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# ADVANCED TURBINE AEROTHERMAL RESEARCH RIG (ATARR) FACILITY MODEL OPERATION

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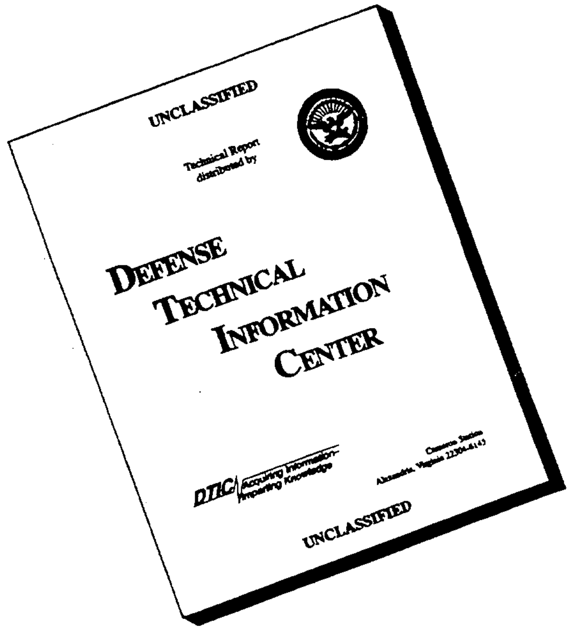


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This facility model is a major operating tool for the ATARR facility. It can provide information about setting the eddy-brake, main valve activation pressures, initial fill pressures, test gas properties as well as predicting performance. It is important to remember that the facility model is just a model, the numbers it produces are approximate. Some time has been spent with the model trying to make the predicted main valve performance reflect its actual motion more accurately. In the future, as systems are added, it should be possible to compare the model predictions of the torque, eddy brake temperature, etc., with data. As a result, the facility model will generally be one which changes with time. This memorandum is written to document some of the history of the model, discuss how it is run presently, and point towards future work.

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# Operation of the Facility Model

By: C. Haldeman and M. Dunn

Date: 5-7-93

## Introduction:

The facility model is a major operating tool for the ATARR facility. It can provide information about setting the eddy-brake, main valve activation pressures, initial fill pressures, test gas properties as well as predicting performance. It is important to remember that the facility model is just a model, the numbers it produces are approximate. Some time has been spent with the model trying to make the predicted main valve performance reflect its actual motion more accurately. In the future, as systems are added, it should be possible to compare the model predictions of the torque, eddy brake temperature, etc. with data. As a result, the facility model will generally be one which changes with time. This memorandum is written to document some of the history of the model, discuss how it is run presently, and point towards future work.

## History:

The facility model (originally called the math model) was built at MIT by Dr. Gerry Guenette. The model arrived at Calspan and was documented initially by Mike Stanton (see included "Original Math Model Description" by Mike Stanton), and not much was done with it until the main valve model verification began. Several changes were made in the default values for the plumbing sizes, and the friction coefficients (to reflect reality). These are all documented in three memorandums[1] attached at the end of this document. All of these changes dealt with the main valve performance aspects of the model.

Some relatively strange behavior has been observed in the valve performance. This has required the examination of the original main valve model (which was a four chamber model) with a view towards incorporating two more choke points. Presently WPAFB is performing this task. In addition, at high temperatures, the main valve did not operate smoothly, requiring more actuator pressure to open. Upon inspection, it was determined that the thermal expansion of the original bearings was incompatible with the surrounding material and that some binding could occur at higher temperatures. These bearings have been redesigned and rebuilt, and testing of the valve should begin shortly.

---

[1] C. Haldeman and M. Dunn, "Main Valve Model Update", Memo 7-27-92; C. Haldeman and M. Dunn, "Main Valve Model Update II", Memo 10-6-92; C. Haldeman, "Math Model Revisions", Memo 10-27-92

In all other respects, the facility model is the same as the one delivered from MIT. What has been changed is the manner in which the model is run, and the interpretation of the results. For detailed discussion about the integration scheme, and the governing equations of the model one should see either Dr. Guenette's notes or Mike Stanton's documentation. The rest of this document will discuss how the model is operated presently.

## Operation of Facility Model

The entire facility model suite of software consists of a main FORTRAN code named "facility.F" which resides in */usr/atarr/src/fortran* , collections of subroutines called by "facility" (also contained in the same directory), and an X-11 interface called mm (which resides in */usr/atarr/src/mathmodel*). Listed in "facility" are all of the subroutines which the main code calls. It should be noted that all executable code placed in */usr/atarr/bin* can be enacted in any directory and this is where copies of all DAS system executable code exist. The program can be run either as a stand-alone program by typing "facility" or using an X-11 interface invoked by typing "mm". In both cases the program requires at least two files: a parameters file and a configuration file. The FORTRAN code presupposes that those already exist, the X-11 interface allows you to make these files. The variables which are listed in these files are included in a note called "Facility Model Parameters", located at the back of this report.

Output of the program consists of several files. The original files were BD.OUT and BD.PLT. These files regurgitate the parameter and configuration files as well as the time histories of various properties (in ASCII format). The only difference in these files is that the BD.PLT file was designed to be used with a plotting routine. New output files have been added. One is defined by the user as a comma separated file containing main valve data only (default name is valve.dat). This is a consolidation of information contained in BD.PLT which has been used to analysis the main valve performance. This file is easily portable to other operating systems and other programs for more detailed analysis. In addition, there are several files of the form P(5-8)_FM.3, POS_FM.3, and VEL_FM.3. These are time history files of the main valve pressures and motion (position and velocity) which have been placed into a DAS context (i.e. they conform to the DAS architecture). These files can be directly read by DRP (the data reduction package) and plotted against data making model vs. data comparison quite easy.

The program has two modes of operation; called normal and final mode. In normal mode one is using the code to predict the behavior of the facility based on ideal test conditions. One provides as input the desired operating conditions: final temperature, pressure and specific heat ratio, and the program calculates design conditions (based on the test turbine), gas properties etc. This mode of operation can exist completely outside the DAS context (i.e. it does not require any DAS format file input) and is used to develop initial testing conditions. The second mode of operation is called the final mode and it differs from the normal mode of operation in that it takes gas properties recorded during the fill process and standards reduction process and generates the test gas properties.

**Determining the Test Gas Properties**

In normal mode, the facility model assumes a desired test specific heat ratio ($\gamma$), final test temperature, final test pressure, and the two types of gas used in the test (x for the first component and y for the second one). The program calculates mass fractions based on the following formula:

$$M_r \Rightarrow \frac{m_y}{m_x} = \frac{C_{v,x}}{C_{v,y}} \frac{(\gamma - \gamma_x)}{(\gamma_y - \gamma)} \qquad (1)$$

where $\gamma$ is the desired test condition and all other properties are functions of the individual gases at the present temperature[2]. All properties of the test gas mixture are functions of the mass ratio and the property ratios (gas constant, specific heat, etc.) of the two gases. In the final configuration mode, one takes the fill data (which is partial pressure and temperature data for the initial gas and the final conditions), and uses that to produce a mass ratio.

$$M_r \Rightarrow \frac{m_y}{m_x} = \frac{1}{R_r} \left( \frac{P_r}{T_r} - 1 \right) \qquad (2)$$

where the subscript r denotes a ratio of the property of gas y to gas x. Once the actual mass ratio has been obtained, the gas property calculation proceeds as listed in the normal case. One can see that in normal mode, one finds the desired test conditions; final mode takes the data from the run and generates the test gas conditions.

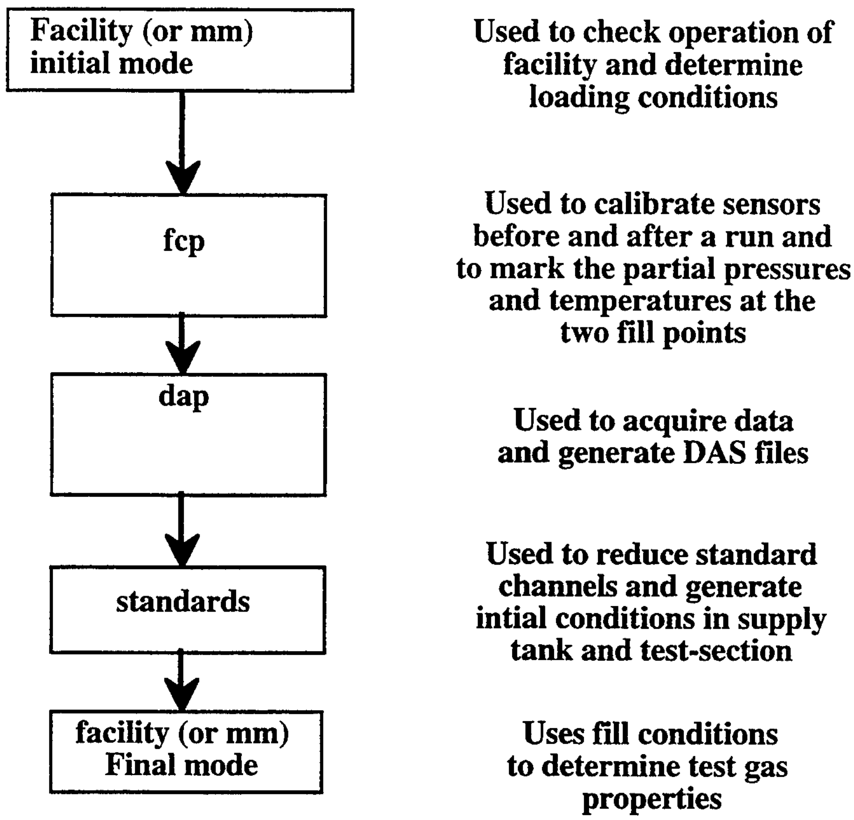
The partial pressures and temperatures are obtained in the process FCP. This process marks the partial pressures and temperatures, as well as calibrates sensors, and stores these values in the RCDF. There is an assumption that the test gas properties are determined just from these ratios. However, there may be some difference between the final fill point conditions and those at which the facility is run. This could arise due to changes in temperature, venting of the gas, or just leakage over time. Thus one more piece of information is needed before the facility model can be run in final mode, that is the initial pressures and temperatures in the supply tank and the test section just before a test.

This information is obtained by the DAS system in the time after the main valve is triggered, but before the main valve opens. The initial conditions are determined using the "standards" process. In this process, the standards channels are used to create four files (time

[2] The present facility model only models gas properties as a function of temperature. The Calspan analysis shows how this data could be modified to account for pressure variations as well. All of this analysis is discussed in more detail in that document

histories), and four scalar values. The four files are the defined pressure and temperature of the supply tank and test section. The four scalar values are the average of these files over the beginning of the test. The four scalar values, and the time range over which they were averaged are stored in the RCDF by the standards process. The standards process controls which instruments are used to create these files.

Once standards has been run, the RCDF is sufficiently complete for facility to run in final mode and generate the actual gas properties. Thus the programs which must be run to determine the gas properties used in the test are:




## Operation of "mm"

The operation of the program "facility" is relatively straight forward. However, the operation of its' X-11 interface may not be in the beginning as clear. When one invokes mm there are two lines of options (see figure 1). The two top left buttons (full printout, and startup dynamics) control the number of data points plotted in the output files. Basically, if one would like to examine the main valve motion, these should be highlighted. These responses are put into the parameters file. The next three buttons control file operations, running the model, and plotting the results. The next button is an on-line help menu and the last button terminates the program. The buttons on the second layer control the parameter file and configuration file (except for the button marked "Final Mode Params". The far left button (Parameters) displays all the values which go into the parameters files (these are the values displayed in figure 1). The last three buttons display all the values that go into the configuration file (figure 2, 3, and 4). These can be viewed and edited.

If one were to run in initial mode, one could go to the file options button and load in an old parameters file, or one could use the X-11 information to create a parameters file. The same holds true for the configuration file. The last file which needs to be specified is the valve data file, which could either be an old or a new file. If one makes any changes to either the parameter file or the configuration file after they have been loaded in, the program automatically stores these changes to temporary files, which are used to run the program facility. However, if one wants to save these files for future use, one has to explicitly save them using the file options button. The other two options, load and save RCDF are used only if the program is being run in final configuration mode.

If one wants to run mm in final configuration mode, one would load or create parameter and configuration files as noted above, and select a valve data file. Then one could go into the final mode set-up by pushing the "Final Mode Params" button. This creates a window (figure 5) that has all of the parameters set by "facility" when run in the final mode. If at this point one loads a RCDF (which has come from a run, and has been operated on by "standards") one should see that only the first four parameters (the partial pressure data) have values, as well as the four initial conditions. One operates in final mode by pushing the "set final mode button" and then using the run model button. After the program has stopped, the values for the test gas properties will be stored into a temporary RCDF and can be viewed, but not edited, in the final mode window. If these values are correct, which they should be, one then pushes the "save RCDF file" button from the file options menu. This will result in a statement saying that if one continues, these values will be stored in the RCDF and resulting changes in the RDRs will be translated to all data files in the run. Once this has been done, the action is also logged in the run log file.

The results of the model run can be displayed by running the plot mode while in mm, running "bdplot" outside of mm, or by using "drp" to plot the DAS files. It is important to note that while one can be in any directory to run the initial mode configuration, one should run the final mode configuration from the run directory since the program requires an RCDF, broadcasts the changes in the RDR to all existing DAS files in the run directory and either creates or updates the run log file.

## Future Work:

There is some possibilities of improving the facility model. One item would be to have the facility model generate the partial pressure fill conditions when running in initial mode. In addition, the gas properties presently used in the model are ideal gas properties and are only a function of temperature. It may be desirable to updated the model to include pressure dependency which would require some rework of the gas selection subroutines and should probably be evaluated in the context of an overall uncertainty analysis of the facility. Clearly one of the main goals of running the facility model in normal mode is deciding how to set the opening and closing reservoirs on the main valve. The issues involved with the six chamber model need to be resolved. Once that is done, the facility program will have to be updated to reflect these changes.

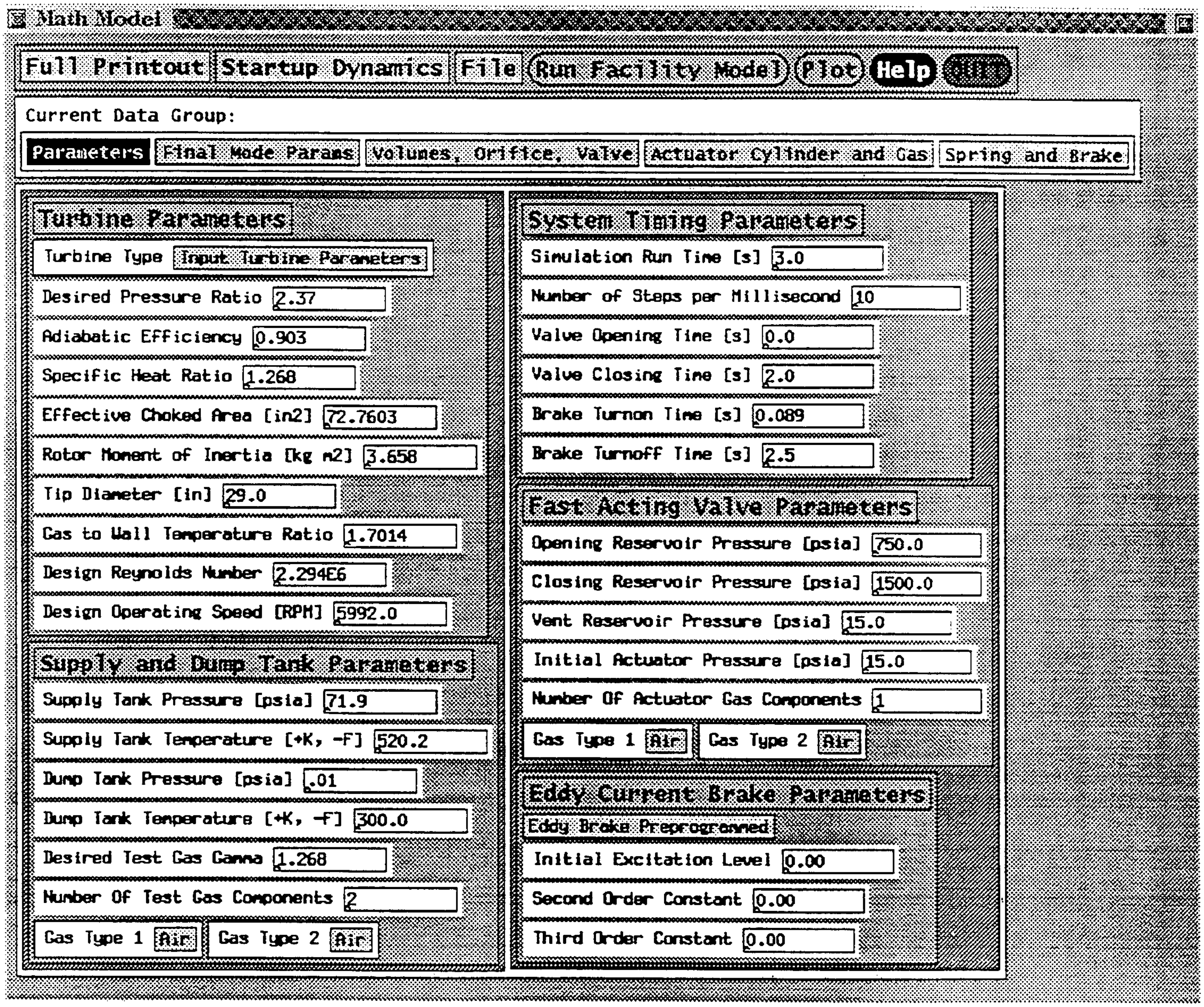



Figure 1: X-11 Interface Screen for "facility" (mm)

