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THE USE OF A BLOCK DIAGRAM SIMULATION LANGUAGE FOR RAPID MODEL PROTOTYPING

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ABSTRACT

The research performed this summer was a continuation of work performed during the 1995 NASA/ASEE Summer Fellowship. The focus of the work was to expand previously generated predictive models for liquid oxygen (LOX) loading into the external tank of the shuttle. The models which were developed using a block diagram simulation language known as VisSim, were evaluated on numerous shuttle flights and found to work well in most cases. Once the models were refined and validated, the integration of the predictive methods were integrated into existing software utilized by Rockwell known as Propulsion Advisory Tool (PAT). Although time was not sufficient to completely integrate the models developed into PAT, the ability to predict flows and pressures in the orbiter section and graphically display the results was accomplished.

INTRODUCTION

Development of advanced software systems for launch support has been an ongoing task at KSC for a number of years. One launch support system which has received much attention is the loading of liquid oxygen LO_2. Two examples of software which have focused on this particular system for the purpose of fault detection and diagnosis are the Knowledge-based Autonomous Test Engineer (KATE) and the Propulsion Advisory Tool (PAT). The ability to develop predictive models for use in these or other software applications, can be a difficult task for a complex process such as LO_2 loading. The objectives of this work were two fold: 1)To develop predictive models for the LO_2 loading process using the block diagram simulation language VisSim and 2) Integrate the developed models into existing software for launch support.

MODEL DEVELOPMENT

The LO_2 predictive models were developed using a PC-based version of VisSim. VisSim is a block diagram simulation language which can be used to solve both differential and algebraic equations. Modeling equations which describe a physical system are transformed into a block diagram which is numerically solved as a function of time. A graphical interface is provided with pull down menus which allow blocks to be selected and wired together with the use of a mouse. In addition complex blocks can be formed in a hierarchial fashion to allow for natural organization of the blocks which comprise the model. Figure 1 which gives a process flow and instrumentation diagram for the hardware in the vicinity of the orbiter associated with LO_2 loading is also a complex block using a bitmap image for representation. On top of the image are other complex blocks (i.e. pressure gauges, flow meters, valves, etc.), which if examined would reveal additional blocks underneath.

Before any modeling could be done on the LO_2 system, data from previous loading operations, pertaining to the instrumentation associated with the system had to be obtained. This was achieved by first broadcasting data recorded on a CD ROM using PC Goal over the network. The data was then recorded using KATE. Data was recorded from the T-6 hr mark which is prior to the LO_2 being loaded, until approximately two hours after the replenish phase had started. Once this data was recorded, it had to be put into a form which could be used by the VisSim program. This was done by running several PERL scripts which sorted through the recorded data and stored the data in a proper form in a series of ASCII files. These files have been compressed and stored on several floppy disks for future use if desired.

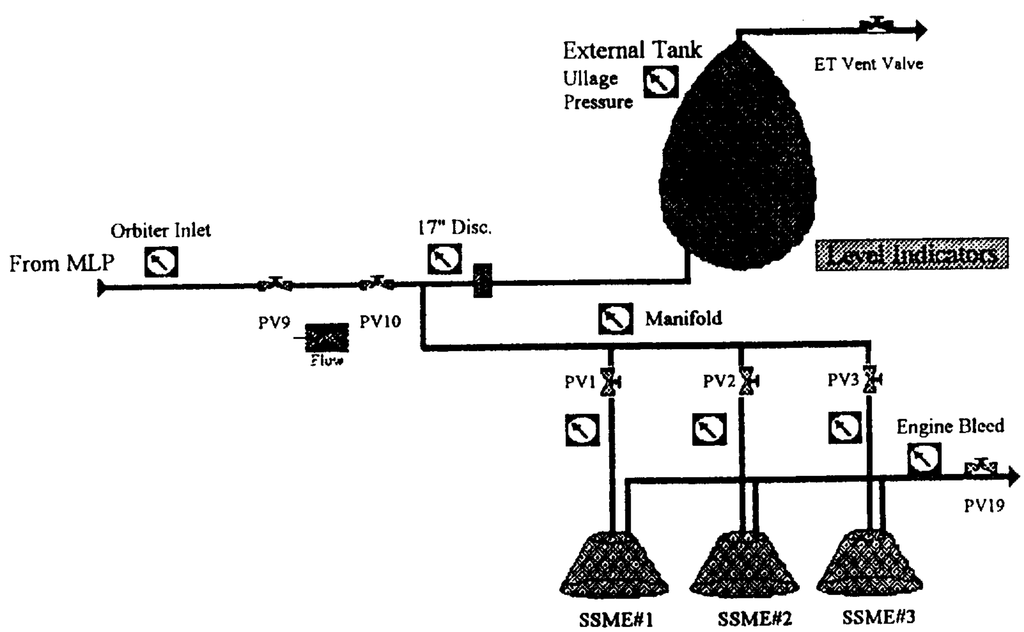

Figure 1 LO_2 Loading Process Flow & Instrumentation Diagram for the Orbiter Section

To completely model the loading of liquid oxygen into the external tank of the space shuttle, six separate phases as outlined in Table 1 must be accounted for. This work has primarily focused on the Fast Fill, Topping and Replenish phases and hence the description of the modeling effort outlined here pertains primarily to these regimes. Although the slow fill process is not explicitly modeled, the predictions should be applicable to this loading phase, since presumably only liquid oxygen is present. Chill down on the other hand can not be readily modeled and the models should not be used during this period, due to the presence of two phase flow, sensor saturation and rapidly changing dynamic conditions.

