1 UNTIL 4 DO BEGIN
RP1 = FAC3 * XU
V1 = FAC3 * XU
IF HPI >= 200 THEN BEGIN PRINT + V1 + RP1; STOP + 12 GO TO END
IF HPI <= 200 THEN F = FAC4 * XU ELSE F = 5.5 * (1 + (FAC5 + 1) * 0.33333)
IF K12 > 3 THEN H2 * H2 + 3 ELSE H2 + 0.01
IF TANKS > 3 THEN P = PUO * Cl + XEP
IF HAP1 = 0.0 THEN H1 = H1 ELSE H1 = H1
IF HAP1 = 0.0 THEN CV1 = CV1 + 0.07 + 0.01 * H1 + (NMLE1 = 1) * 0.3
ELSE IF HAP1 = 0.0 THEN CV1 = CV1 + 0.07 + 0.01 * H1 + (NMLE1 = 1) * 0.3
ELSE IF HAP1 = 0.0 THEN CV1 = CV1 + 0.07 + 0.01 * H1 + (NMLE1 = 1) * 0.3
ELSE CV1 = CV1
H1 = CM + X2
IF TANKS > 3 THEN PRINT

123
IF \( H1A2 > -L \) AND \( H1X2 < DH \) THEN BEGIN
IF \( VLAST = 0 \) THEN BEGIN
\( XT = 0.0 \);
GO TO BOB;
END;
IF \( K = 2 \) OR \( K = 3 \) THEN \( TH = T1 + UT/2 \);  
IF \( T1SUDTIM \) THEN \( XT = T1/00TIM \) ELSE \( XT = 1.0 \);
GO TO BOB;
END;
IF \( H1A2 > -L \) THEN BEGIN
IF \( VLAST = 0 \) THEN \( TH = 0.0 \) ELSE BEGIN
IF \( K = 2 \) OR \( K = 3 \) THEN \( TH = T1 + UT/2 \);
\( VLAST = V1 \);
IF \( T1SUDTIM \) THEN \( XT = T1/00TIM \) ELSE \( XT = 1.0 \);
GO TO BOB;
END;
\( VLAST = 0 \);
\( XT = 0.0 \);
GO TO BOB;
END;
IF \( TH = 0.0 \) THEN BEGIN
\( XT = HTX2/FAC0 + 0.82 \);
IF \( XT < 0.0 \) THEN \( XT = 0.0 \);
IF \( XT > 1.0 \) THEN \( XT = 1.0 \);
GO TO BOB;
END;
IF \( K < 0.0 \) THEN \( XT = 0.0 \);
IF \( K > 0.0 \) THEN \( XT = 1.0 \);
\( OT3 = KJ * (CFA1) * (Pl - Po) / G - H2 - C27.B / CR * C2 * (XT - 1)) \times CV1 + 2 \times 3 * FX2
\times FAC2 \times X1) \times DT;
IF \( N = 3 \) THEN \( OT3 = KJ \times (O2 + 0,0) \) ELSE \( OT3 = KJ \times (O2 + FAC0) \times (Pl - Po) / G - H2 - C27.B / CR * C2 * (XT - 1)) \times CV1 + 2 \times 3 * FX2
\times FAC2 \times X1) \times DT;
GO TO HAX;
BOB: IF 
(UNIF = 1) THEN IF \( KT < 0.0 \) THEN \( X1 = U0(T1) \times G1 \times (K1 + 1) \times FAC1 \times (PI - Po) / 2 \times 0.0 + \Phi \times (K1 - 1) \times CV1 \times (Po + 0.0) + 3 \times FX2
\times FAC2 \times (K1 + 1) \times DT) \times 0.0;
IF X>2 THEN C2(A+2)+AC26[X(2)]=FLOUT*DT
ELSE C2(A+2)+AC26[X(1)]=FLOUT*DT
IF X<0 THEN IF CONFIG=2 THEN BEGIN
RP3=FAC30*X[N-1]
RV3=FAC30*X[N]
IF RP3<200 THEN BEGIN IF PR1 THEN PRINT FL201:=RP3; IF Q THEN GO TO L6 J END
IF RP3>200 THEN F4=FAC40/X[N]
ELSE F4=3.5+3*(FAC50+1.06/RP3)*0.33333
IF RV3<1000 THEN CV3=CVCN3*(0.707+0.11*(LN(RV3)-5.3))
ELSE IF RV3<5000 THEN CV3=CVCN3*(0.884+0.0398*(LN(RV3)-6.91))
ELSE IF RV3<10000 THEN CV3=CVCN3*(0.948+0.01734*(LN(RV3)-8.52))
ELSE CV3=CVC13

0=K/N-(FAC10*(P0-P7)/G+X[N]+(27.8/(K20*CV3)*2+2.1*P-3*F4/FAC20)*X[N])
END

IF KS4 THEN GO TO L31 ELSE IF K=2 THEN GO TO L10

L10 P*0.5L
IF K<3 THEN P+1.0J
FOR 1+1 STEP 1 UNTIL N DO X[I]+0C1*K]+0C1*K]+P
IF X[I]<0.0 THEN GO TO L12
IF UNBUFF=1 THEN IF X[I]<150*ORIGX[I] THEN GO TO L31
IF X[I]<3.0*ORIGX[I] THEN GO TO L31

L12 U=3F7/(10)

L31 IF K<1 THEN FOR 1+1 STEP 1 UNTIL M DO X[I]+0C1*K]+1111
GO TO L0I
L7 IF K<1 THEN FOR 1+1 STEP 1 UNTIL M DO X[I]+0C1*K]=0.5*ORIGX[I]+111
IF X[I]<0.0 THEN GO TO L73
IF UNBUFF=1 THEN IF X[I]<150*ORIGX[I] THEN GO TO L31
IF X[I]<3.0*ORIGX[I] THEN GO TO L31
L73 U=U+0I10L