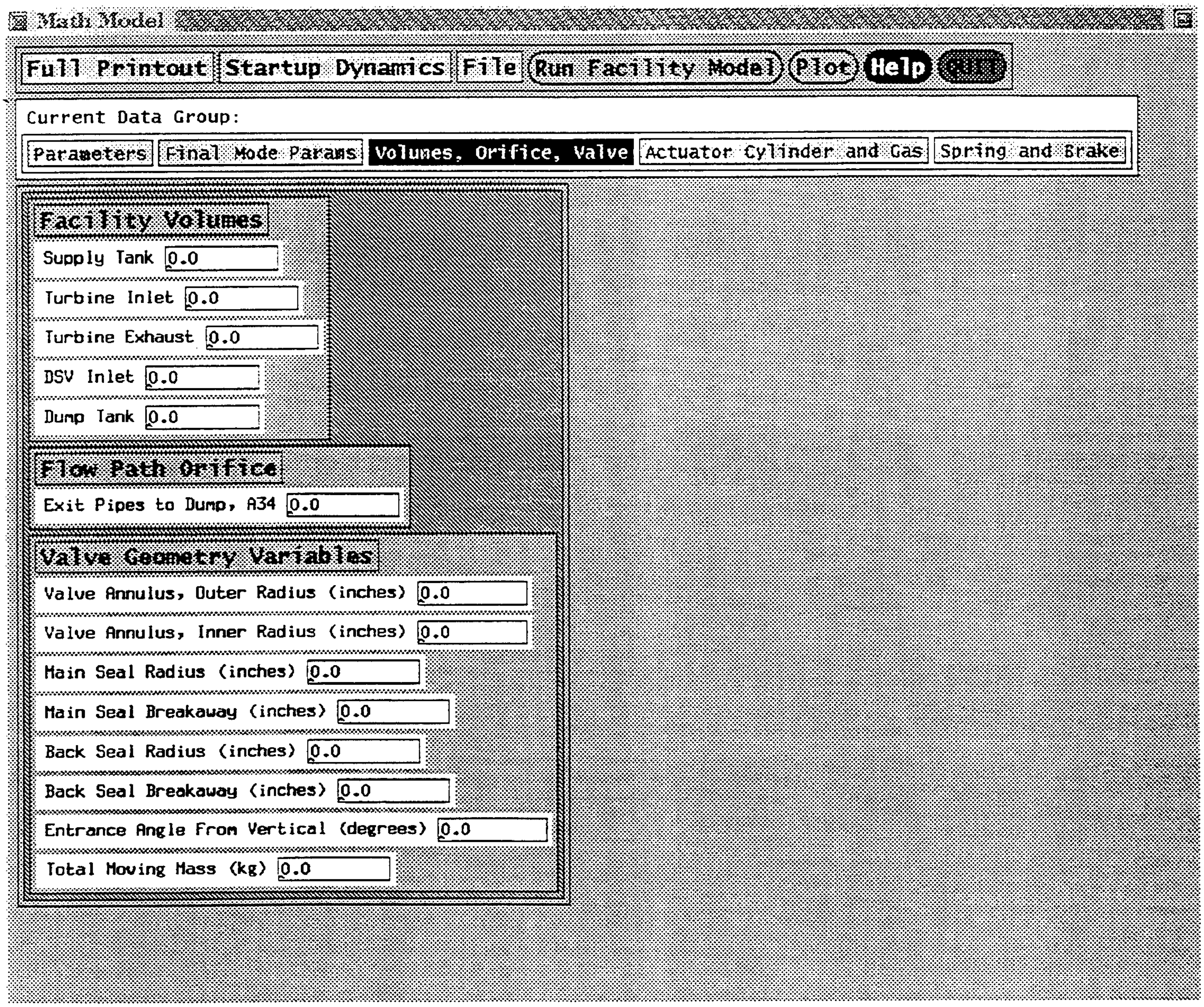



Figure 2: Volumes, Orifice, Valve Window

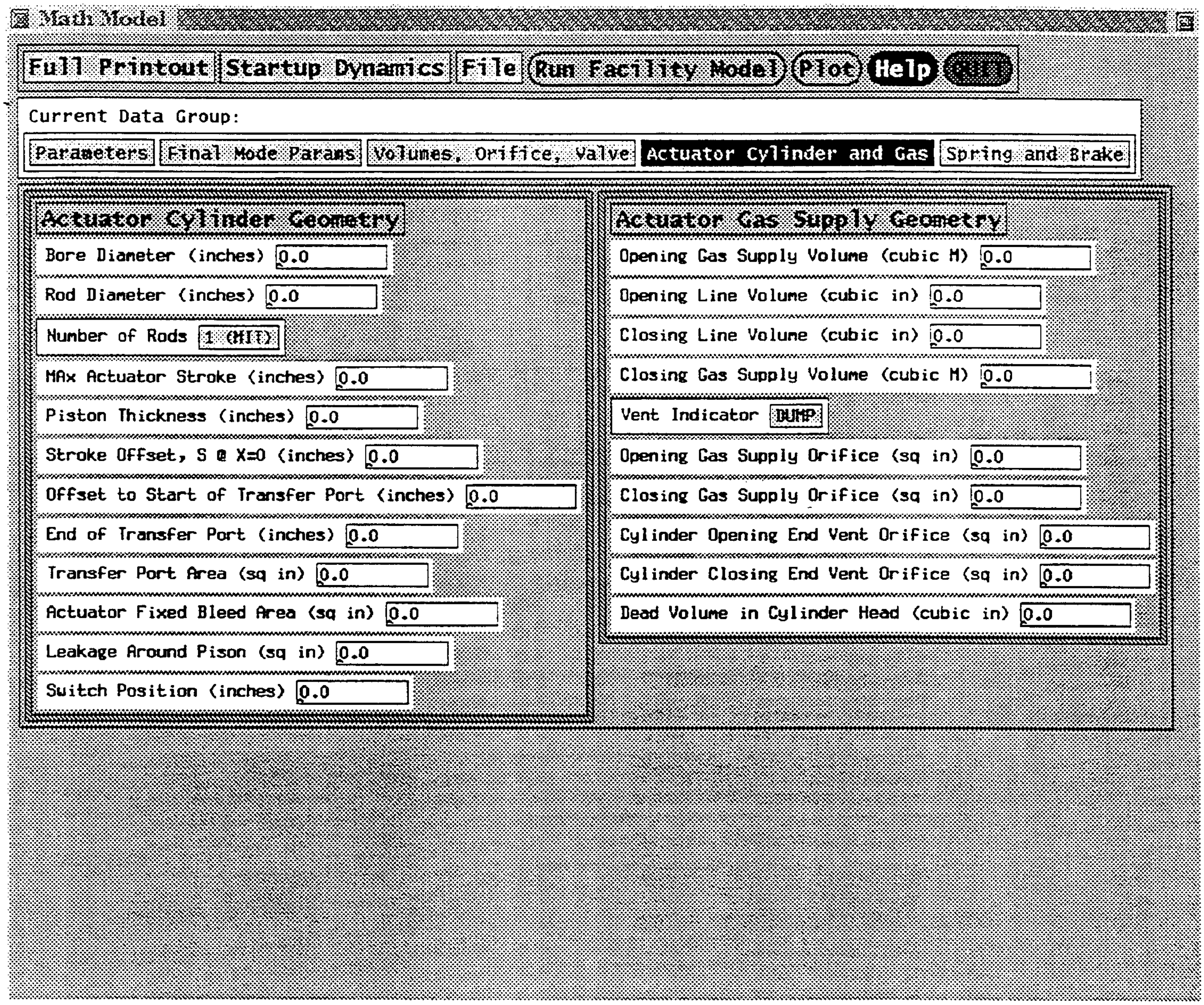



**Figure 3: Actuator Cylinder and Gas Window**

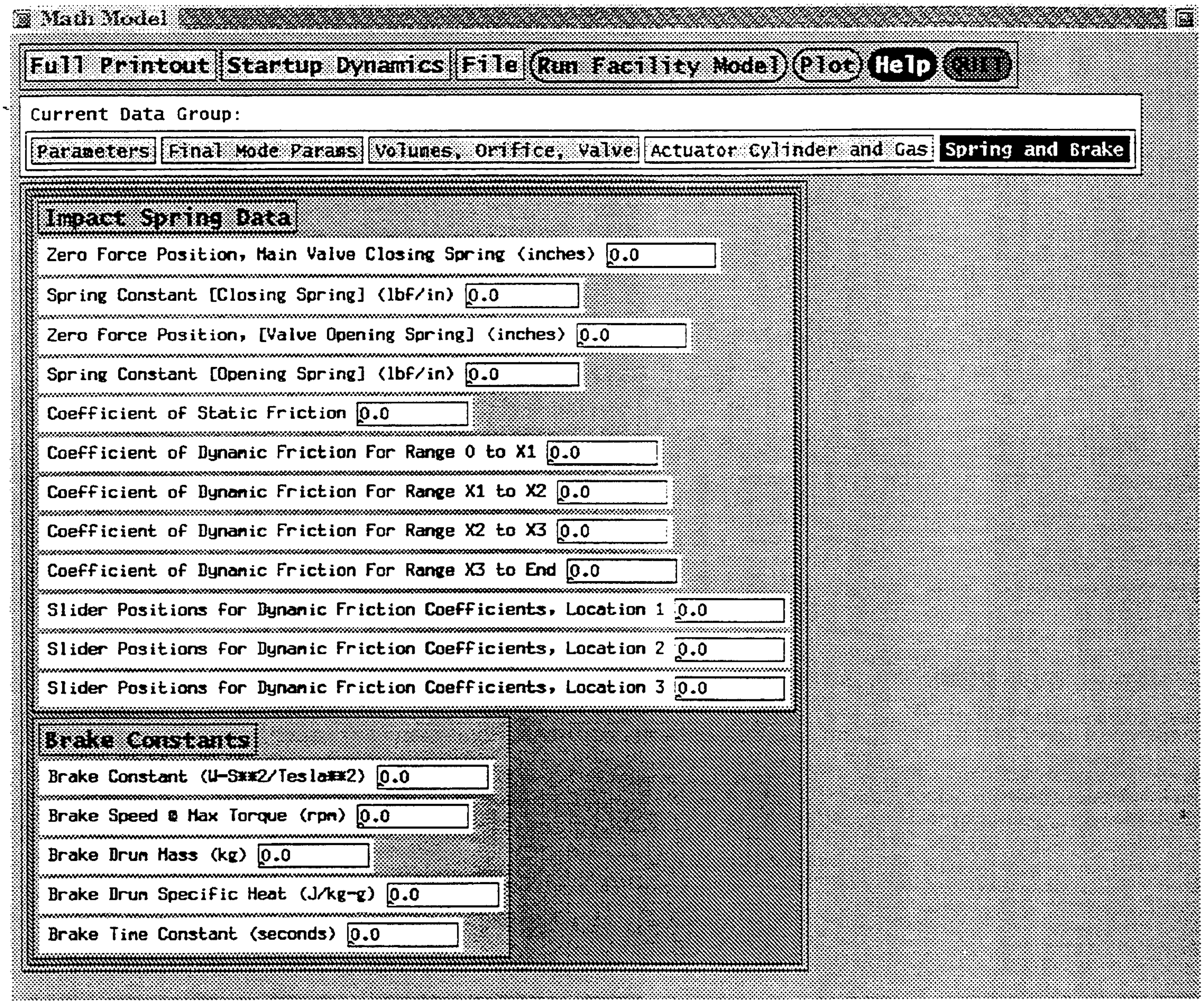



Figure 4: Spring and Brake

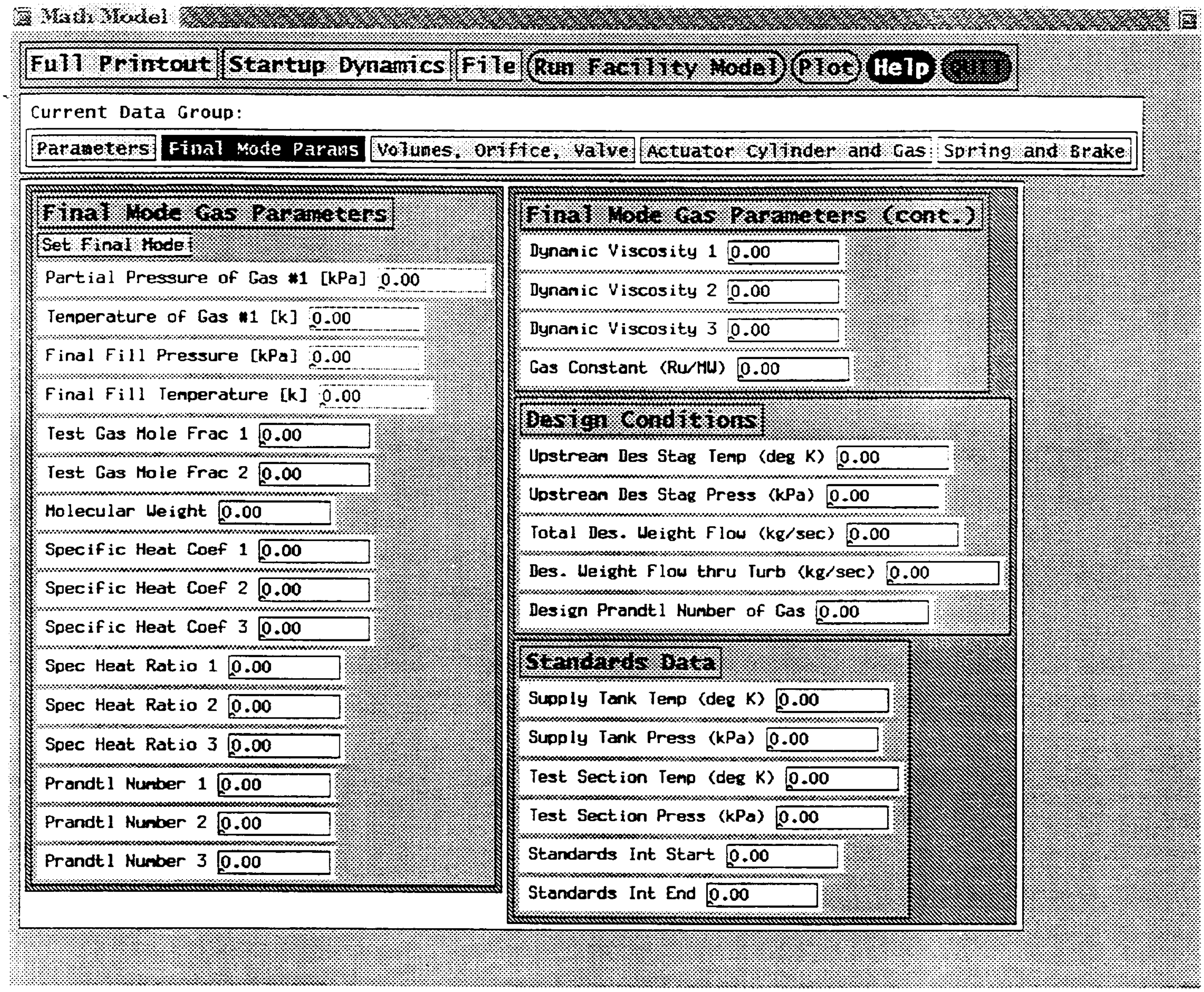



Figure 5: Final Mode Parameters Window

# Original Math Model Description

**by: Mike Stanton**

# 1 Gas Properties

The thermodynamic properties of a gas mixture are calculated from the properties of the component gases. A one or two component gas can be selected. The gases in the database are: $Air$, $Argon$, $Freon_{12}$, $N_2$, $and\ CO_2$. The gas component concentrations are those whose mixture specific heat ratio give the best match to the desired specific heat ratio. The database for the the gas components was derived from the following sources:

1. Hilsenrath, NBS CIR564, QC286.H655 - all but $Freon_{12}$.
2. Ashrae, Thermophysical Properties of Refrigerants, TP492.A54 - for $Freon_{12}$.