Table 1 Phases of Liquid Oxygen Loading

Chill down (T-8:00 to T-5:30)
Slow Fill ET to 2% (T-5:30 to T-5:15)
Fast Fill ET to 98% (T-5:15 to T-3:25)
Topping of ET to 100% (T-3:25 to T-3:20)
Auto Replenish (T-3:20 to Pre-launch)
Stop/Revert Flow (Abnormal Case)
Phases of Liquid Oxygen Loading

As with all physical systems which involve the transport of mass or energy, the principals of conservation apply. An equation for LO_2 conservation of mass for the external tank (ET) can be written as:

$$\rho A \frac{dh}{dt} = \rho F_{17'' \, inlet} - \rho F_{ET \, vent} \tag{1}$$

where:
ρ = *the density of* LO_2
A = *the cross sectional area of the ET*
h = *the level of* LO_2
$F_{17'' \, inlet}$ = *the flow of* LO_2 *through the* $17''$ *inlet*
$F_{ET \, vent}$ = *the flow of gaseous* O_2 *through the* $17''$ *inlet*

Due to the geometry of the ET, the cross sectional area changes as a function of liquid height and thus must be accounted for. This is done with VisSim using lookup tables contained in files in which values of area are obtained as a function of height. From the conditions modeled, the liquid density of the LO_2 is approximately constant although also included in the VisSim program are lookup tables for density as a function of temperature and pressure.

The flow of a fluid in a pipe between two points is proportional to the square root of the pressure difference between the points. Thus flow terms in equation 1 are defined by the equation:

$$F = \gamma(\Delta P)^{0.5} \tag{2}$$

where:
γ = *a flow coefficient (i.e. admittance)*
ΔP = *the pressure differential for the section of pipe considered*

Conservation of energy equations can also be written for key sections of the LO_2 loading process, however the observable variable temperature, has spatial variations as well as time dependency. This leads to complex solutions for partial differential equations as at each time step a temperature grid has to be solved by a numerical procedure such as finite differences. A simplification can be made if each section of pipe which is to be modeled is assumed to be a series of well stirred compartments. The partial differential equations can thus be transformed into a series of ordinary differential equations. For a given section of pipe where only one compartment is assumed with one stream entering and one stream exiting the energy balance can be written :

$$\rho V C_p \frac{dT_o}{dt} = \rho C_p F T_i - \rho C_p F T_o + Q_{gain} \tag{3}$$

where:
T_o = *the temperature exiting the pipe*
T_i = *the temperature entering the pipe*
C_p = *the specific heat of the* LO_2
Q_{gain} = *the heat gain the surroundings*
F = *the flow of* LO_2 *through the pipe*
V = *the volume of the pipe*
ρ = *the density of the* LO_2 *inside the pipe*

In equation 3 the heat gained from the surroundings can be written as:

$$Q_{gain} = UA(T_a - T_o) \tag{4}$$

where:
T_a = *the ambient temperature*
T_o = *the* LO_2 *temperature exiting the pipe*
U = *an overall heat transfer coeffìcent*
A = *the surface area of the pipe section*

The LO_2 loading data for STS55 was used as the base case for model development. In developing the model it was assumed that all flow measurements were accurate and hence could be used to aid in the conservation of mass equations. Since there are two flow meters associated with the LO_2 pumps, the two values were averaged and then passed through a simple first order filter to eliminate some of the noise. From a mass balance, the flow of LO_2 going to the orbiter is equal to this filtered value for the pump flow, minus the flow recycled to the storage tank (bypass line). The first step in the model development was to assume a flow coefficient for the flow being returned to the storage tank as given by equation 2. The pressure drop used in the equation was from the pump discharge to the pressure in the bypass line. There are two separate return lines to the storage tank in the recycle stream. The smaller line is always open, while the larger line has a valve which is only opened after the fast fill operation has been completed. This leads to a need for different admittance values for the flow through this line. The flow coefficient for the bypass line can be readily determined during the replenish loading phase, since the total flow to the orbiter is equal to the flow through the replenish flow meter, since the valve on the transfer line fill valve is closed at that time.