END
FOR I=1 STEP 1 UNTIL 4 DO X(I)=ORG(I)
GO TO L00
L00: END
FOR I=1 STEP 1 UNTIL 4 DO
X(I)=X(I-1)+2*D(I-1)+D(I)-3+D(I+1)+D(I+2)+6.0+D(I+3)
IF X(I)<0.0 THEN GO TO L13
IF X(I)>0.0 THEN IF X(I)<1.00 THEN GO TO L14
IF X(I)<1.00 THEN GO TO L15
L15: D=D/10;
T=0.09
FOR I=1 STEP 1 UNTIL 4 DO X(I)=OMG(I)
GO TO L00
L13: IF T(2)>PD THEN GO TO L03
IF T(1)>PD THEN T(1)=T(1)+T(2)/2
GO TO L15
END
IF X(I)<1.00 THEN IF X(I)<OMG(I)+X(I)<OMG(I)+X(I)+1.00 THEN GO TO L03
THEN GO TO L15
GO TO L03
L13: T(1)=T(1)+T(2)/2
IF T(2)>PD THEN GO TO L03
IF T(1)>PD THEN T(1)=T(1)+T(2)/2
IF TRAY=PD THEN BEGIN WRITE(PRINT,FL3) STOP END
IF RESTART=PD THEN BEGIN WRITE(PRINT,FL3) STOP END
IF RESTART=PD THEN BEGIN WRITE(PRINT,FL3) STOP END
IF RESTART=PD THEN BEGIN WRITE(PRINT,FL3) STOP END
IF RESTART=PD THEN BEGIN WRITE(PRINT,FL3) STOP END
FOR I=1 STEP 1 UNTIL 4 DO X(I)=OMG(I)
IF \text{TEST12} \text{ THEN GO TO L61}

IF \text{TEST20} \text{ THEN BEGIN

IF \text{PAMO} = 0.30 \text{ THEN GO TO L222}

IF \text{RESTART} \text{ THEN BEGIN

IF \text{PAMO} \text{ THEN BEGIN

IF \text{MIN} = 0.25 \text{ THEN BEGIN

IF \text{RTK} < 0.25 \text{ THEN BEGIN

SETTLNG\text{-}1 = 0

IF \text{PAM} = 1 \text{ THEN BEGIN

FOR \text{I FROM 1 \ UNTIL \text{NO}} \text{ DO EXIT}

GO TO START

END}

PAM = PAM\text{-}1

IF \text{PAM} \geq \text{PAMMAX} \text{ THEN BEGIN

WRITE(CPRINT\text{-}FLG)

STOP\text{-}1 \text{ THEN GO TO L61}

END}

FOR \text{I FROM 1 \ UNTIL \text{NO}} \text{ DO EXIT}

GO TO START

END}

WRITE(CPRINT\text{-}FLG)

\text{L201 IF \text{TEST20} \text{ THEN GO TO L61}

IF \text{ABS}((\text{X(2)})\text{XXS} \text{ THEN BEGIN

IF \text{TEST1} \text{ THEN GO TO L61}

IF \text{TEST21} \text{ THEN \text{GO TO L61}

IF \text{RESTART} \text{ THEN BEGIN

IF \text{PAMO} \text{ THEN BEGIN

IF \text{PAMO} \geq 0.30 \text{ THEN BEGIN

PAM = PAM\text{-}0.025

FOR \text{I FROM 1 \ UNTIL \text{NO}} \text{ DO EXIT}

GO TO START

END}

PAM = PAM\text{-}0.05

IF \text{PAM} \geq \text{PAMMAX} \text{ THEN BEGIN

WRITE(CPRINT\text{-}FLG)

STOP\text{-}1 \text{ THEN GO TO L61}

END}

FOR \text{I FROM 1 \ UNTIL \text{NO}} \text{ DO EXIT}

GO TO START

END}

WRITE(CPRINT\text{-}FLG)

\text{L201 IF \text{TEST20} \text{ THEN GO TO L61}

IF \text{ABS}((\text{X(2)})\text{XXS} \text{ THEN BEGIN

IF \text{TEST1} \text{ THEN GO TO L61}

IF \text{TEST21} \text{ THEN \text{GO TO L61}

IF \text{RESTART} \text{ THEN BEGIN

IF \text{PAMO} \text{ THEN BEGIN

IF \text{PAMO} \geq 0.30 \text{ THEN BEGIN

PAM = PAM\text{-}0.025

FOR \text{I FROM 1 \ UNTIL \text{NO}} \text{ DO EXIT}

GO TO START

END}

PAM = PAM\text{-}0.05

IF \text{PAM} \geq \text{PAMMAX} \text{ THEN BEGIN

WRITE(CPRINT\text{-}FLG)