## 1.1 List of Variables

| | | |
|---|---|---|
| $c_{p,mix}$ | specific heat at constant pressure of the gas mixture | $\frac{J}{kg-^\circ K}$ |
| $c_{p,i}$ | specific heat at constant pressure of gas component i | $\frac{J}{kg-^\circ K}$ |
| $c_{v,mix}$ | specific heat at constant volume of the gas mixture | $\frac{J}{kg-^\circ K}$ |
| $c_{v,i}$ | specific heat at constant volume of gas component i | $\frac{J}{kg-^\circ K}$ |
| $\gamma_{mix}$ | ratio of specific heats of the gas mixture | |
| $\gamma_i$ | ratio of specific heats of gas component i | |
| $k_{mix}$ | thermal conductivity of the gas mixture | $\frac{W}{m-^\circ K}$ |
| $k_i$ | thermal conductivity of gas component i | $\frac{W}{m-^\circ K}$ |
| $\mu_{mix}$ | dynamic viscosity of the gas mixture | $\frac{N-s}{m^2}$ |
| $\mu_i$ | dynamic viscosity of gas component i | $\frac{N-s}{m^2}$ |
| $Pr_{mix}$ | Prandtl Number of the gas mixture | |
| $\mathcal{M}_{mix}$ | molecular weight of the gas mixture | $\frac{g}{mole}$ |
| $\mathcal{M}_i$ | molecular weight of gas component i | $\frac{g}{mole}$ |
| $R_0$ | Gas Constant | $\frac{J}{mole-^\circ K}$ |
| $R_{gas}$ | gas constant for the mixture | $\frac{J}{kg-^\circ K}$ |
| $\chi_i$ | mole fraction of gas component i | |
| $X_i$ | concentration of gas component i | $\frac{grams}{gram\ of\ mix}$ |

## 1.2 Defining Relationships for Properties of the Gas Mixture

The gas mixture properties are calculated via the following:

$$X_2 = \frac{\gamma_2 c_{p,1}(\gamma - \gamma_1)}{\gamma_2 c_{p,1}(\gamma - \gamma_1) - \gamma_1 c_{p,2}(\gamma - \gamma_2)} \tag{1}$$

subject to $X_2 = \text{Minimum}(1.,X_2)$ and $X_2 = \text{Maximum}(0.,X_2)$

$$X_1 = 1.0 - X_2 \tag{2}$$

$$\mathcal{M}_{mix} = \chi_1 \mathcal{M}_1 + \chi_2 \mathcal{M}_2 \tag{3}$$

$$\chi_i = X_i \frac{\mathcal{M}_{mix}}{\mathcal{M}_i} \tag{4}$$

$$c_{v,i} = \frac{c_{p,i}}{\gamma_i} \tag{5}$$

$$R_{gas} = \frac{R_0}{\mathcal{M}_{mix}} \tag{6}$$

$$c_{p,mix} = X_1 c_{p,1} + X_2 c_{p,2} \tag{7}$$

$$c_{v,mix} = X_1 c_{v,1} + X_2 c_{v,2} \tag{8}$$

$$\gamma_{mix} = \frac{c_{p,mix}}{c_{v,mix}} \tag{9}$$

$$\phi_{21} = (1. + \sqrt{\frac{\mu_2}{\mu_1}} \sqrt[4]{\frac{\mathcal{M}_1}{\mathcal{M}_2}})^2 / \sqrt{8(1 + \frac{\mathcal{M}_2}{\mathcal{M}_1})} \tag{10}$$

$$\phi_{12} = (1. + \sqrt{\frac{\mu_1}{\mu_2}} \sqrt[4]{\frac{\mathcal{M}_2}{\mathcal{M}_1}})^2 / \sqrt{8(1 + \frac{\mathcal{M}_1}{\mathcal{M}_2})} \tag{11}$$

$$\mu_{mix} = \frac{\chi_2 \mu_2}{\chi_2 + \phi_{21}\chi_1} + \frac{\chi_1 \mu_1}{\chi_1 + \phi_{12}\chi_2} \tag{12}$$

$$k_{mix} = \frac{\chi_2 k_2}{\chi_2 + 1.065\phi_{21}\chi_1} + \frac{\chi_1 k_1}{\chi_1 + 1.065\phi_{12}\chi_2} \tag{13}$$

$$Pr_{mix} = \frac{\mu_{mix} c_{p,mix}}{k_{mix}} \tag{14}$$

## 2 Facility Geometric Parameters

These consist of volumes, flow areas, and pressure face areas.

Volumes:

| | | |
|---|---|---|
| $V_0$ | blowdown supply tank | fixed |
| $V_1$ | turbine inlet passage | fixed |
| $V_2$ | turbine exhaust passage | fixed |
| $V_3$ | down stream of throttle | fixed |
| $V_4$ | dump tank | fixed |
| $V_5$ | actuator reservoir (opening) | fixed |
| $V_8$ | actuator reservoir (closing) | fixed |
| $V_6$ | actuator bore (opening) | variable |
| $V_7$ | actuator bore (closing) | variable |
| $V_{F6}$ | actuator line (opening) | fixed |
| $V_{F7}$ | actuator line (closing) | fixed |

Flow Areas:

| | | |
|---|---|---|
| $A_{01}$ | main valve | variable |
| $A_{12}$ | turbine throat | fixed |
| $A_{14}$ | boundary layer bleed $= 0.3A_{12}$ | fixed |
| $A_{23}$ | throttle area $= A_{12}\sqrt{\frac{TT_2}{TT_1}}/\frac{P_2}{P_1}$ | variable |
| $A_{34}$ | dump tank inlet | fixed |
| $A_{56}$ | actuator supply (opening) | fixed |
| $A_{87}$ | actuator supply (closing) | fixed |
| $A_{7V}$ | actuator vent (opening) | fixed |
| $A_{6V}$ | actuator vent (closing) | fixed |
| $A_{F67}$ | actuator fixed leakage | fixed |
| $A_{V67}$ | actuator transfer port | variable |
| $A_{67}$ | actuator leakage $= A_{F67} + A_{V67}$ | variable |

Pressure Face Areas:

| | | |
|---|---|---|
| $A_O$ | area of actuator piston (opening face) | fixed |
| $A_C$ | area of actuator piston (closing face) | fixed |

# 3 Facility Chamber Pressures and Temperatures

Pressures:

| | |
|---|---|
| $p_0$ | blowdown supply tank |
| $p_1$ | turbine inlet passage |
| $p_2$ | turbine exhaust passage |
| $p_3$ | down stream of throttle |
| $p_4$ | dump tank |
| $p_5$ | actuator reservoir (opening) |
| $p_8$ | actuator reservoir (closing) |
| $p_6$ | actuator bore (opening) |
| $p_7$ | actuator bore (closing) |

Temperatures:

| | |
|---|---|
| $T_0$ | blowdown supply tank |
| $T_1$ | turbine inlet passage |
| $T_2$ | turbine exhaust passage |
| $T_3$ | down stream of throttle |
| $T_4$ | dump tank |
| $T_5$ | actuator reservoir (opening) |
| $T_8$ | actuator reservoir (closing) |
| $T_6$ | actuator bore (opening) |
| $T_7$ | actuator bore (closing) |
| $T_{ij}$ | temperature of the upstream gas |

# 4 Flow Rates at Orifices

The flow rates are calculated for adiabatic flows. The flow conditions are considered to be either choked or unchoked flow.

## 4.1 List of Variables

| | |
|---|---|
| $p_i$ | pressure, chamber i |
| $p_j$ | pressure in adjacent chamber, chamber j |
| $A_{ij}$ | area of the orifice |
| $w_{ij}$ | flow rate through the orifice from chamber i to chamber j |
| $w$ | absolute value of flow rate |
| $p_{up}$ | chamber pressure, high pressure side = Maximum($p_i$,$p_j$) |
| $p_{down}$ | chamber pressure, low pressure side = Minimum($p_i$,$p_j$) |
| $p_{critical}$ | critical pressure at which the flow is choked |
| $T_{up}$ | chamber temperature, high pressure side |
| $T_{down}$ | chamber temperature, low pressure side |
| $T_{ij}$ | chamber temperature, high pressure side |
| $\gamma$ | ratio of specific heats of the gas mixture = $\gamma_{mix}$ |

## 4.2 Defining Relationships for Orifice Flow Rates

$$p_{critical} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \cdot p_{up} \tag{15}$$

if $p_{down} \leq p_{critical}$, the flow is choked and:

$$w = \sqrt{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \cdot \frac{p_{up}A_{ij}}{\sqrt{R_{gas}T_{up}}} \tag{16}$$

else if $p_{down} > p_{critical}$, the flow is unchoked and:

$$w = \sqrt{\left(\frac{2\gamma}{\gamma-1}\right)\left(1-\left(\frac{p_{down}}{p_{up}}\right)^{\frac{\gamma-1}{\gamma}}\right)} \cdot \left(\frac{p_{down}}{p_{up}}\right)^{\frac{1}{\gamma}} \frac{p_{up}A_{ij}}{\sqrt{R_{gas}T_{up}}} \tag{17}$$

$$w_{ij} = \frac{p_i - p_j}{|p_i - p_j|} \cdot w \tag{18}$$

*Facility Configuration Model*

$$T_{ij} = T_{up} \tag{19}$$

# 5 Turbine and Brake Properties

## 5.1 List of Variables

| | |
|---|---|
| $p_1$ | turbine inlet pressure |
| $p_2$ | turbine exit pressure |
| $p_{ratio}$ | turbine pressure ratio |
| $TT_1$ | turbine inlet temperature |
| $TT_2$ | turbine exit temperature |
| $T_{ratio}$ | turbine temperature ratio |
| $A_{23}$ | boundary layer bleed |
| $\dot{TT}_1$ | time rate of change of turbine inlet temperature |
| $T_{room}$ | ambient temperature |
| $T_{gas\ to\ wall}$ | turbine gas to wall temperature |
| $e_a$ | adiabatic efficiency of the turbine |
| $h_t$ | turbine power |
| $\mathcal{T}_t$ | turbine shaft torque |
| $\mathcal{T}_n$ | net shaft torque |
| $I_r$ | rotor moment of inertia |
| $\omega_s$ | turbine shaft speed |
| $\omega_{ss}$ | scaled turbine shaft speed |
| $\omega_{ds}$ | turbine shaft design speed |
| $\omega_{sds}$ | scaled turbine shaft design speed |
| $Re$ | turbine Reynolds Number |
| $D_{tip}$ | tip diameter for turbine rotor |
| $\mathcal{T}_b$ | actual brake torque |
| $\mathcal{T}_{br}$ | required brake torque |
| $h_b$ | brake power |
| $Q_b$ | total energy absorbed by the brake |
| $k_b$ | brake coefficient |
| $\omega_{b,max}$ | shaft speed at which maximum brake torque develops |
| $T_{drum}$ | brake temperature (with no dissipation) |
| $m_{drum}$ | mass of brake drum |
| $c_{p,drum}$ | heat capacity of brake drum |
| $B$ | actual brake excitation |
| $B_r$ | required brake excitation |
| $B_c$ | total brake constant |
| $B_0$ | first order brake constant |
| $B_1$ | second order brake constant |
| $B_2$ | third order brake constant |
| $\tau$ | brake time constant |
| $t$ | run time |
| $t_{brake\ on}$ | time at which braking action starts |
| $t_{brake\ off}$ | time at which braking action stops |

## 5.2 Defining Relationships for Turbine and Brake Properties

$$p_{ratio} = \frac{p_2}{p_1} \tag{20}$$

$$T_{ratio} = 1 - e_a(1 - p_{ratio}{}^{\frac{\gamma-1}{\gamma}}) \tag{21}$$

$$TT_1 = T_1 \tag{22}$$

$$TT_2 = TT_1 \cdot T_{ratio} \tag{23}$$

$$A_23 = A_{12} \cdot \frac{\sqrt{T_{ratio}}}{P_{ratio}} \tag{24}$$

$$h_t = w_{12} \cdot c_{p,mix} \cdot (TT_1 - TT_2) \tag{25}$$

$$\mathcal{T}_t = \frac{h_t}{\omega_s} \tag{26}$$

$$\omega_{ss} = \frac{\omega_s}{\sqrt{TT_1}} \tag{27}$$

$$\omega_{sds} = \frac{\omega_{ds}}{\sqrt{TT_1}} \tag{28}$$

$$Re = \frac{w_{12}}{D_{tip}\mu_{mix}} \tag{29}$$

$$T_{gas\ to\ wall} = \frac{TT_1}{T_{room}} \tag{30}$$

$$\mathcal{T}_{br} = \frac{h_t}{\omega_{ds}} - \frac{\dot{TT}_1 I_r \omega_{sds}}{2\sqrt{TT_1}} \tag{31}$$

$$B_r = \sqrt{\frac{\mathcal{T}_{br}(1 + (\frac{\omega_{ds}}{\omega_{b,max}})^2)}{k_b \omega_{ds}}} \tag{32}$$

*if* $t < t_{brake\ on}$ *or* $t > t_{brake\ off}$ *then*

$$B = 0 \tag{33}$$

*else*
*if excitation is not preprogrammed then*

$$B = B_r \tag{34}$$

*otherwise for a preprogrammed excitation*

$$B_c = B_0 + B_1(t - t_{brake\ on}) + B_2(t - t_{brake\ on})^2 \quad (35)$$

*and*

$$B = B_c \cdot (1 - e^{-\frac{t - t_{brake\ on}}{\tau}}) \quad (36)$$

$$h_b = k_b \cdot B^2 \cdot \frac{{\omega_s}^2}{1 + (\frac{\omega_s}{\omega_{b,max}})^2} \quad (37)$$

$$T_b = \frac{h_b}{\omega_s} \quad (38)$$

$$T_n = T_t - T_b \quad (39)$$

$$T_{drum} = \frac{Q_b}{m_{drum} \cdot c_{p,drum}} + T_{room} \quad (40)$$

# 6 Main Slider Valve and Actuator Variables

## 6.1 List of Variables

| | |
|---|---|
| $x$ | the displacement of main slider valve at which the front seal is fully compressed |
| $v$ | velocity of main slider valve = velocity of actuator piston |
| $r_s$ | radius from centerline of chamber 1 to the back seal |
| $r_m$ | radius from centerline of chamber 1 to the front seal |
| $x_m$ | displacement at which the front seal is closed but uncompressed |
| $x_{ksc}$ | x displacement at which the front slider spring is in equilibrium |
| $x_{kso}$ | x displacement at which the back slider spring is in equilibrium |
| $s_o$ | offset of actuator piston from front of bore at x=0 |
| $A_m$ | maximum area of main valve |
| $\theta$ | angle from vertical of the main valve bevel |
| $F_t$ | total force on slider assembly |
| $F_{st}$ | total force excepting friction on slider assembly |
| $F_p$ | pressure force contribution to total force on slider assembly |
| $F_s$ | spring force contribution to total force on slider assembly |
| $F_a$ | actuator force contribution to total force on slider assembly |
| $F_t$ | frictional force contribution to total force on slider assembly |
| $K_{sc}$ | spring constant for front spring |
| $K_{so}$ | spring constant for back spring |
| $\mu_{sliding}$ | coefficient of sliding friction for the main slider valve |
| $\mu_{static}$ | coefficient of static friction for the main slider valve |
| $m$ | mass of sliding assembly |
| $g$ | gravitational acceleration |

## 6.2 Defining Relationships for Main Valve and Actuator

$$A_{01} = 0 \quad x < x_m \tag{41}$$

$$A_{01} = A = 2\pi r_m(x-x_m)\sin\theta + \pi(x-x_m)^2\sin^2\theta\cos\theta \quad x \geq x_m \; and \; A < A_m \tag{42}$$

$$A_{01} = A_m \quad x \geq x_m \; and \; A \geq A_m \tag{43}$$

$$V_6 = A_O(s_o + x) + V_{F6} \tag{44}$$

$$V_7 = A_C(s_o + x) + V_{F7} \tag{45}$$

$$F_p = -\pi({r_m}^2 - {r_s}^2)(p_0 - p_1) \quad x < x_m \tag{46}$$

$$F_p = 0 \quad x \geq x_m \tag{47}$$

$$F_a = p_6 \cdot A_O - p_7 \cdot A_C \tag{48}$$

$$F_s = -K_{sc}(x - x_{ksc}) \quad x < x_{ksc} \tag{49}$$

$$F_s = 0 \quad x_{ksc} \leq x \leq x_{kso} \tag{50}$$

$$F_s = -K_{so}(x - x_{kso}) \quad x > x_{kso} \tag{51}$$

$$F_{st} = F_p + F_a + F_s \tag{52}$$

$$F_f = -\frac{v}{|v|} \cdot \mu_{sliding} mg \quad v \neq 0 \tag{53}$$

$$F_f = -\frac{F_{st}}{|F_{st}|} \cdot \mu_{static} mg \quad v = 0, \; |F_{st}| \geq \mu_{static} mg \tag{54}$$

$$F_f = -F_{st} \quad v = 0, \; |F_{st}| < \mu_{static} mg \tag{55}$$

$$F_t = F_{st} + F_f \tag{56}$$

# 7 Method of Integration

## 7.1 List of State Variables

| | |
|---|---|
| $\omega_s$ | shaft speed |
| $v$ | slider velocity |
| $x$ | slider displacement |
| $m_i$ | mass of gas in chamber i (i=0...8) |
| $E_i$ | internal energy of gas in chamber i (i=0...8) |
| $TT_1$ | turbine inlet gas temperature |

## 7.2 Calculation of the Derivatives of State Variables

$$\dot{\omega}_s = \frac{\mathcal{T}_n}{I_r} \tag{57}$$

$$\dot{v} = \frac{F_t}{m} \tag{58}$$

$$\dot{x} = v \tag{59}$$

$$\dot{m}_0 = -w_{01} \tag{60}$$

$$\dot{m}_1 = +w_{01} - w_{12} - w_{14} \tag{61}$$

$$\dot{m}_2 = +w_{12} - w_{23} \tag{62}$$

$$\dot{m}_3 = +w_{23} - w_{34} \tag{63}$$

$$\dot{m}_4 = +w_{14} + w_{34} + w_{6V} + w_{7V} \tag{64}$$

$$\dot{m}_5 = -w_{56} \tag{65}$$

$$\dot{m}_6 = +w_{56} - w_{67} - w_{6V} \tag{66}$$

$$\dot{m}_7 = +w_{67} + w_{87} - w_{7V} \tag{67}$$

$$\dot{m}_8 = -w_{87} \tag{68}$$

$$\dot{E}_0 = -w_{01}c_{p,mix}T_{01} \tag{69}$$

$$\dot{E}_1 = +w_{01}c_{p,mix}T_{01} - w_{12}c_{p,mix}T_{12} - w_{14}c_{p,mix}T_{14} \tag{70}$$

$$\dot{E}_2 = +w_{12}c_{p,mix}T_{12} - w_{23}c_{p,mix}T_{23} \tag{71}$$

$$\dot{E}_3 = +w_{23}c_{p,mix}T_{23} - w_{34}c_{p,mix}T_{34} \tag{72}$$

$$\dot{E}_4 = +w_{14}c_{p,mix}T_{14} + w_{34}c_{p,mix}T_{34} + w_{6V}c_{p,mix}T_{6V} + w_{7V}c_{p,mix}T_{7V} \tag{73}$$

$$\dot{E}_5 = -w_{56}c_{p,mix}T_{56} \tag{74}$$

$$\dot{E}_6 = +w_{56}c_{p,mix}T_{56} - w_{67}c_{p,mix}T_{67} - w_{6V}c_{p,mix}T_{6V} \tag{75}$$

$$\dot{E}_7 = +w_{67}c_{p,mix}T_{67} + w_{87}c_{p,mix}T_{87} - w_{7V}c_{p,mix}T_{7V} \tag{76}$$

$$\dot{E}_8 = -w_{87}c_{p,mix}T_{87} \tag{77}$$

$$\dot{TT}_1 = \frac{\dot{E}_1 - CvmixT_1\dot{m}_1}{m_1 c_{v,mix}} \tag{78}$$

*The integration scheme is :*

$$\int_t^{t+\Delta t} dS = S_{t+\Delta t} - S_t = \dot{S}_t \Delta t \tag{79}$$

$$S_{t+\Delta t} = S_t + \dot{S}_t \Delta t \tag{80}$$

*Pressure and Temperature are updated from the integrated state variables :*

$$T_i = \frac{E_i}{m_i c_{v,gas}} \tag{81}$$

$$p_i = \frac{E_i R_{gas}}{V_i c_{v,gas}} \tag{82}$$

# 8 User Specified Parameters to the Facility Model Program

IPNTOUT 1 = full printout
0 = short printout

ISD 1 = startup dynamics are modelled
0 = start with turbine inlet and outlet at design pressure and temperature ratio. Also inlet conditions = supply conditions

ITURB 0 = user specified turbine
3 = T3 Turbine
7 = MIT Model Ace Turbine
8 = Full Scale Ace Turbine

PIDP (entered when ITURB=0) design outlet pressure to inlet pressure ratio

ETADP (entered when ITURB=0) design adiabatic efficiency

GDP (entered when ITURB=0) design $\gamma$

REDP (entered when ITURB=0) design Reynold's number

AT (entered when ITURB=0) turbine throat area ($in^2$)

DTIP (entered when ITURB=0) rotor diameter ($in$)

TGTWDP (entered when ITURB=0) design gas to wall temperature

IR (entered when ITURB=0) rotor moment of inertia ($kg - m^2$)

NS0 design operating speed ($RPM$)

IBEX 1 = brake excitation is computed
2 = brake excitation is preprogrammed via the quadratic constant, $B_c$,
$B_c = B_0 + B_1 t + B_2 t^2$

B0 (entered when IBEX=2) zero order constant

B1 (entered when IBEX=2) first order constant

B2 (entered when IBEX=2) second order constant

P0PSI initial supply tank pressure (psia)

T0IN initial supply tank temperature where a positive number indicates a temperature in $^{\circ}K$ and a negative number in $^{\circ}F$

P4PSI initial dump tank pressure (psia)

T4IN initial dump tank temperature where a positive number indicates a temperature in $^{\circ}K$ and a negative number in $^{\circ}F$

GD desired $\gamma$ for the test gas

NCMP number of gas components in the gas mixture ( 1 or 2 )

ICMP index of gas components in the gas mixture
1 for $Air$
2 for $Argon$
3 for $Freon_{12}$
4 for $N_2$
5 for $CO_2$

P5PSI actuator reservoir (opening) initial pressure (psia)

P8PSI actuator reservoir (closing) initial pressure (psia)

PVRPSI vent reservoir initial pressure (psia)

PVA0PSI actuator bore initial pressure (psia)

TSIM length of simulation (seconds)

NPMS number of time steps per millisecond - 10 is recommended. MIT Experience has shown that too few time steps per millisecond will show up as pressure oscillations on the order of a time step in the solution.

TOPEN actuator valve opening time (seconds)

TCLOSE actuator valve closing time (seconds)

TON brake turn on time (seconds)

TOFF brake turn off time (seconds)

## 9 Facility Configuration File Parameters

V0 SUPPLY TANK

V1 TURBINE INLET

V2 TURBINE EXHAUST

V3 DSV INLET

V4 DUMP TANK

ADSO EXIT PIPES TO DUMP ($in^2$)

ISS =1 FOR SLIDING SLEEVE (ATAR), =0 FOR COWCATCHER (MIT)

RO VALVE ANNULUS, OUTER RADIUS (INCHES)

RI VALVE ANNULUS, INNER RADIUS (INCHES)

RM MAIN SEAL RADIUS (INCHES)

XM MAIN SEAL BREAKAWAY (INCHES)

RS BACK SEAL BREAKAWAY (INCHES)

XS BACK SEAL BREAKAWAY (INCHES)

THETA ENTRANCE ANGLE FROM VERTICAL (DEGREES)

MASS TOTAL MOVING MASS (KG)

XKSC NO FORCE POSITION, MAIN VALVE CLOSING SPRING (INCHES)

KSC SPRING CONSTANT ($\frac{LBF}{INCH}$), CLOSING SPRING

XKSO NO FORCE POSITION, VALVE OPENING SPRING (INCHES)

**KSO** SPRING CONSTANT ($\frac{LBF}{INCH}$), CLOSING SPRING

**CSF** COEFFICIENT OF STATIC FRICTION

**CDF** COEFFICIENT OF SLIDING FRICTION

**DB** BORE DIAMETER (INCHES)

**DR** ROD DIAMETER (INCHES)

**NRODS** 2 FOR ATAR, 1 FOR MIT

**SMAX** MAXIMUM ACTUATOR STROKE (INCHES)

**SP** PISTON THICKNESS (INCHES)

**S0** STROKE OFFSET, S @ X=0 (INCHES)

**S1** OFFSET TO START OF TRANSFER PORT (INCHES)

**S2** END OF TRANSFER PORT (INCHES)

**AV67** TRANSFER PORT AREA ($in^2$)

**AF67** ACTUATOR FIXED BLEED AREA ($in^2$)

**V5** OPENING GAS SUPPLY VOLUME ($m^3$)

**VF6** OPENING LINE VOLUME ($in^3$)

**VF7** CLOSING LINE VOLUME ($in^3$)

**V8** CLOSING GAS SUPPLY VOLUME ($m^3$)

**IVNT** VENT TO DUMP=0, VENT TO ROOM=1

**AO56** OPENING GAS SUPPLY ORIFICE ($in^2$)

**AO7V** CYLINDER CLOSING END VENT ORIFICE ($in^2$)

**AC87** CLOSING GAS SUPPLY ORIFICE ($in^2$)

**AC6V** CYLINDER OPENING END VENT ORIFICE ($in^2$)

**KB** BRAKE CONSTANT ($\frac{W-s^2}{Tesla^2}$)

**NB** BRAKE SPEED @ MAXIMUM TORQUE (rpm)

MDRUM BRAKE DRUM MASS (KG)

CPD BRAKE DRUM SPECIFIC HEAT ($\frac{J}{KG^{o}K}$)

TAUB BRAKE TIME CONSTANT (SECONDS)

## 10 Operating the Facility Model Programs

The programs, "bd" and "bdplt", are the programs which produce the computational results of the modeling and the plot. The program, "bd", is operated by typing "bd" and answering the prompts for the user selected parameters. The facility configuration file named "configuration.dat" must exist in the present working directory. Two output files are produced by this program. The file, "BD.OUT" contains a listing of the computational results of the run. The file, "BD.PLT" contains the data file which is used as input to "bdplt".

The program, "bdplt", is operated by typing "bdplt". This program produces the plots. Plots can be generated on the screen or on a laser plotter. The environment variable, mplotfile. is used to pass the names of the input file to "bdplt". The variable mplotfile contains the name of the plotfile produced by "bd". It is set by typing the unix command "setenv mplotfile BD.PLT" or whatever else the input file is named.

## Facility Model Parameters

Program *facility* has two basic forms of supplying input data. The first consists of a file containing facility configuration parameters. There are seven distinct groups of data which are entered using the FORTRAN namelist convention.

| NAMELIST | CONTENTS |
|---|---|
| **FD1** | Facility Volumes |
| **FD2** | Flow Path Orifice |
| **VD1** | Valve Geometry Variables |
| **VD2** | Impact Spring Data |
| **VD3** | Actuator Cylinder Geometry |
| **VD4** | Actuator Gas Supply Geometry |
| **BRK** | Brake Constants |

Each namelist has one or more parameter names which are used to enter the associated input data. The namelist parameters are presented for the user's convenience:

| **FD1** | **Facility Volume Data (Cubic Feet)** |
|---|---|
| V0 | SUPPLY TANK |
| V1 | TURBINE INLET |
| V2 | TURBINE EXHAUST |
| V3 | DSV INLET |
| V4 | DUMP TANK |

| **FD2** | **Facility Flow Path Orifice (Square Inches)** |
|---|---|
| ADSO | EXIT PIPES TO DUMP, A34: 2-20"DIA, CD=.62 |

| **VD1** | **Valve Geometry Variables** |
|---|---|
| ISS | INTEGER INDICATOR [0=MIT COWCATCHER; 1=ATARR SLIDING SLEEVE] |
| RO | VALVE ANNULUS, OUTER RADIUS (INCHES) |
| RI | VALVE ANNULUS, INNER RADIUS (INCHES) |
| RM | MAIN SEAL RADIUS (INCHES) |
| XM | MAIN SEAL BREAKAWAY (INCHES) |
| RS | BACK SEAL RADIUS (INCHES) |
| XS | BACK SEAL BREAKAWAY (INCHES) |
| THETA | ENTRANCE ANGLE FROM VERTICAL (DEGREES) |
| MASS | TOTAL MOVING MASS (KG) |

## Facility Model Parameters

| | |
|---|---|
| **VD2** | **Impact Spring Data** |
| XKSC | ZERO FORCE POSITION, MAIN VALVE CLOSING SPRING (INCHES) |
| KSC | SPRING CONSTANT [CLOSING SPRING] (LBF/IN) |
| XKSO | ZERO FORCE POSITION [VALVE OPENING SPRING] (INCHES) |
| KSO | SPRING CONSTANT [OPENING SPRING] (LBF/IN) |
| CSF | COEFFICIENT OF STATIC FRICTION |
| | COEFFICIENTS OF DYNAMIC FRICTION FOR SLIDER RANGES SHOWN: |
| CD1 | 0 TO X1 |
| CD2 | X1 TO X2 |
| CD3 | X2 TO X3 |
| CD4 | X3 TO END |
| | SLIDER POSITIONS FOR DYNAMIC FRICTION COEFFICIENTS: |
| X1 | LOCATION 1 (INCHES) |
| X2 | LOCATION 2 (INCHES) |
| X3 | LOCATION 3 (INCHES) |

| | |
|---|---|
| **VD3** | **Actuator Cylinder Geometry** |
| DB | BORE DIAMETER (INCHES) |
| DR | ROD DIAMETER (INCHES) |
| NRODS | NUMBER OF RODS [1 FOR MIT; 2 FOR ATARR] |
| SMAX | MAXIMUM ACTUATOR STROKE (INCHES) |
| SP | PISTON THICKNESS (INCHES) |
| S0 | STROKE OFFSET, S @ X=0 (INCHES) |
| S1 | OFFSET TO START OF TRANSFER PORT (INCHES) |
| S2 | END OF TRANSFER PORT (INCHES) |
| AV67 | TRANSFER PORT AREA (IN**2) |
| AF67 | ACTUATOR FIXED BLEED AREA (IN**2) |
| ALEAK | LEAKAGE AROUND PISTON (IN**2) |
| SSW | SWITCH POSITION (INCHES) |

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| | |
|---|---|
| **VD4** | **Actuator Gas Supply Geometry** |
| V5 | OPENING GAS SUPPLY VOLUME (M**3) |
| VF6 | OPENING LINE VOLUME (IN**3) |
| VF7 | CLOSING LINE VOLUME (IN**3) |
| V8 | CLOSING GAS SUPPLY VOLUME (M**3) |
| IVNT | VENT INDICATOR [0=DUMP; 1=ROOM] |
| AO56 | OPENING GAS SUPPLY ORIFICE (IN**2) |
| AO7V | CLOSING GAS SUPPLY ORIFICE (IN**2) |
| AC87 | CYLINDER CLOSING END VENT ORIFICE (IN**2) |
| AC6V | CYLINDER OPENING END VENT ORIFICE (IN**2) |
| VDEAD | DEAD VOLUME IN CYLINDER HEAD (IN**3) |

| | |
|---|---|
| **BRK** | **Brake Constants** |
| KB | BRAKE CONSTANT (W-S**2 / TESLA**2) |
| NB | BRAKE SPEED @ MAXIMUM TORQUE (RPM) |
| MDRUM | BRAKE DRUM MASS (KG) |
| CPD | BRAKE DRUM SPECIFIC HEAT (J/KG-K) |
| TAUB | BRAKE TIME CONSTANT (SECONDS) |

*Guidelines for entering each namelist name and parameters:*

First line contains a dollar sign ($) in column 2 and the namelist name starting in column 3. For each namelist parameter, open a new line and enter its name anywhere beyond column 1 followed by an equal sign (=), the value to be assigned the parameter, and a terminating comma (,). For example, the line " V3 = 250," appearing in the FD1 namelist input stream would specify a DSV inlet volume of 250 cubic feet. To terminate input for a namelist, its last line should contain the four characters "$END" starting in column 2.

The second form of input to program *facility* consists of the responses to screen prompts for input data. These responses may be entered interactively or placed in an ASCII file to be read by the program. Since the data are order dependent, there is no recovery from input errors when a response file is used. Even considering this limitation, it is preferable to use this form of input because it provides an automatic record and a convenient platform for changes. For the most part, a response file consists of lines of single numbers whose meanings are explained in the outline presented below.