STOP\text{-}1 \text{ THEN GO TO L61}

END}

FOR \text{I FROM 1 \ UNTIL \text{NO}} \text{ DO EXIT}

GO TO START

END}
GO TO START

LET IF USU*1 THEN GO TO L9
LET IF S104((X2+4)XCHANG THEN GO TO L15
LET IF DE2*34*001 THEN GO TO L8
LET IF 151IF 1=1*E21*003 THEN BEGIN (SIGN*12)
LET IF ((PRINT+FL4)X GO TO L6 ENDF
LET IF RESTING THEN BEGIN Resume GO TO L10 ENDF
LET IF PHA*30 THEN GO TO L22
LET IF READO THEN BEGIN
LET IF K=0.25 THEN BEGIN WRITECPR 1 NT,FL5) STOPXStdG GO TO LF ENDF
FOR I=1 STEP 1 UNTIL A UQ X'H 1 = URI
IF X<TRR/2 THEN GO TO L4 ENDF
LET PB=P8+0.13
LET IF P8+PRIME THEN BEGIN
LET IF ((PRINT+FL5)X STOP恰恰 GO TO LF ENDF
FOR I=1 STEP 1 UNTIL A UQ X2+1#(RIGA13)
GO TO START
LET IF SETLING=1 THEN GO TO L20
LET IF ABS((X2=0.0)001 THEN T3+3+0F ELSE BEGIN
T=0.02 GO TO L6 ENDF
LET IF S104((X21*PRIME(1*E21) THEN GO TO L16
LET IF (X2=0.0)00 THEN GO TO L10
LET IF ((T3+HRA/2 THEN GO TO L3
DEL((X2+10)/2)
GO TO L17
LET IF T3+T2*00 THEN GO TO L10
LET IF T3+HRA/2 THEN IF B ELSE BEGIN
T3=0.2
LET IF 1 THEN GO TO L10
DEL((X2+15)(REAL-15)(REAL)
DEL((X2+15)(REAL-15)(REAL)
IF RH<0.0 THEN GO TO L21
RH=RH*0.5
FOR 1=1 STEP 1 UNTIL 4 DO BEGIN X=0 OR1GX=1,3
FOR 1=1 STEP 1 UNTIL 4 DO X=1 OR1GX=1,3
GO TO START
L21: RH=RH-0.25
IF RH<0.25 THEN BEGIN RH=RH*0.5 GO TO L6 END
FOR 1=1 STEP 1 UNTIL 4 DO X=1 OR1GX=1,3
GO TO START
L6: END RUNGKUTT

BEGIN
LABEL L2=L50=L51=L100=L6

START OF SEGMENT **********

ZTIME(I)

READ(CARD)=FL1=CONFL+TANK+REOM+SLURRY+TANKING+NESS+POD+FL1+P11AL+PRIM+
WRITE(FL1=CONF+TANK+REOM+SLURRY+INRATME+NESS+POD+P11+P1)
READ(CARD)=FL2=DS=FL3=FL4=FL9=FL10
WRITE(FL2=DS=FL3=FL4=FL9=FL10)
READ(CARD)=FL1=FL9=FL10
WRITE(FL1=FL9=FL10)

REAL(CARD)=UX1=UX2=UX3=UX4, UX1=UX2=UX3=UX4
FOR I = 1 STEP 1 UNTIL 5 DO BEGIN
  IF LT[I] = 0 THEN FOR J = 1 STEP 1 UNTIL 20 DO NFI[I,J] = 0
  ELSE HAU(CA = 0) FOR J = 1 STEP 1 UNTIL 20 NFI[I,J] > 0
  SUML = 0
  FOR J = 1 STEP 1 UNTIL 20 DO SUML = SUML + NFI[I,J] x LD[I,J]
  IF NFI[I,21] = 0 THEN GO TO L100
  SUML = SUML + NFI[I,21] x LD[I,21]
END;
CLOSE(CARO); RELEASE;
IF UNOFF = 1 THEN XM1 = XM1 + SUM + SUMH(EJ)(K)(LD(J))
IF NFI[21] = 0 THEN GO TO L100
T1 = SUML + SUMH(EJ)(K)(LD(J))
SUML = SUML + SUMH(EJ)(K)(LD(J))
L100 IF I > 3 THEN L63 = (L3 + 0.3) + SUM ELSE L3 = L3 + SUML
END;
ELSE IF PS15000 THEN CVCN1=CVS/(14.88X10^-6+0.398X10^-6X(LP11/4.91))
ELSE IF PS1<10000 THEN CVCN1=CVS/(0.41+0.0398X(LP11/4.91))
ELSE CVCN1=CVS
NEXTV
0V1=0.05
SELECTIF UNK=1 THEN P2MAX=15.0 ELSE IF TANK=2 THEN P2MAX=P13 ELSE
P2MAX=P00J
CVMN=FMNxCVCN1X0.26
CVMAX=FMAXxCVCN1X0.26
P8=P2MAX;
66 HAU(TAPE1)*A,FAR 0X1*1 STEP 1 UNTIL 10000 BCOY1=UNTIL=MEDM~
00 REAOCTAPE1*FAR 0X1*1 STEP 1 UNTIL A=9999J
FOR I=1 STEP 1 UNTIL 10 0U 3*01
FUI 1*2*3*4 00 NBI(I]«-0; 
GO TO L50J END;
J«-0;
FOR I=1 STEP 1 UNTIL A NO BEGIN
0M=4511E1111
RATN11E11E1
RATN11E12E2
IF UNK=1 OR DUM2=1 OR DUM2=1 OR DUM2=1 THEN BEGIN
J=J+1
NUE[(J]=0E11]
END ENDE
FOR I=1 STEP 1 UNTIL 10 0U 3*011
FOR I = 1 STEP 1 UNTIL 60 BEGIN
IF N(I) = 0 THEN GW TO L2011
CUMAR [H(I)] = 1
GW TO SWHII [DUM]
L101 IF P(I) > 125 THEN GO TO L311
IF T(I) > 35 THEN GW TO L41
RANGEST(I) = 1251
RANGEST(I) = 1251
GW TO L201
L31 IF P(I) > 175 THEN GW TO L51
IF T(I) > 150 THEN GW TO L61
RANGEST(I) = 1251
RANGEST(I) = 1251
GW TO L201
L41 IF T(I) > 300 THEN BEGIN
RANGEST(I+1) = 2501
RANGEST(I+2) = 2501
GW TO L201
L51 IF P(I) > 250 THEN GO TO L81
IF T(I) > 150 THEN GW TO L71
RANGEST(I+1) = 2501
RANGEST(I+2) = 2501
GW TO L201
L71 IF P(I) > 125 THEN GO TO L61
IF T(I) > 400 THEN GW TO L81
RANGEST(I+2) = 1251
GW TO L201
L81 IF P(I) > 150 OR T(I) > 400 THEN GW TO L81
RANGEST(I+1) = 3001
GW TO L201
L61 IF P(I) > 150 OR T(I) > 400 THEN GW TO L81
RANGEST(I+1) = 1501
GW TO L201
GO TO L20;
L91 IF P9>175 THEN GO TO L91
IF T7>150 THEN GO TO L131
RATNGIC2x3x4=125;
GO TO L20;
L131 IF T7>400 THEN GO TO L71
RATNGIC2x3x4=250;
GO TO L20;
L91 IF P9>250 THEN GO TO L91 IF P9>250 THEN GO TO L71
IF P9>400 THEN GO TO L101
L151 IF T7>150 THEN RATNGIC2x3x4=300;
GO TO L20;
L141 IF P9>250 THEN GO TO L20;
IF T7<150 THEN RATNGIC2x3x4=300;
GO TO L20;
L121 IF DUM=3 THEN P15+3.0105262P2=1.6769565P3=1.7777709P4+3.1777709P5=1.00570057
+1.2550600P6=19477-4.6526453P7+104.94P8=2.5649156P9=2.6594156P10=2.4596504
-1.1208283P11=4.6534505P12=12477+5.1.1252509P13=1577777
IF P9>P8 THEN GO TO L20;
RATNGIC(DUM+1)=150;
RATNGIC(DUM+2)=300;
GO TO L201;
L121 IF DUM=3 THEN P10+7.125645783+7.152645783+1.6777709P12=2.458141910P13=3.4577709
+4.0492029P2=44777+1.632564588P3=9.7777709P4+104.94P5=2.0025777
+2.3457202P6=2.0025777+8.7949908P7+54777+2.0181753P8=7.7777709
+4.3268141P9+10477+5.1.1252509P10=12477+5.1.1252509P11=1577777
IF P9>P8 THEN GO TO L121;
RATNGIC(DUM+1)=300;
RATNGIC(DUM+2)=300;
GO TO L20
GO TO L30J
L33J IF P8=400 THEN GO TO L24J
MONEY=0
FOR T=1 STEP 1 UNTIL T=400 THEN IF STEEL=4 THEN GO TO L32J
IF STEEL=0 THEN BEGIN
WRITE(PRINT#12,11) GO TO LX1
END
GO TO L30J
L22J IF T7S-4 OR T7>32 THEN GO TO L23J
EXTCOL=13
GO TO L30J
L25J IF T7S5 OR T7>12 THEN GO TO L24J
GO TO L30J
L32J IF T7S0 OR T7>45 THEN GO TO L35J
RAOFIN=17
L36J FOR T=1 STEP 1 UNTIL T=100 THEN IF STEEL=1 THEN GO TO L37J
IF DELTP>350 THEN BEGIN
IF DELTP>300 THEN GO TO L32 ELSE GO TO L35J
END
H=21
WRITE
IF IN0=0 THEN NTI(1)=0 ELSE NTI(1)=0
L35J H=21
WRITE
IF IN0=0 THEN NTI(2)=0 ELSE NTI(2)=0
L38J IF DN0F=1 THEN GO TO L39J
L37J IF NT1L(1)+1 ELSE NT1L(1)=0
L38J IF NT1L(2)+1 ELSE NT1L(2)=0
L39J IF NT1L(3) OR NT1L(2)>0 THEN GO TO L33J
L33J IF DN0F=1 THEN GO TO L39J
NT1L(1)=0
GO TO L33J
L39J M=51
WRITE

IF UC[1:0] = 0 THEN GO TO L46
K = NUMC[1:0]
IF CV[1:3] CVMIN OR CV[1:3] CVMAX THEN GO TO L46
J = J + 1
AVAIL(J) = 1
L46: END
GO TO L47
LAST FOR J = 1 UNTIL NALVS DO BEGIN
FOR K = INIT*LMVFC[1:1] UNTIL IFINAL DO BEGIN
IF CV[1:3] CVMIN OR CV[1:3] CVMAX THEN GO TO L11
J = J + 1
AVAIL(J) = 1
GO TO L31
L31 END
L31: IF J = 1 THEN BEGIN WRITE(NH[1:3],FL100)
GO TO L46
END
COMPAT = J5
FOR J = 1 UNTIL COMPAT DO BEGIN
M = AVAIL(J);
UNIT(J) = 0
FOR J = 1 UNTIL M DO BEGIN
IF NH[1:3] THEN GO TO L46
L = J
FOR K = 1 UNTIL 3 DO IF AUSE(NH[1:3]) = NH[1:3] THEN L = L + 1
IF LH[1:1] THEN GO TO L46
L46 END
UNIT(1)=11
LONG END
TAKING
IF COMPARE THEN BEGIN
WRITE(PRINT,FL1005) ON TO (8)
END
FOR J=1 STEP 1 UNTIL COMPAT DO BEGIN
N=AVAIL(J)
UNIT(J)=0
L=0
FOR J=1 STEP 1 UNTIL N DO BEGIN
DEefd
IF N[I](J) THEN GO TO L43
FOR K=1 STEP 1 UNTIL L DO IF ABS(N[I](J))=N[I](J) THEN L=K
IF L=0 THEN GO TO L43
IF RATNG(J)=0 THEN GO TO L42
FOR K=1 STEP 1 UNTIL 3 DO IF RATNG(K,J)=RATNG(K,J) THEN L=K
L=L+K
IF L>0 THEN GO TO L44
L42 IF L=0 THEN GO TO L43
L43 IF L=0 THEN GO TO L43
L44 IF L=0 THEN GO TO L43
L=0
END
UNIT(1)=11
LONG END
TAKING
IF COMPARE THEN BEGIN
WRITE(PRINT,FL1005) ON TO (8)
END
IF COMPARE THEN GO TO (8)
FOR J=1 STEP 1 UNTIL COMPAT DO BEGIN
N=AVAIL(J)
0043
0050
0067
0074
0081
0088
0095
0102
0109
0116
0123
0130
0137