## Facility Model Parameters

*Outline of Response File Entries for the Facility Model Program*

| Parameter | Usage in Facility Model Program |
|---|---|
| IFRCDF | MODE INDICATOR [0=PREDICTIVE; 1=GENERATE RCDF VALUES] |
| IPNTOUT | GENERATE FULL PRINTOUT INDICATOR [0=NO; 1=YES] |
| ISD | START-UP DYNAMICS INDICATOR [0=NO; 1=YES] |
| ITURB | TURBINE# [0=INPUT LIST; 3=TURBINE 3; 7=MIT ACE; 8=FULL ACE] |

```
If ITURB=0, insert the following turbine parameters (one per line).
PIDP        DESIRED PRESSURE RATIO
ETADP       ADIABATIC EFFICIENCY
GDP         SPECIFIC HEAT RATIO
AT          EFFECIVE CHOKED AREA (SQUARE INCHES)
IR          ROTOR MOMENT OF INERTIA (KG M**2)
DTIP        TIP DIAMETER (INCHES)
TGTWDP      GAS TO WALL TEMPERATURE RATIO
REDP        DESIGN REYNOLDS NUMBER
```

| | |
|---|---|
| NS0 | DESIGN OPERATING SPEED [RPM] |
| IBEX | EDDY-BRAKE OPTION [1-COMPUTED BY MODEL, 2-PREPROGRAMMED] |

```
If IBEX=2, insert the following parameters (one per line).
B0          INITIAL EXCITATION LEVEL
DB_DT       SECOND ORDER EXCITATION CONSTANT
D2B_DT2     THIRD ORDER EXCITATION CONSTANT
```

| | |
|---|---|
| P0PSI | SUPPLY TANK PRESSURE (PSIA) |
| T0IN | SUPPLY TANK TEMPERATURE (+K \| -F) |
| P4PSI | DUMP TANK PRESSURE (PSIA) |
| T4IN | DUMP TANK TEMPERATURE (+K \| -F) |
| GD | DESIRED TEST GAS GAMMA |

```
If IFRCDF=1, input a single line with the following four values:
PFILL(1)     PARTIAL PRESSURE OF GAS #1 (PSIA)
TFILLK(1)    TEMPERATURE OF GAS #1 (K)
PFILL(2)     FINAL FILL PRESSURE (PSIA)
TFILLK(2)    FINAL FILL TEMPERATURE (K)
```

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*Outline of Response File Entries for the Facility Model Program (continued)*

| Parameter | Usage in Facility Model Program |
|---|---|
| NTGCMP | NUMBER OF TEST GAS COMPONENTS [NTGCMP = 1 OR 2] |
| ITGCMP | TEST GAS INDICATOR(S) [1=AIR; 2=ARGON; 3=FREON12; 4=N2; 5=CO2] |
| P5PSI | OPENING RESERVOIR PRESSURE (PSIA) |
| P8PSI | CLOSING RESERVOIR PRESSURE (PSIA) |
| PVRPSI | VENT RESERVOIR PRESSURE (PSIA) |
| PVA0PSI | INITIAL ACTUATOR PRESSURE (PSIA) |
| NAGCMP | NUMBER OF ACTUATOR GAS COMPONENTS [USUALLY 1] |
| IAGCMP | ACTUATOR GAS INDICATOR [1=AIR; 2=ARGON; 3=FREON12; 4=N2; 5=CO2] |
| TSIM | SIMULATION RUN TIME (SECS) |
| NPMS | NUMBER OF STEPS PER MILLISECOND |
| TOPEN | VALVE OPENING TIME (SECS) |
| TCLOSE | VALVE CLOSING TIME (SECS) |
| TON | BRAKE TURN-ON TIME (SECS) |
| TOFF | BRAKE TURN-OFF TIME (SECS) |

Hopefully, this document provides an accurate summary of the input data required to successfully use program *facility*. It is important to note that when the program is run in the mode to generate RCDF values, it is essential that a file of the form "run*.rcdf" (* = run number) be present in the current working directory. No such restriction is imposed when the program is run in predictive mode.

# PREVIOUS CORRESPONDENCE

To: Dr. C. MacArthur
From: C. Haldeman, M. Dunn
Subject: Main Valve Model Update
Date: 7-27-92

Dr. MacArthur-

The purpose of this brief note is to bring you up-to-date on our progress with the main valve model, show you some results, outline the testing intended for this week, and discuss quickly some concerns so that you can be thinking about them.

First of all we have a model which predicts the X vs T of the main valve well, and it predicts the pressures in the chambers (although not quite as well). This model was developed by examining one run of a test matrix in detail and then using the best model from that one run to predict other runs, varying only those parameters which varied from run to run. Thus things like the friction and grove placement would remain the same for both runs and only the valve areas would change. The particular matrix we were examining was test matrix 3 consisting of:

| Run | P1 Open Res. (psia) | P2 Act. Res. (psia) | P3 Close Res. (psia) | Notes |
|---|---|---|---|---|
| 1 | 331 | 174 | 426 | Both Vent valves removed, All other valves set to 10.5 turns open |
| 2 | 335 | 181 | 443 | Same as Run one but all valves wide open |
| 3 | 335 | 180 | 432 | Same as Run 2, but Vent lines removed |

The real purpose of this test was to: 1) examine the effect of the smaller reservoir installed on the opening side and 2) see if the vent lines were restricting the valve motion.

Run 1 was used as the design run, with all the parameters being set to achieve "optimal" agreement, and then this model was used to predict runs 2 and 3. By way of summary, the model has been changed in three key areas:

**Actuator volumes:**

Original:

V(6)=AO*S+VF6

V(7)=AC*(SMAX-S)+VF7, SMAX =12

New:

V(6)=AO*S+VF6+VDEAD

V(7)=AC*(SMAX-S-SP)+VF7+VDEAD

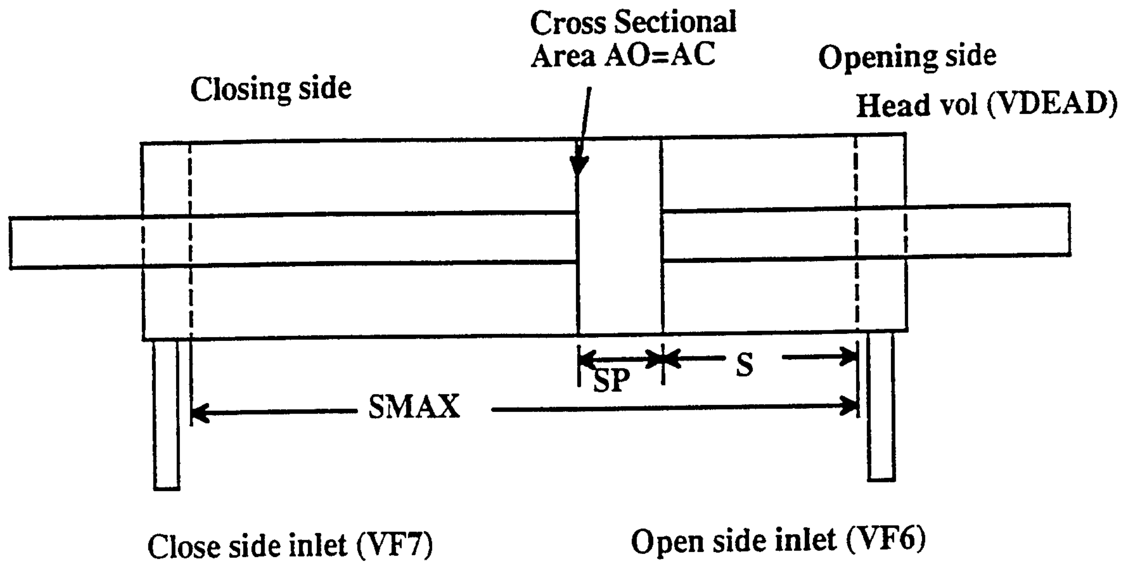
Where SMAX = internal length of main valve piston chamber = 15.5

AO=AC= Cross sectional area of piston

S = position of Actuator piston

VF7, VF6 = the volumes of the respective fill lines

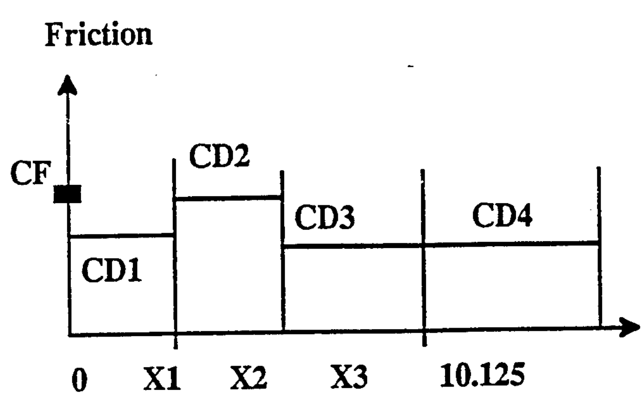
VDEAD = Volume of the head plate




The key difference here is the addition of the volume (9.6 $in^3$) under the head which was not originally accounted for. Previously, I thought that Gerry did not account for the piston thickness (3.5"). This was because I thought he was using SMAX = 15.5; however, he ran his models with a different SMAX ( = 12) which intrinsically accounts for the piston thickness.

**Frictional Coefficients:**

Originally the model had only two friction values; a static and dynamic friction. I have found that a more complicated scheme provides better agreement. This is a piecewise continuous system




which has a basis in the fact that the the friction is reduced dramatically when the piston rings are over the grooved area of the cylinder.

**Actuator Bypass Area**

Original:

If ($S \le S1$) Then A67= AF67

If (S>S1 and S<S2) Then A67 = AF67 +AV67

If (S≥S2) Then A67= AF67

S1=5, S2=10.5, AF67 = Cross over area (outside), AV67 = Area of grooves

New:

If (S ≤ S0 or S ≥SSW) Then A67= AF67

If (S > SO and S≤ S1) Then A67= AF67+ ALEAK

If (S>S1 and S<S2) Then A67 = AF67 +AV67

If (S≥S2 and S <SSW ) Then A67= AF67 + ALEAK

Where ALEAK is an extra leakage which stops when the valve stops moving at either end and SSW is a variable (usually fixed) at the maximum displacement of the valve (11.125 ").

**Results:**

The main criteria for a good model were, in the order of preference:

1) Match of X vs T
2) Match of chamber pressures after valve stops
3) Match of reservoir pressures
4) Similarity between closing and opening characteristics
5) Match of chamber pressures during valve motion

Figure 1 shows the X vs T for all three runs, the differences in closing time is due to the manual firing of the main valve. Figure 2 shows the model calculated from run 1 (called model 96) used to predict the motion of run 2. A couple of important points. First the model shows the compression of the springs (which we do not measure), thus the model shows a greater final X position. Secondly, the two places of greatest discrepancy occur at the same relative position in the stroke, after about 9 inches of movement. Finally, it is important to realize that after the valve is opened 8.5" it is fully open, any more distance does not change the flow area. The sources of these inconsistencies in the model are shown in figure 3. Both on the opening and closing side, the model over-predicts the dampening pressure. I am not sure why this occurs. Figure 4 shows the reservoir pressures which agree well.

The last major inconsistency in the model is this over-prediction on the dampening side of the piston and the offset in the dampening side (i.e. closing side for the opening stroke and opening side for the closing stroke) after the piston stops moving. Any corrections to account for this make the X vs T change.

For comparison purposes, figures 5 and 6 show the output from the original math model with the same areas and volumes that I use in my models but with the contributions of ALEAK grouped into AF67 and with no VDEAD. One can see that the original model under-predicts both position and pressure differences greatly during the valve motion.

**Future Work**

Using the model as it now exists, two predictions have been made. Figure 7 shows the first run which will be tried with pressure in the supply tank. This test corresponds to 15 psig across the valve. One can see that the velocity is low (.25 m/s) as the valve closes (nominal run conditions according to Gerry's model were about .75 m/s). Figure 8 shows a nominal high $\Delta P$ run. One important point to note is the vibrations which occur. This is due to the fact that it requires so much initial pressure to overcome the supply tank pressure that once this occurs, the piston goes extremely fast, compressing the gas in the dampening side. However, we do know that the model as it presently exists, over-predicts these pulses, and thus these vibrations may in fact be much less. Even if they did occur, they are occurring at a location where the main valve is not influencing the flow area (after about 8.5"). And finally the velocities seem to be reasonably low during the final stages of motion.

With this in mind, the goal of these week is to steadily increase supply tank pressure while measuring valve performance. At this point we have reason to believe that:

1) The model does predict pressures and position fairly well
2) The possibility for damage to the valve during this ramp up process is minimal

There is still work which needs to be be done on the model. The two areas which need to be addressed are the pressure inconstancies mentioned earlier and the questions involving the proper prediction of velocity. The model uses a $\Delta X/\Delta T$ system to predict velocity. This is clearly an approximation to the real velocity which is $\partial X/\partial T$. Presently an inconsistency exists between the $\Delta X/\Delta T$ data and the data which is obtained by fitting a polynomial through X vs.T and then analytically differentiating it. To some degree this problem, while annoying, is not major since the impact criteria can be set for velocities in either system. Presently our design criteria is not to hit the O-ring sealing plate any harder then we have been, and in no case to hit it such that the springs compress entirely. At this point, any future improvements in the model can be relegated to a future task, when other more critical issues have been resolved.

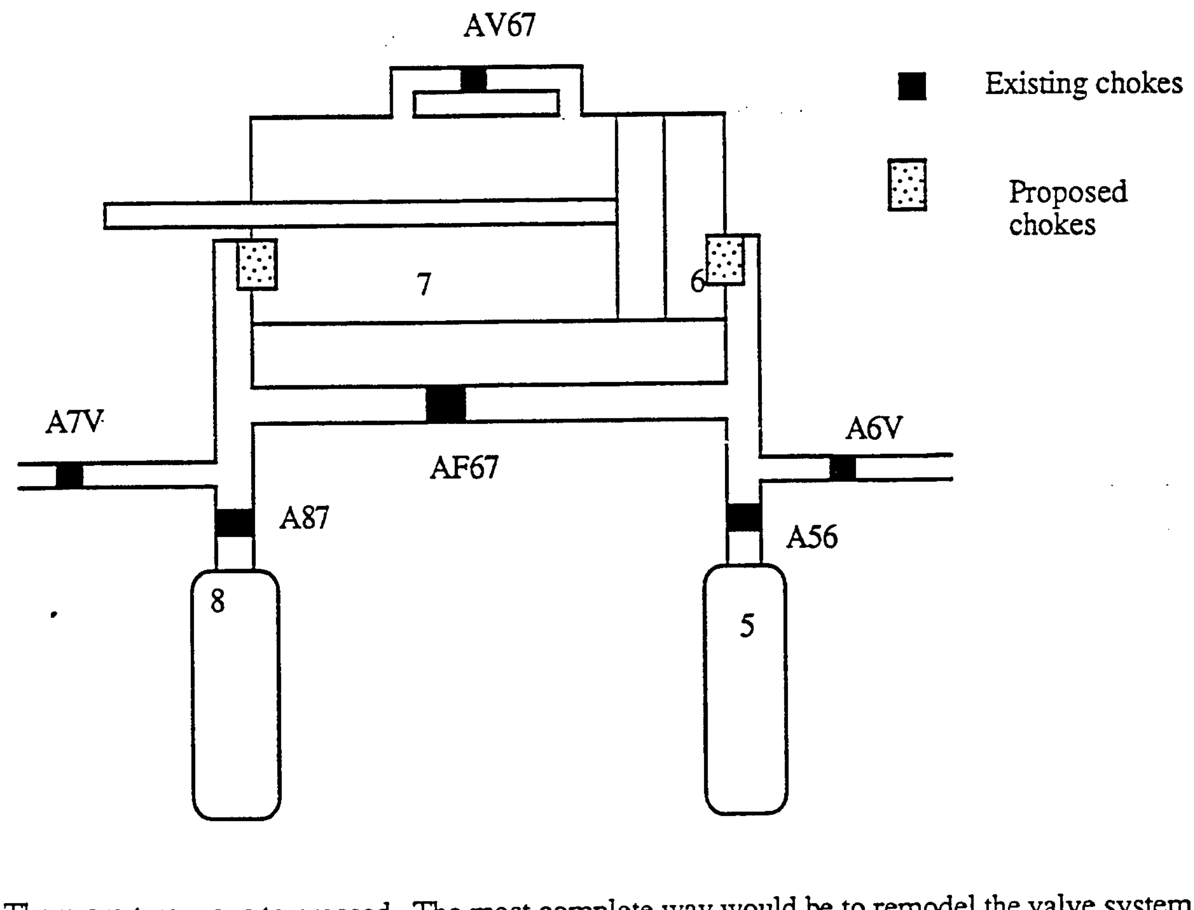
To: C. MacArthur and R. Bergerly
From: C. Haldeman
Subject: Math Model Revisions
Date: 10-27-92

I have become convinced that during valve motion there is something physically happening which we are not modeling well. This comes from two important facts:

1) The long term pressure traces (i.e over 2-5 seconds) agree well for the reservoir pressures, and the patterns are similar for chambers 6 and 7 (although the offsets are off)

2) Any attempt to correct the short-term pressure distribution in chambers 6 and 7 (i.e while the piston is moving) degrades our relatively good agreement with the reservoir pressures.

One explanation of this is that during valve motion another choking condition appears. This would explain the high back pressure in the compression chamber. The figure below shows where I believe these two choke conditions occur.




There are two ways to proceed. The most complete way would be to remodel the valve system as comprising of 6 chambers instead of the existing 4. However that could become quite complicated. A simpler, quicker solution may be to change the **venting areas and**

**compression volumes** when the piston is moving. Thus, on the opening stoke when the piston is moving, the total volume of chamber 7 would only be chamber 7 and not the line volume and VDEAD, and the choke area would be different from A7V. After the piston stops moving the total volume increases by the line volume and VDEAD and the choke are changes to A7V. On the closing stroke the same thing would happen to chamber 6.