IF SEAL1320 THEN GO TO L63
IF EXTCOL1 THEN IF EXTCOL1 THEN GO TO L63 ELSE GO TO L63
IF ADDEND1 THEN IF ADDEND1 THEN GO TO L63 ELSE GO TO L63
GO TO L64
L63 IF SEAL1320 THEN GO TO L63
L64 IF MUNELM THEN GO TO L66
FOR M+1 STEP 1 UNTIL 90 00 FOR J+1 STEP 1 UNTIL 40
IF ASE1SH(J)+ASE1H(J) THEN L64
GO TO L63
L66 FOR M+1 STEP 1 UNTIL 90 00 FOR J+1 STEP 1 UNTIL 40
IF ASE1SH(J)+ASE1H(J) THEN L64
L67 IF L>0 THEN GO TO L64
L68 END
END
IF COMPA1320 THEN BEGIN
WRITE(PRINT1000B) J GO TO L68
END;
FOR M+1 STEP 1 UNTIL COMPAT DO BEGIN
FOR J+1 STEP 1 UNTIL 1000 BEGIN
IF NTJ(J) THEN GO TO L69
FOR J+1 STEP 1 UNTIL 1000 BEGIN
IF TPEM(J)+TPEM(J) THEN GO TO L69
L69 END;
L70 FOR M+1 STEP 1 UNTIL 1000 BEGIN
IF TPEM(J) THEN GO TO L69
L71 END;
L72 END;
OUTTOUTJ
TAKOUTJ
IF COMPAT = 0 THEN BEGIN
WRITE(PRINT,FL3006) GO TO L21
END
IF COMPAT THEN GO TO L20
FOR I=1 STEP 1 UNTIL COMPAT DO BEGIN
  IF CMTR(A) MOD 100=6 THEN BEGIN
    FOR I=1 TO 100 DO IF CMTR(A) MOD 100=6 THEN GO TO L22
  END
END
IF COMPAT = 0 THEN BEGIN
WRITE(PRINT,FL3006) GO TO L20
END
GO TO HE58
IF CMTR(A) MOD 100=6 THEN BEGIN
  FOR I=1 TO 100 DO IF CMTR(A) MOD 100=6 THEN GO TO L22
END
END;
IF ( fraudulent mu 5054 THEN go to line 1030)

M1031*33

L103E END

TAKOUT

L1030 FOR J+1 STEP 1 UNTIL CUMPAT DO BEG

TOTCUST[101000]

M+AVAIL[N1]


IF DELTPX/K+X100 THEN BEGIN UX1+1 THEN GO TO L1031 END

FOR D1+12 DO IF DELTPSDELEP/K+DX1 THEN GO TO L1031

L1031 TOTCUST[T+P+CTCOSTX/K+M1]

FOR J+1 STEP 1 UNTIL a DO FOR K=12 DO BEGIN


END

FOR J+1 STEP 1 UNTIL a DO BEGIN

IF MBX[I,J] THEN GO TO L751

FOR M+1 STEP 1 UNTIL D DO BEGIN

IF MBX[I,J]=D THEN BEGIN

IF MBX[I,J]<MBX[I,J+D] THEN BEGIN

MBX[I,J]=MBX[I,J+D]

MBX[I,J]=MBX[I,J+D]

CUST[I,J]=CUST[I,J]+D1

GO TO L751

END

END

L751 IF MBX[I,J]=D THEN GO TO L761

IF MBX[I,J]<MBX[I,J+D] THEN BEGIN

MBX[I,J]=MBX[I,J+D]

MBX[I,J]=MBX[I,J+D]