We measure the chamber pressures (6 and 7) outside of the main valve itself, and thus, outside of the new proposed choke areas. This would imply that our measured values on **the compression side** are actually lower than what would be in the chamber during this choking condition. However this could explain quite a bit about the compression spike. Looking at figure 9 on the last main valve memo I sent (10-6-92), one sees that the model predicts a large compression spike which we do not see. If there was a secondary choke occurring this could in effect isolate our compression pressure transducer from measuring this spike. This scenario would also explain the strange friction factors we obtain from our measurements since the compression side pressure would not be accurate. Here are my suggestions:

1) Use timing information, rather than valve position to set when the choke areas are activated.

2) Assume that the choke starts in front of the head (so VDEAD is added to the line volume).

3) Make all these parameters controllable from cwh_config.dat

To: Dr. C. MacArthur, C.Murawski, and J. Finnegan

From: C. Haldeman, M. Dunn

Subject: Main Valve Model Update II

Date: 10-6-92

The purpose of this brief note is to outline the results of the main valve model for the high pressure runs (Matrix 6), describe the status of the model, and to transfer to WPAFB the capability of running the model. The present changes in the model are outlined in the memo dated 7-27-92 to Dr. MacArthur.

**Nomenclature:**

The model results conform to Dr. Guenette's original notation. Figure 1 is a schematic of what the different areas and chambers represent. $V_5$ is the open reservoir and $V_8$ is the closing reservoir. The five choke areas A7V, A87, AF67, A6V, and A56 are physically created by the five needle valves. AV67 represents the grooves cut into the piston cylinder housing. The following terms are used in the model and are sometimes used on the graphs:

POS- Valve position, sometimes referred to as X, units are inches

VEL - Valve velocity, unites are m/s

$P_x$- Where x is the chamber number, refers to the pressure in the chamber, units are psi

Throughout the write-up there are several terms used to describe the main valve behavior and pressure fluctuations in chambers 6 and 7. These are shown on figure 4 and are summarized below.

**Opening Stroke-** The operation of the valve going from closed to open position

**Closing Stroke-** The operation of the valve going from open to closed position

**Initial Pressure Spike -** The first pressure pulse in the actuating side of the piston ($P_6$ during the opening stroke and $P_7$ during the closing stroke)

**Compression Pressure Spike -** The first pressure pulse in the compression side of the piston ($P_7$ during the opening stroke and $P_6$ during the closing stroke)

**Predicted Performance of Main Valve:**

Figures 2-6 show the predicted performance of the main valve (for the present model configuration) for differential pressures of 50 psi, 80 psi and 95 psi. Figure 2 shows the position and velocity prediction of the valve. Figure 3 shows the pressure histories of the opening and closing reservoirs. Figure 4 shows the pressure histories of volumes 6 and 7 (this figure also has examples of the pressure spikes). Figure 5 and 6 are the position and velocity curves for the 80 and 95 psi cases respectively.

**Model Summary:**

Figures 7-9 show the analysis for the last set of data points obtained (the 55 psi run, Matrix 6, Run 6) Figure 7 shows the pressure histories for the open and close reservoir, while figure 8 shows the valve position and figure 9 the pressure histories inside the piston. While figure 7 shows good agreement between the recorded reservoir pressures and the model, figure 8 shows that the piston position does not agree as well. Originally the model initial pressure spike (see figure 9) was in a significantly different time position relative to the experimental data. This was found to be a timing problem which was easily corrected. While the model still shows all the same characteristics (i.e. there are spikes at the same time on both the model and experimental data, the absolute levels differ significantly.

The initial pressure spike is a very strong function of the reservoir choke areas: A87 or A56 (meaning that very small changes in the area make the model either over-predict or under-predict this phenomenon). And from the valve position histories, it is clear that the absolute values have little influence on the valve motion. It is the compression spike that is causing problems for the valve motion. Several attempts have been made to adjust the model to make the compression spike more compatible with experimental results (discussed later), but none were successful. At this point, the model can be used predictive tool to estimate the valve motion. Since we have shown that the system is over-damped, the chances of damaging the valve have been reduced considerably and it is our recommendation to continue with the high pressure testing.

**Model Analysis:**

Several attempts were made to make the compression spike more closely approximate the experimental data. The spike could be reduced by increasing the leakage area (ALEAK) to about .1 $in^2$ (which is about 2.5 times the flow area of the gas leaving the reservoirs). However, the predicted decaying pressure history of the closing actuator (from .8 to 2.1 seconds, see figure 9) was still much lower than the experimental one. In addition, the volume of the closing side was decreased dramatically (with no influence).

It has been generally concluded that the size of the reservoirs and the opening and venting choke areas (A87, A56, A7V, A6V) set the macro (0-5 secs) pressure decay of the reservoirs and the timing of the initial pressure spike. The slope of the decay (see figure 7) is dictated by the internal passages in the piston cylinder. The slope of the decay of the inner chambers (see figure 9) is dictated by the bypass ratio, AF67.

Since the valve motion is dictated by the difference between $P_6$ and $P_7$ in the first second of operation, the pressures after that may not need to line up. However, pressures that are far off when the valve goes to close, cause much larger differences between prediction and experiment for the closing stroke.

**Running the Valve Model:**

It is clear, that the best way to improve valve performance is to integrate the model testing with valve testing. The most inexpensive and expedient way to do this is to have the people at WPAFB do the integration. The model is stored in Haldeman's account and can be accessed simply by typing "facility" from that account. It requires two input files. One is the configuration file "cwh_config.dat" (a copy is enclosed). This file has all the information about the main valve such as the choke areas, the reservoir volumes, etc. The second file "facility.startup" contains all the initial conditions of the facility such as the supply tank pressure, opening time of valve, etc. Thus if the valve were working perfectly, one would only need to modify this last file to run any test condition.

The model has three types of output. There is the traditional output (labeled BD.OUT and BD.PLT) which contain all the model information. BD.OUT also contains the initial information stored in "cwh_config.dat" and "facility.setup". BD.PLT has its data comma delimited. A new file is called "valve.dat" which contains information specific to the valve (comma delimited). These three files are ASCII and can be read by other programs or computers (like a Macintosh). The third set of output are the velocity, pressure and positions associated with the main valve in DAS format. These are called P5_FM.3, P6_FM.3, etc. These files can be used as input to the DRP, so it is easy to make comparisons between the model and the experimental data.

There are three Fortran routines which help in data processing. One is called "d2vfmt.F" which converts from DAS to ASCII format. This program can be used to take several DAS files and create a multiple column ASCII file (which is quite large). The correct usage can be determined by just typing the program name, and it responds with the appropriate syntax. Once this ASCII file has been created, another program called"timint.F" can be used to select a piece of this bigger file based on time (i.e. all data between 1 and 2 seconds) or select every $n^{th}$ data point. The output can then usually be handled by commercially available analysis programs. The final program is called "foraft.F" which takes as its input the two LED files used to measure the position of the main valve. This program finds the corners of the pulses and is used to determine when the main valve reverses direction. The output is also ASCII and can be ported to other data analysis programs. This has been used as input to the Macintosh which actually develops the position of the valve over time.

**Future Work:**

Preliminary predictions suggest that if all needle valves were eliminated, then the main valve may move smoother at higher pressures (i.e. with less vibration). Choke areas are approximately .06 $in^2$ without the needle valves, .04 $in^2$ with the needle valves wide open, and .025 $in^2$ with the needle valves ten turns open. All values shown in "cwh_config.dat" are the best ones known to date.

We believe that the present configuration will work at all pressure values, although we also believe that the system could be optimized by tweaking some of the valves on the closing side. Figure 8 shows that the main valve covers about 90% (9 inches) of its closing stroke, relatively quickly, while the last 10% (1") takes 150 ms. This should be capable of being improved upon.

It is clear that something is happening in the compression chamber which causes the pressure to be quite high, compared to that predicted by the model, and that this is not a function of the vent or inlet choke areas (otherwise the reservoir pressure histories would not agree). Understanding this may take some extra experimentation, and possibly some derivation of internal properties based on measured values. Presently, this can best be done by the personnel at WPAFB who have access to the main valve. We are, of course, ready and willing to help if any difficulties should arise.

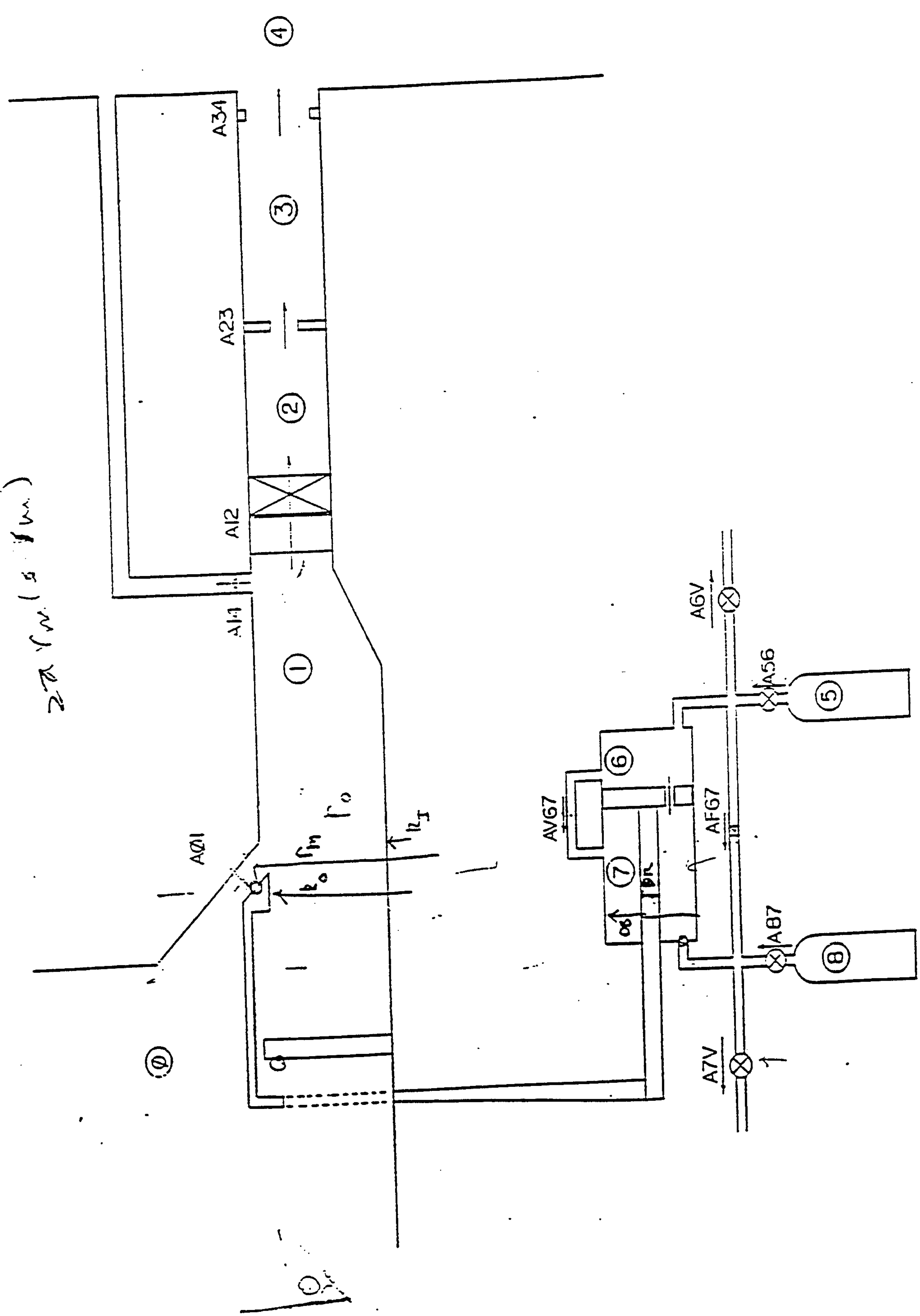



Figure 1.

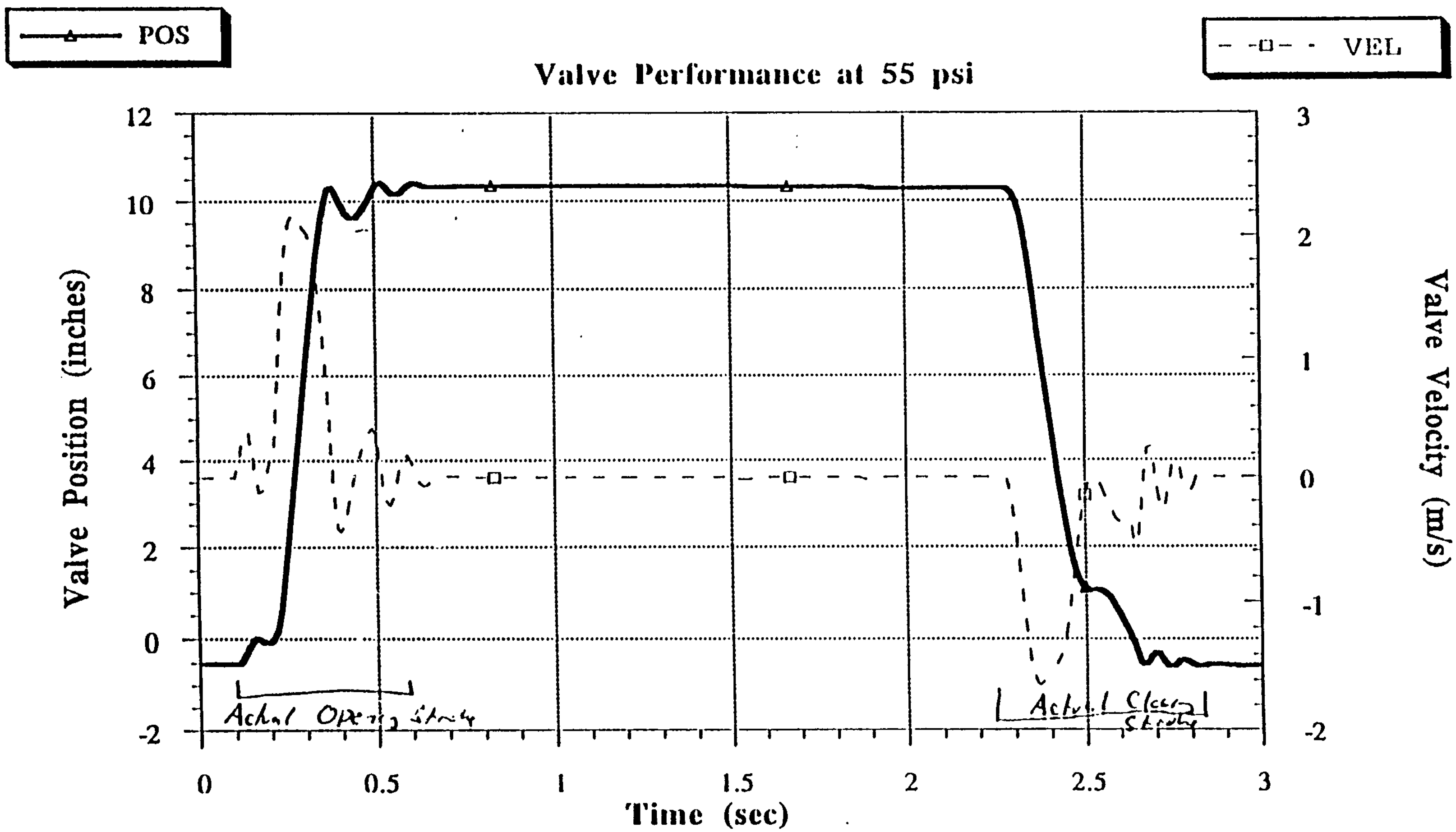
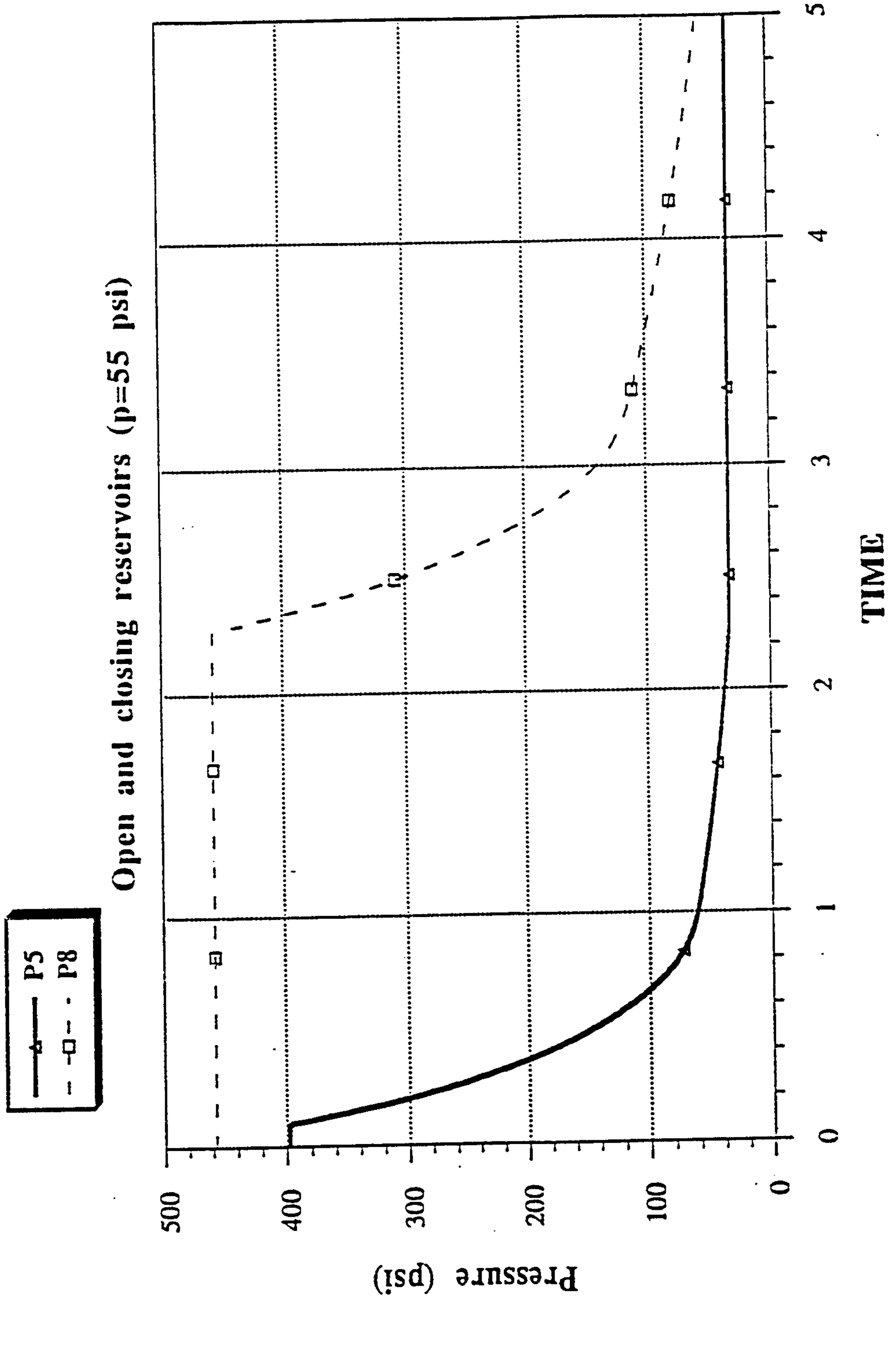