CUST[I,J]=CUST[I,J]+D1

GO TO L751

END

L761 END END

143
FOR $i=1$ STEP 1 UNTIL $8$ DO
  L90: END
  TOTCOST[$i$] = TOTCOST[$i$] + TMCOST[$M,K$]
  TMCUST[$M,NN$] = TMCUST[$M,NN$] + $i$
  IF $K=1$ THEN GO TO L90
  TOTCOST[$i$] = TOTCOST[$i$] + TMCOST[$M,K$]
  L90: IF POSCOST[$M,NN$] > TOTC0ST[$M,K$] THEN GO TO L91
  TOTCOST[$i$] = TOTCOST[$i$] + POSCOST[$M,K$]
  GO TO L92
  L91: IF POSCOST[$M,K$] > TOTC0ST[$M,K$] THEN GO TO L92
  TOTCOST[$i$] = TOTC0ST[$M,K$] + POSCOST[$M,K$]
  L92: END
FOR $i=1$ STEP 1 UNTIL COMPAT DO BEGIN
  AUSAVAIL[$i$] = AUSAVAIL[$i$] + CHEAP[$i$] = 0 END
  J+1
  IF (FINAL=COMPAT) THEN L92
  L93: J+1
  K+1
  FOR $i=1$ STEP 1 UNTIL $K=1$ DO
    IF TOTCOST[$i$] > TOTCOST[$K$] THEN $K$+1
  CHEAPE[$K$] = AUSAVAIL[$K$] = 0 END
 FOR $K=1$ STEP 1 UNTIL $K=1$ DO BEGIN
  TOTC0ST[$M$] = TOTC0ST[$M$] + AUSAVAIL[$M$] = 0 END
  IF (FINAL=FINAL+1) THEN L93
  IF (FINAL=0) THEN GO TO L92
  GO TO L93
L93: J+1
  M+1
  L93: IF PREUti OR NN=0 THEN GO TO L91
  IF TANK=1 THEN GO TO L91
  L91:
IF H157.27G AND P157.235 THEN GO TO L353
L352 IF DNOFF THEN BEGIN A=MUNGE(CHRAPS1) GO TO L737 END
FOR I=1 STEP 1 UNTIL COMPAT DO IF AVG1TE(CHRAPS1) THEN GOTO L751
L750 END CYCLE=CHRAPS1:I=1/0.26
NEXT=I
FOR I=1 STEP 1 UNTIL 5 DO X1=TRIG(X1)
RUNG91617(0,357167:CHRAPS1) AND THEN GOTO CHRAPS1)
ELSE GOTO L72
IF NEXT=0 THEN BEGIN M=M+1 CHEAP(CHRAPS1) END
IF M>1 THEN GO TO L751
IF JSCOMPAT THEN GO TO L737
L736 END ELIMINATION BLOCK
BEGIN
COMMENT "PRINTING BLOCK"
FORMAT FL4001("PRINTING = CHECK DISPLACER COMPATIBILITY"")
FL4002("MODEL NO. 750")
FL4008("M0DEL NO. 75")
FL4009("MODEL NO. 76")
FL4006("MODEL NO. 75")
FL4007("MODEL NO. 76")
FL4002("NO TRANSmitter AVAILABLE")
FL4003("SYSTEM = SLN6.*COMPONENT = IX6.*CO6F")
FL4008("TYPE 72-75, SERIES 1*, X0*, F0, 2")
FL4005("TYPE 72-75, SERIES 1*, X0*, F0, 2")
FL4007("MODEL NO. 75")
FL4005("MODEL NO. 76")
FL4003("M0DEL NO. 75")
FL4002("M0DEL NO. 76")
FL4001("M0DEL NO. 75")
FL4006("M0DEL NO. 76")
FL4001("M0DEL NO. 75")
FL4003("M0DEL NO. 76")
FL4001("M0DEL NO. 75")
FL4003("M0DEL NO. 76")
FL4001("M0DEL NO. 75")
FL4003("M0DEL NO. 76")
FL4001("M0DEL NO. 75")
FL4003("M0DEL NO. 76")
FL4001("M0DEL NO. 75")
FL4003("M0DEL NO. 76")
FL4001("M0DEL NO. 75")
FL4003("M0DEL NO. 76")
FL4001("M0DEL NO. 75")
FL4003("M0DEL NO. 76")
L3: IF TARG=1 THEN GO TO L51
L51: FOR J=1 STEP 1 UNTIL 10 DO BEGIN
IF ABS(K(J))=1 THEN GO TO L51
END
L52: FOR J=1 STEP 1 UNTIL 10 DO BEGIN
IF ABS(K(J))=1 THEN GO TO L51
END
WRITE(PRINT/FL4000) 007
L71: IF (INCRTNS)<350.0 THEN BEGIN K=31 GO TO L81 END;
IF (INCRTNS)<300.0 THEN BEGIN K=32 GO TO L81 END;
WRITE(PRINT/FL4001) 008
SPECIAL=1
GO TO L9;
L9: FOR J=1 STEP 1 UNTIL 9 IF CMGISP(L J) THEN GO TO L91
L91: WRITE(PRINT/FL1) 009
L91: WRITE(PRINT/FL1) 010
IF HAPP<L J) THEN WRITE(PRINT/FL4001)
WRITE(PRINT/FL4002) 011
IF SPECIAL=1 THEN BEGIN TOTAL=0.91 GO TO L271 END;
COST=DISCOST+0.91
IF HAPP<L J) THEN BEGIN COST=COST+25.01 TOTAL=COST
WRITE(PRINT/FL4001) 012
L271: WRITE(PRINT/FL4002) 013
L271: WRITE(PRINT/FL4002) 014
L30: FOR J=1 STEP 1 UNTIL COMPAT=10 IF AVAIL(J,J) THEN WRITE(PRINT/FL4001)
WRITE(PRINT/FL4002) 015
IF (J J)*" OS" AND (J J)*" SS" THEN GO TO L201
IF (J J)*" OS" THEN TYPE(J J)=" SUITABLE" ELSE TYPE(J J)=" SINGLE"
WRITE(PRINT/FL4001) 016
WRITE(PRINT/FL4001) 017
WRITE(PRINT/FL4001) 018
IF UPLCP(J,J)=1.0 THEN WRITE(PRINT/FL4001) 019
WRITE(PRINT/FL4001) 020
IF UPLCP(J,J)=1.0 THEN BEGIN K(J)=13 GO TO L201 END;
L201: WRITE(PRINT/FL4001) 021
WRITE(PRINT/FL4001) 022
WRITE(PRINT/FL4001) 023