POS
VEL
Valve Performance at 55 psi
Valve Position (inches)
Valve Velocity (m/s)
Time (sec)
Actual Opening Stroke
Actual Closing Stroke
12
10
8
6
4
2
0
-2
3
2
1
0
-1
-2
0
0.5
1
1.5
2
2.5
3

Figure 2



Open and closing reservoirs (p=55 psi)
P5
P8
Pressure (psi)
500
400
300
200
100
0
TIME
0
1
2
3
4
5


Figure 3

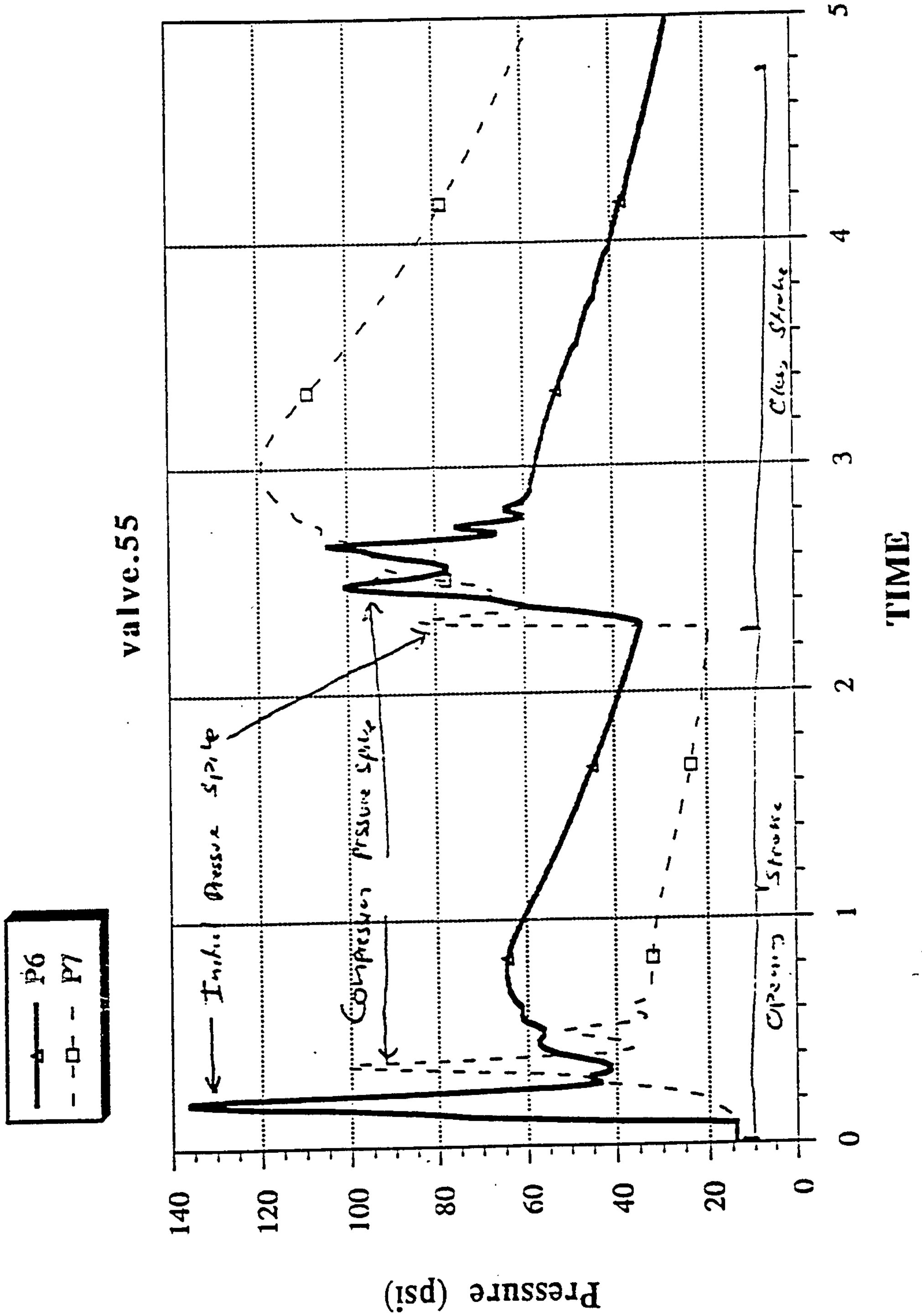



Figure 4

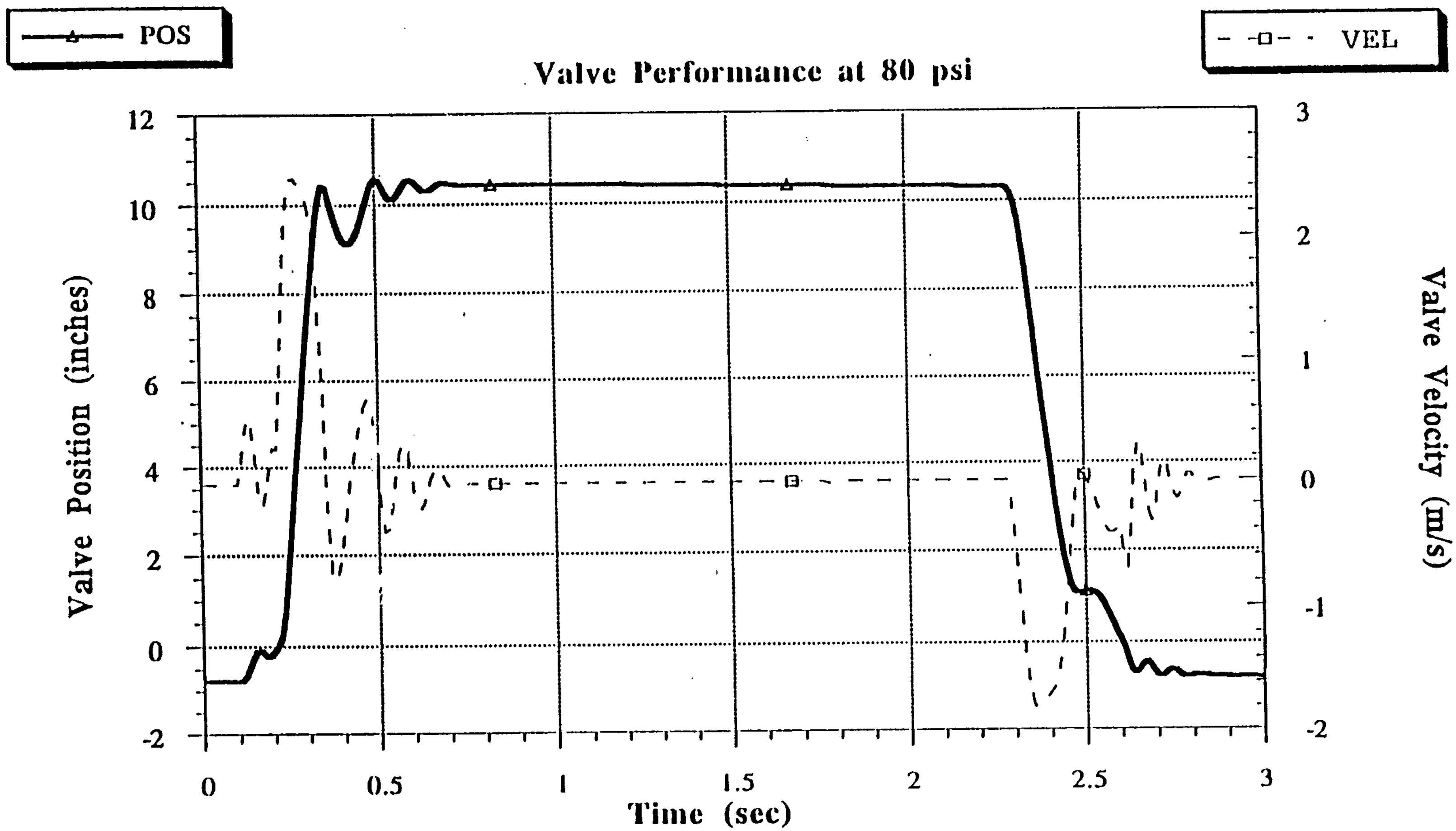

POS
VEL
Valve Performance at 80 psi
Valve Position (inches)
Valve Velocity (m/s)
Time (sec)
12
10
8
6
4
2
0
-2
3
2
1
0
-1
-2
0
0.5
1
1.5
2
2.5
3

Figure 5

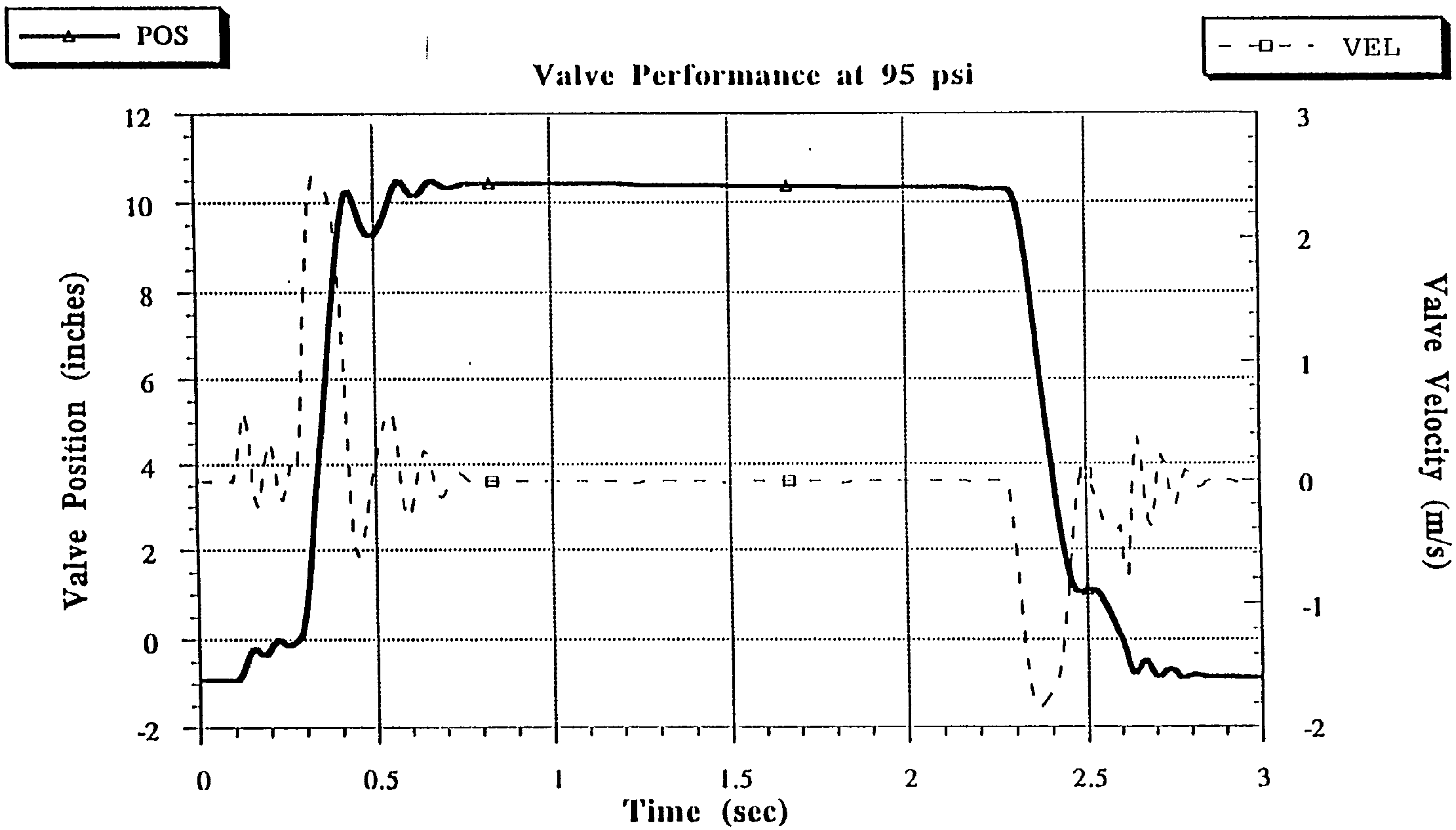

POS
VEL
Valve Performance at 95 psi
Valve Position (inches)
Valve Velocity (m/s)
Time (sec)
12
10
8
6
4
2
0
-2
3
2
1
0
-1
-2
0
0.5
1
1.5
2
2.5
3

Figure 6

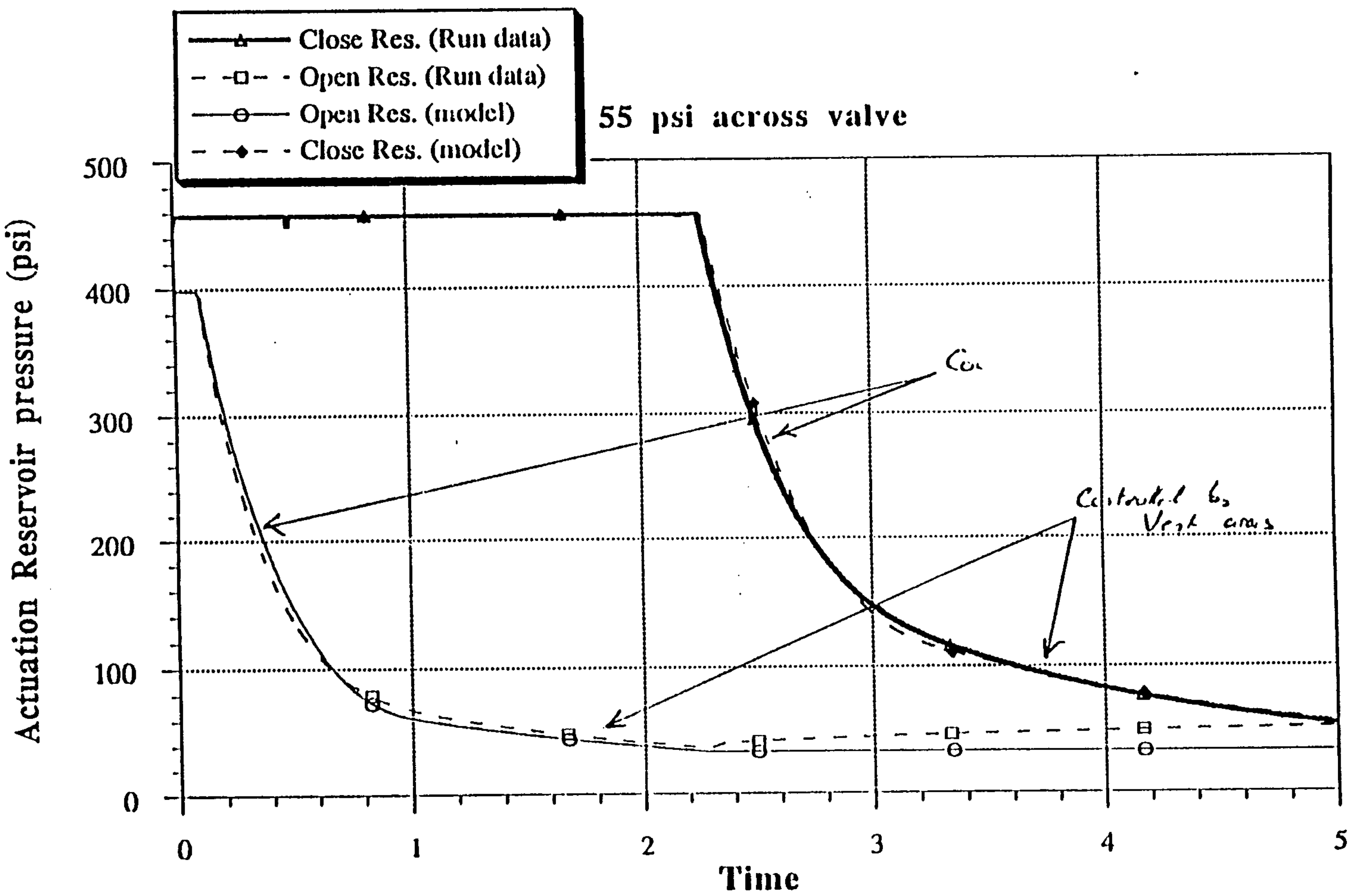

Close Res. (Run data)
Open Res. (Run data)
Open Res. (model)
Close Res. (model)
55 psi across valve
Actuation Reservoir pressure (psi)
500
400
300
200
100
0
0
1
2
3
4
5
Time
Controlled by Vent areas