WRITE(PRINT/FL4001) 024
WRITE(PRINT/FL4001) 025
WRITE(PRINT/FL4001) 026
L31: ENDF
IF J = 0 THEN GO TO L32
CHEAPE[21] = 0
L32: IF J = 0 THEN COMPONENT("B") ELSE COMPONENT("A")
WRITE(PHINT*,FL1,PB))
WRITE(PRINT*,FL80003)
IF COMPONENT("A") THEN COST = 187,0 ELSE COST = 187,0
TOTAL + COST
WRITE(PRINT*,FL4007,COMPONENT,COST))
J = CHEAPE[21] + 1
L34: FOR I = 1 STEP 1 UNTIL COMPAT DO IF AVAIL[I,J] THEN M = COL[I,J]
WRITE(PHINT*,FL2,HODDLJ1 SIZE(I,J))
IF TYPE(I,J) = 0,0 AND TYPE(I,J) = SS THEN GO TO L00
IF TYPE(I,J) = 0,0 AND TYPE(I,J) = DOUBLE THEN TYPE(I,J) = SINGLE
WRITE(PRINT*,FL3,TYPETJ3)
GO TO L63
L60: IF TYPE(I,J) = ANG THEN WRITE(PRINT*,FL4) ELSE WRITE(PRINT*,FL53)
L61: WRITE(PRINT*,FL6,CYJ3)
IF DELP[I,J] = "DOMI" THEN BEGIN DX[I,J] = 0.0 THEN BEGIN DX[I,J] = 0.0 END
FOR DX1 = 0.2 DO IF DELP[I,J] = "DOMI" THEN GO TO L43
L43: COST = ACTCOST [J, M, I, J] TOTAL + TOTAL + COST
WRITE(PRINT*,FL7,ACTNOIT1, M, 0X1, COST))
WRITE(PRINT*,FL8,COST)
IF CHEAPE[21] = 0 OR J = CHEAPE[2] THEN GO TO L34
J = CHEAPE[23] + 1
WRITE(PRINT*,GOBL1)
IF M THEN BEGIN COST = 85,00 TOTAL + COST
WRITE(PRINT*,FL9001+COST))
COST = 310,00 TOTAL + TOTAL + COST
WRITE(PRINT*,FL8001+COST))
GO TO L34
END
COST+IF COMPONENT="A" THEN 110.0 ELSE 147.0
TOTAL*COST;
WRITE(PRINT,FL1009*COMPONENT,COST);
GO TO L34;
L34 IF "STATIC" THEN GO TO L119;
WRITE(PRINT,FL1008*PB);
WRITE(PRINT,FL0803*PB);
WRITE(PRINT,FL6003*PB);
WRITE(PRINT,FL6009*PB);
WRITE(PRINT,FL4003*PB);
COST=85.01 TOTAL*COST;
WRITE(PRINT,FL4009*PB);
WRITE(PRINT,FL4010*PB);
WRITE(PRINT,FL4011*PB);
WRITE(PRINT,FL4012*PB);
WRITE(PRINT,FL4013*PB);
WRITE(PRINT,FL4014*PB);
WRITE(PRINT,FL4015*PB);
WRITE(PRINT,FL4016*PB);
L601 FOR I=1 STEP 1 UNTIL CDPAINT
IF A[I] < 0 THEN COST=95.0;
WRITE(PRINT,FL1001*PB);
WRITE(PRINT,FL6001*PB);
WRITE(PRINT,FL4001*PB);
WRITE(PRINT,FL4002*PB);
WRITE(PRINT,FL4003*PB);
WRITE(PRINT,FL4004*PB);
WRITE(PRINT,FL4005*PB);
WRITE(PRINT,FL4006*PB);
WRITE(PRINT,FL4007*PB);
WRITE(PRINT,FL4008*PB);
WRITE(PRINT,FL4009*PB);
WRITE(PRINT,FL4010*PB);
WRITE(PRINT,FL4011*PB);
WRITE(PRINT,FL4012*PB);
WRITE(PRINT,FL4013*PB);
WRITE(PRINT,FL4014*PB);
WRITE(PRINT,FL4015*PB);
WRITE(PRINT,FL4016*PB);
L601 FOR I=1 STEP 1 UNTIL CDPAINT
IF A[I] < 0 THEN COST=95.0;
WRITE(PRINT,FL1001*PB);
WRITE(PRINT,FL6001*PB);
WRITE(PRINT,FL4001*PB);
WRITE(PRINT,FL4002*PB);
WRITE(PRINT,FL4003*PB);
WRITE(PRINT,FL4004*PB);
WRITE(PRINT,FL4005*PB);
WRITE(PRINT,FL4006*PB);
WRITE(PRINT,FL4007*PB);
WRITE(PRINT,FL4008*PB);
WRITE(PRINT,FL4009*PB);
WRITE(PRINT,FL4010*PB);
WRITE(PRINT,FL4011*PB);
WRITE(PRINT,FL4012*PB);
WRITE(PRINT,FL4013*PB);
WRITE(PRINT,FL4014*PB);
WRITE(PRINT,FL4015*PB);
WRITE(PRINT,FL4016*PB);
L601 FOR I=1 STEP 1 UNTIL CDPAINT
IF A[I] < 0 THEN COST=95.0;
WRITE(PRINT,FL1001*PB);
WRITE(PRINT,FL6001*PB);
WRITE(PRINT,FL4001*PB);
WRITE(PRINT,FL4002*PB);
WRITE(PRINT,FL4003*PB);
WRITE(PRINT,FL4004*PB);
WRITE(PRINT,FL4005*PB);
WRITE(PRINT,FL4006*PB);
WRITE(PRINT,FL4007*PB);
WRITE(PRINT,FL4008*PB);
WRITE(PRINT,FL4009*PB);
WRITE(PRINT,FL4010*PB);
WRITE(PRINT,FL4011*PB);
WRITE(PRINT,FL4012*PB);
WRITE(PRINT,FL4013*PB);
WRITE(PRINT,FL4014*PB);
WRITE(PRINT,FL4015*PB);
WRITE(PRINT,FL4016*PB);
L601 FOR I=1 STEP 1 UNTIL CDPAINT
IF A[I] < 0 THEN COST=95.0;
WRITE(PRINT,FL1001*PB);
WRITE(PRINT,FL6001*PB);
WRITE(PRINT,FL4001*PB);
WRITE(PRINT,FL4002*PB);
WRITE(PRINT,FL4003*PB);
WRITE(PRINT,FL4004*PB);
WRITE(PRINT,FL4005*PB);
WRITE(PRINT,FL4006*PB);
WRITE(PRINT,FL4007*PB);
WRITE(PRINT,FL4008*PB);
WRITE(PRINT,FL4009*PB);