Figure 7

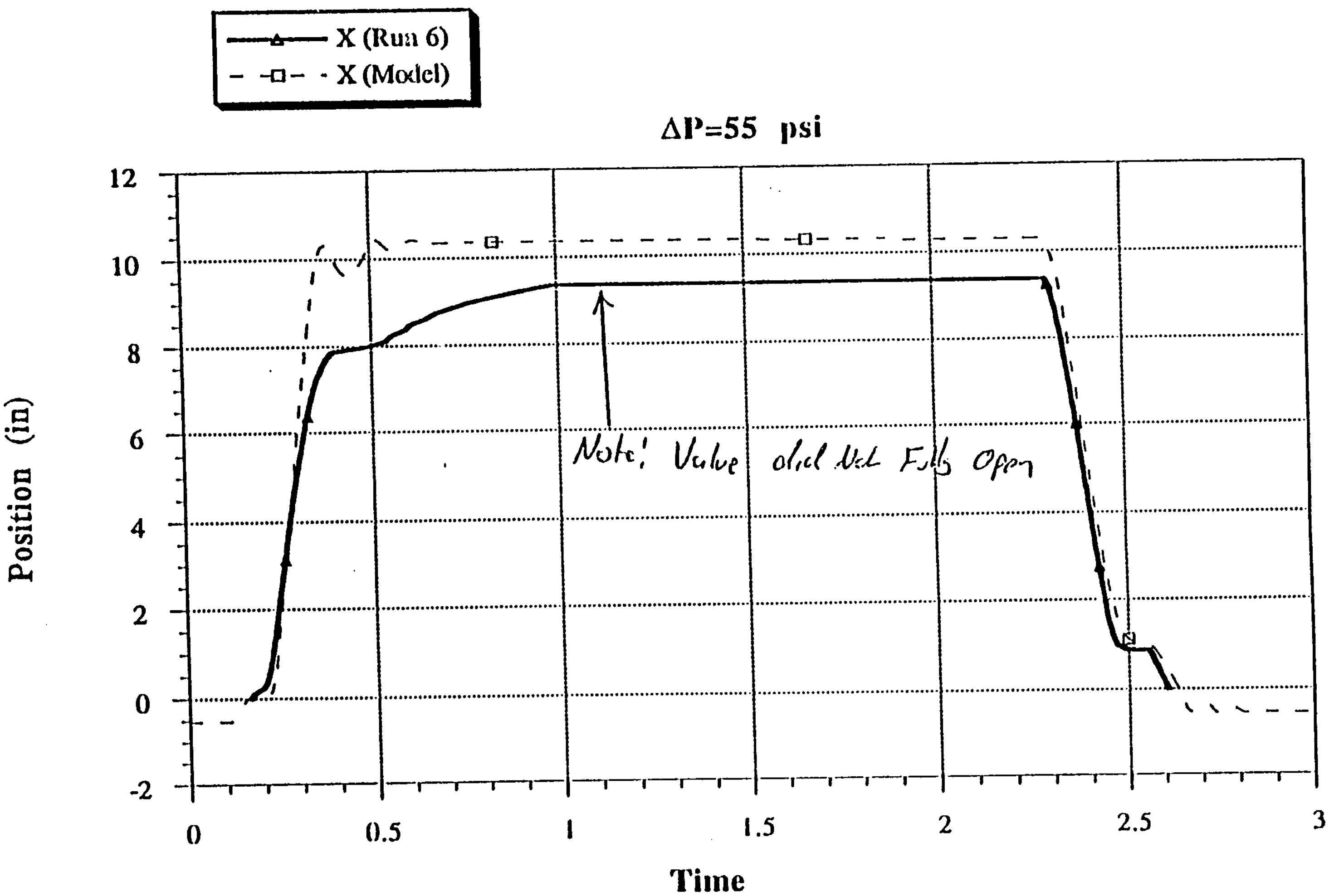

X (Run 6)
X (Model)
ΔP=55 psi
Position (in)
Time
12
10
8
6
4
2
0
-2
0
0.5
1
1.5
2
2.5
3

Figure 8

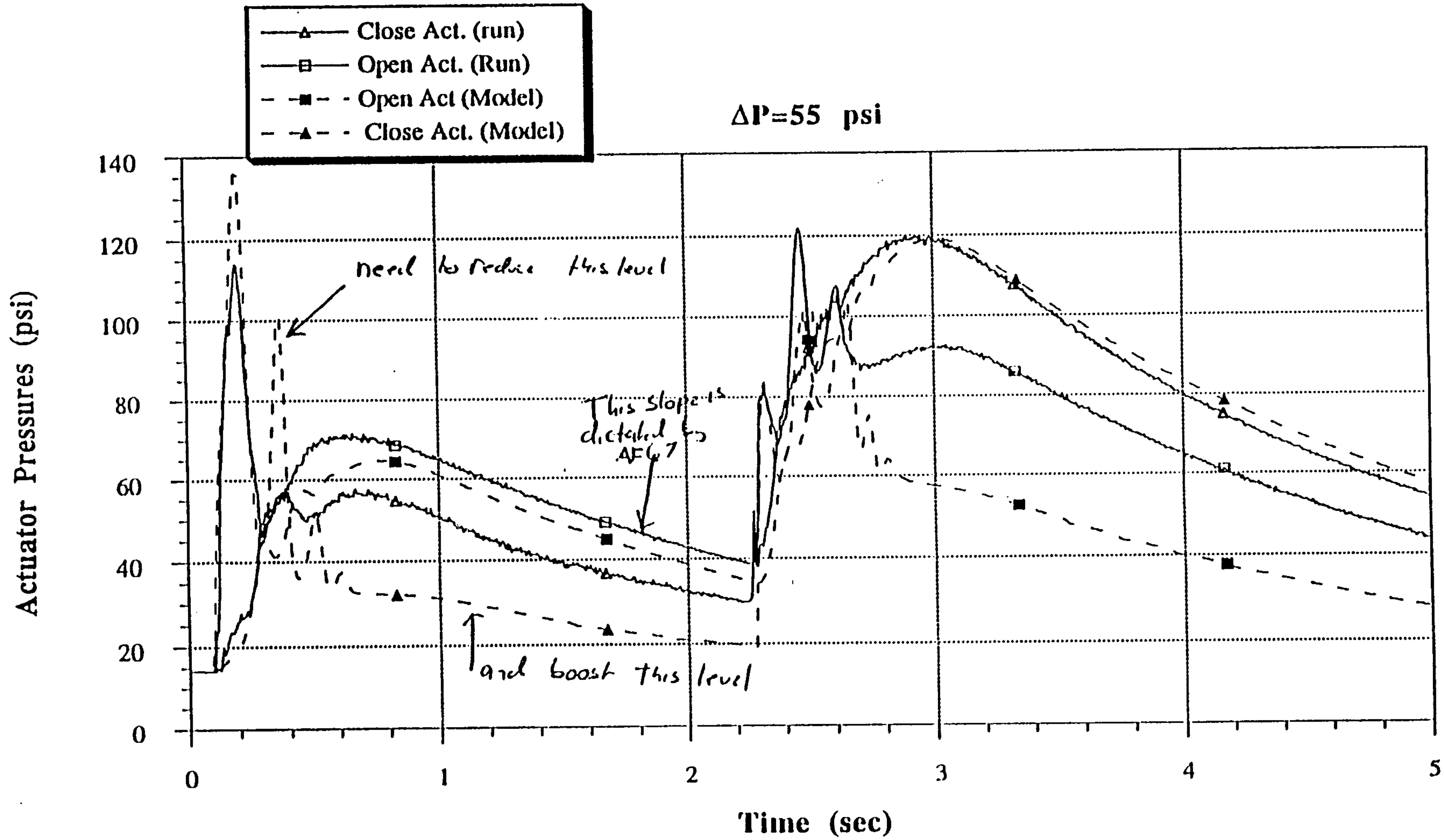

ΔP=55 psi
Close Act. (run)
Open Act. (Run)
Open Act (Model)
Close Act. (Model)
Actuator Pressures (psi)
140
120
100
80
60
40
20
0
Time (sec)
0
1
2
3
4
5
need to reduce this level
and boost this level

Figure 9.

**cwh_config.dat**

```
*/  Facility Configuration Data File
*/ FD1 has Facility Volume Data, ft**3
*/V0 - SUPPLY TANK
*/V1 - TURBINE INLET
*/V2 - TURBINE EXHAUST
*/V3 - DSV INLET
*/V4 - DUMP TANK
 $FD1
  V0= 3200.,
  V1=  21.,
  V2=   2.,
  V3=  250.,
  V4= 6400.
 $END
*
*/FD2 has Facility Flow Path Orifice, in**2
*/ADSO - EXIT PIPES TO DUMP, A34: 2-20"DIA,CD=.62
 $FD2
  ADSO=  390.
 $END
*
*/VD1 has Valve Geometry variables
*/ISS =1 FOR SLIDING SLEEVE (ATAR), =0 FOR COWCATCHER (MIT)
*/RO - VALVE ANNULUS, OUTER RADIUS (INCHES)
*/RI - VALVE ANNULUS, INNER RADIUS (INCHES)
*/RM - MAIN SEAL RADIUS (INCHES)
*/XM - MAIN SEAL BREAKAWAY (INCHES)
*/RS - BACK SEAL RADIUS (INCHES)
*/XS - BACK SEAL BREAKAWAY (INCHES)
*/THETA - ENTRANCE ANGLE FROM VERTICAL (DEGREES)
*/MASS - TOTAL MOVING MASS (KG)
 $VD1
  ISS= 1,
  RO= 17.25,
  RI=  7.75,
```

```
 RM= 18.00,
 XM= 0.058,
 RS= 17.30,
 XS= 0.041,
 THETA = 45.0,
 MASS = 277.0
$END
*
* VD2 has Impact Spring Data
*/XKSC - ZERO FORCE POSITION, MAIN VALVE CLOSING SPRING (IN)
*/KSC - SPRING CONSTANT (LBF/IN), CLOSING SPRING
*/XKSO - ZERO FORCE POSITION, VALVE OPENING SPRING (IN)
*/KSO - SPRING CONSTANT (LBF/IN), CLOSING SPRING
*/CSF - COEFFICIENT OF STATIC FRICTION
*/    COEFFICIENTS OF DYNAMIC FRICTION FOR SLIDER RANGES SHOWN:
*/CD1 -  0 TO X1
*/CD2 - X1 TO X2
*/CD3 - X2 TO X3
*/CD4 - X3 TO END
*/X1  - FIRST SLIDER POSITION FOR DYNAMIC FRICTION COEFFICIENTS (IN)
*/X2  - SECOND SLIDER POSITION FOR DYNAMIC FRICTION COEFFICIENTS (IN)
*/X3  - THIRD SLIDER POSITION FOR DYNAMIC FRICTION COEFFICIENTS (IN)
$VD2
  XKSC=   0.,
  KSC=  8000.,
  XKSO=   10.125,
  KSO=  5000.,
  CSF=   0.40,
  CD1=   0.27,
  CD2=   0.4,
  CD3=   0.4,
  CD4=   0.27,
   X1=   2.0,
   X2=   5.0,
   X3=   8.0,
 $END
```

```
*
* VD3 has Actuator Cylinder Geometry
*/DB - BORE DIAMETER (IN.)
*/DR - ROD DIAMETER (IN.)
*/NRODS - =2 FOR ATAR, =1 FOR MIT
*/SMAX - MAXIMUM ACTUATOR STROKE (INCHES)
*/SP - PISTON THICKNESS (INCHES)
*/S0 - STROKE OFFSET, S @ X=0 (INCHES)
*/S1 - OFFSET TO START OF TRANSFER PORT (IN.)
*/S2 - END OF TRANSFER PORT (INCHES)
*/AV67 - TRANSFER PORT AREA (IN**2)
*/AF67 - ACTUATOR FIXED BLEED AREA (IN**2)
*/ALEAK - LEAKAGE AROUND PISTON (IN**2)
*/SSW   - SWITCH POSITION (IN)
 $VD3
  DB=     8.0,
  DR=     3.5,
  NRODS=   2,
  SMAX=   15.5,
  SP=     3.5,
  S0=     1.0,
  S1=     4.75,
  S2=     7.75,
  AV67=   2.0,
  AF67=   0.030,
  ALEAK=  0.015
  SSW=    11.125,
 $END
*
* VD4 has Actuator Gas Supply Geometry
*/V5 - OPENING GAS SUPPLY VOLUME (M**3)
*/VF6 - OPENING LINE VOLUME (IN**3)
*/VF7 - CLOSING LINE VOLUME (IN**3)
*/V8 - CLOSING GAS SUPPLY VOLUME (M**3)
*/IVNT - VENT TO DUMP=0, VENT TO ROOM=1
*/AO56 - OPENING GAS SUPPLY ORIFICE (IN**2)
```

```
*/AO7V - CLOSING GAS SUPPLY ORIFICE (IN**2)
*/AC87 - CYLINDER CLOSING END VENT ORIFICE (IN**2)
*/AC6V - CYLINDER OPENING END VENT ORIFICE (IN**2)
*/VDEAD - DEAD VOLUME IN CYLINDER HEAD (IN**3)
 $VD4
  V5= 2472.0E-6,
  VF6=  33.2,
  VF7=  32.0,
  V8= 4206.0E-6,
  IVNT=   1,
  AO56=  0.0360,
  AO7V=  0.060,
  AC87=  0.042,
  AC6V=  0.064,
  VDEAD= 9.6,
 $END
*
* BRK has BRAKE CONSTANTS
*/KB - BRAKE CONSTANT (W-s**2 / Tesla**2)
*/NB - brake speed @ maximum torque (rpm)
*/MDRUM - BRAKE DRUM MASS (KG)
*/CPD - BRAKE DRUM SPECIFIC HEAT (J/KG-K)
*/TAUB - BRAKE TIME CONSTANT (SECONDS)
 $BRK
  KB= 80.829,
  NB= 7461,
  MDRUM= 33.36,
  CPD= 427.0,
  TAUB= 0.01
 $END
```

**facility.setup**

```
0     /Generate RCDF values ,1-yes,.0-no/
1     /Generate full printout, 1-yes, 2-no/
1     /Start-uo dynamics? 1-yes, 0-no/
3     /Turbine number/
5992  /Operating speed/
1     /Eddy-brake option 1-computed by model, 2-preprogrammed/
95.0  /supply tank pressure/
300.0 /supply tank temperature K/
1.40  /Dump tank pressure/
300   /Dump tank temp./
1.4   /Gamma/
1     /# of test gas components/
1     /1 - air, 4 - nitrogen/
500.0 / open resevoir Press/
600.0 / close reservoir pressure/
14.30 /  vent pressure/
14.30 / Actuation initial pressure/
1     /# of actuator gas components/
4     /gas type 1-air, 2-argon, 3-R12, 4-N2, 5-CO2/
5     /run time/
10    /number of timesteps per ms/
.097  /open time/
2.28  /close time/
.089  /Brake turn-on time/
2.5   /Brake turn-off time/
```