WRITE(PRINT,FL4010*PB);
WRITE(PRINT,FL4011*PB);
WRITE(PRINT,FL4012*PB);
WRITE(PRINT,FL4013*PB);
WRITE(PRINT,FL4014*PB);
WRITE(PRINT,FL4015*PB);
WRITE(PRINT,FL4016*PB);
IF TYPE(J) = "AN" THEN TYPE(J) = "DOUBLE" ELSE TYPE(J) = "SINGLE"
WRITE(FL4001, TYPE(J))
WRITE(FL4002, TYPE(J))
WRITE(FL4003, TYPE(J))
WRITE(FL4004, TYPE(J))
WRITE(FL4005, TYPE(J))
WRITE(FL4006, TYPE(J))
WRITE(FL4007, TYPE(J))
WRITE(FL4008, TYPE(J))
WRITE(FL4009, TYPE(J))
WRITE(FL4010, TYPE(J))
WRITE(FL4011, TYPE(J))
WRITE(FL4012, TYPE(J))
WRITE(FL4013, TYPE(J))
WRITE(FL4014, TYPE(J))
WRITE(FL4015, TYPE(J))
WRITE(FL4016, TYPE(J))
WRITE(FL4017, TYPE(J))
WRITE(FL4018, TYPE(J))
WRITE(FL4019, TYPE(J))
WRITE(FL4020, TYPE(J))
WRITE(FL4021, TYPE(J))
WRITE(FL4022, TYPE(J))
WRITE(FL4023, TYPE(J))
WRITE(FL4024, TYPE(J))
WRITE(FL4025, TYPE(J))
WRITE(FL4026, TYPE(J))
WRITE(FL4027, TYPE(J))
WRITE(FL4028, TYPE(J))
WRITE(FL4029, TYPE(J))
WRITE(FL4030, TYPE(J))
WRITE(FL4031, TYPE(J))
WRITE(FL4032, TYPE(J))
WRITE(FL4033, TYPE(J))
WRITE(FL4034, TYPE(J))
WRITE(FL4035, TYPE(J))
WRITE(FL4036, TYPE(J))
WRITE(FL4037, TYPE(J))
WRITE(FL4038, TYPE(J))
WRITE(FL4039, TYPE(J))
WRITE(FL4040, TYPE(J))
WRITE(FL4041, TYPE(J))
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WRITE(FL4043, TYPE(J))
WRITE(FL4044, TYPE(J))
WRITE(FL4045, TYPE(J))
WRITE(FL4046, TYPE(J))
WRITE(FL4047, TYPE(J))
WRITE(FL4048, TYPE(J))
WRITE(FL4049, TYPE(J))
WRITE(FL4050, TYPE(J))
WRITE(FL4051, TYPE(J))
WRITE(FL4052, TYPE(J))
WRITE(FL4053, TYPE(J))
WRITE(FL4054, TYPE(J))
WRITE(FL4055, TYPE(J))
WRITE(FL4056, TYPE(J))
WRITE(FL4057, TYPE(J))
WRITE(FL4058, TYPE(J))
WRITE(FL4059, TYPE(J))
WRITE(FL4060, TYPE(J))
WRITE(FL4061, TYPE(J))
WRITE(FL4062, TYPE(J))
WRITE(FL4063, TYPE(J))
WRITE(FL4064, TYPE(J))
WRITE(FL4065, TYPE(J))
WRITE(FL4066, TYPE(J))
WRITE(FL4067, TYPE(J))
WRITE(FL4068, TYPE(J))
WRITE(FL4069, TYPE(J))
WRITE(FL4070, TYPE(J))
WRITE(FL4071, TYPE(J))
WRITE(FL4072, TYPE(J))
WRITE(FL4073, TYPE(J))
WRITE(FL4074, TYPE(J))
WRITE(FL4075, TYPE(J))
WRITE(FL4076, TYPE(J))
WRITE(FL4077, TYPE(J))
WRITE(FL4078, TYPE(J))
WRITE(FL4079, TYPE(J))
WRITE(FL4080, TYPE(J))
WRITE(FL4081, TYPE(J))
WRITE(FL4082, TYPE(J))
WRITE(FL4083, TYPE(J))
WRITE(FL4084, TYPE(J))
WRITE(FL4085, TYPE(J))
WRITE(FL4086, TYPE(J))
WRITE(FL4087, TYPE(J))
WRITE(FL4088, TYPE(J))
WRITE(FL4089, TYPE(J))
WRITE(FL4090, TYPE(J))
WRITE(FL4091, TYPE(J))
WRITE(FL4092, TYPE(J))
WRITE(FL4093, TYPE(J))
WRITE(FL4094, TYPE(J))
WRITE(FL4095, TYPE(J))
WRITE(FL4096, TYPE(J))
WRITE(FL4097, TYPE(J))
WRITE(FL4098, TYPE(J))
WRITE(FL4099, TYPE(J))
WRITE(FL4100, TYPE(J))
}
IF DELT(J,M)+DEL(0,0) THEN BEGIN DX1+1 GO TO L73
FOR DX1=1 TO 2 IF DLFLFL1(T,J,M+DX1) THEN GO TO L73
L73: CUST+ACTCUST(J,M+DX1) TOTAL+TOTAL+COST
IF (MODEL(J,M) MOD 1000) THEN WRITE(PRINT,FL2,0LINKC,J,ACTNO,J,M+DX1) ELSE WRITE(PRINT,FL7,ACTNO,J,M+DX1)
PRINTZ
IF CHEAP(J,J)=0 OK CHEAP(J,J)=J THEN GO TO L8
J=CHEAP(J,J)
WRITE(PRINT,PRINT1))
COST+0.05 TOTAL+CUST
WRITE(PRINT,PRINT2))
COST+0.05 TOTAL+TOTAL+COST
WRITE(PRINT,PRINT3))
GO TO L73
END PRINTING BLK1
L8: WRITE(PRINT,PAGE1))
WRITE(PRINT,FL2000+(TIME(11)+3)/60))
END END.
FILE CNTLC5 IS SEGMENT NUMBER 0030: PRT ADDRESS IS 0015
HEADNLIL IS SEGMENT NUMBER 0031: PRT ADDRESS IS 0016

NUMBER OF ERRORS DETECTED = 000. COMPILED TIME = 0131 SECONDS.

PRT SIZE=0216 TOTAL SEGMENT SIZE=04602 WORDS STORAGE REQ. 905109 WORDS SEG. 0031.
ESTIMATED CORE STORAGE REQUISITION = 10574 WORDS.
LITERATURE CITED


11. Forman and Oriolo, op. cit.


20. Buckley, *op. cit.*