Once the flow to the orbiter is set, the next step is to assume flow coefficients for the LO_2 flow through the main engines of the space shuttle. It was assumed that since these lines are the same dimensions with similar flow paths, that the flow and hence the flow coefficients would be equal through each line. Subtracting this flow through the engines from that which is going to the orbiter, leaves the difference going up to fill the ET. Another flow coefficient which needs to be assumed is that for the ET vent valve during the times in which it is open.

All of the assumptions are checked through integration of the differential equation given in equation 1 to get the level as a function of time. Since level sensors are placed in the external tank at the 5%, 98%, 100-% and 100% marks, the values obtained from the numerical integration can be checked against the actual data. Once the replenish phase is entered the level remains approximately constant under closed loop control. The flow coefficients can then be iterated until reasonable values are achieved.

SIMULATION RESULTS

As previously discussed the LO_2 loading predictive models were developed using STS50 as the base case. Figure 2 shows how the measured values compare to predictive values for the orbiter inlet pressure. The prediction is generated from equation 2, by using the flow rate through the section of pipe between adjacent measurement points, the flow coefficient for the section and the measured pressure of the adjacent point. The other pressure measurements on the orbiter give accuracy similar to that shown in Figure 2.

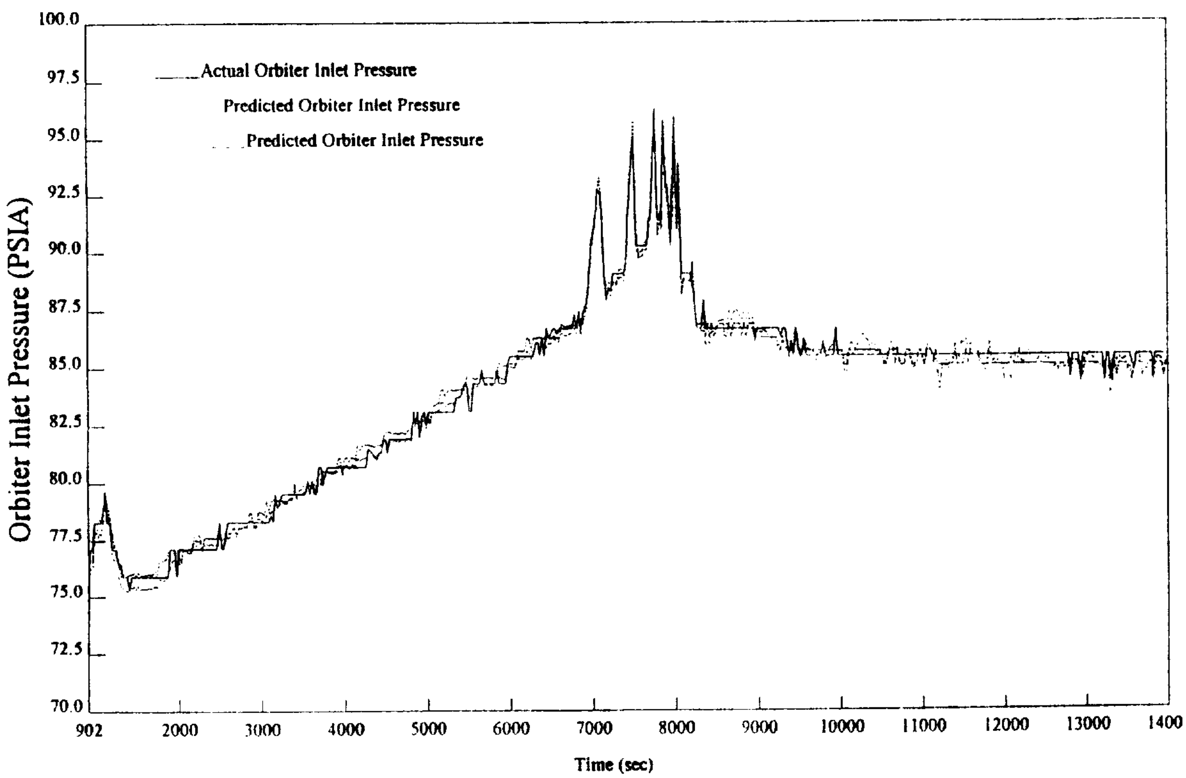

Figure 2 Predicted versus Actual Orbiter Inlet Pressure for STS50

Two predictive methods were used for each of these measurements as one section of pipe used was from the orbiter inlet to the 17 inch disconnect and the other section was from the manifold to each point. Two predictive methods were also used to predict the pressures in the engines, as the primary prediction used an average predicted flow through the engines, a flow coefficient and atmospheric pressure while the second prediction used the manifold pressure as the adjacent point. Since the manifold does not have an actual pressure measurement, one was generated in VisSim by taking a value between the orbiter inlet, 17 inch disconnect and engine inlet pressures. It was found that due to noise in the data and the relatively small differential pressure between measurements during the replenish phase, that an offset needed to be added to the orbiter inlet pressure, in order to insure that the manifold pressure was always between the measured values. While this worked well for STS50, using the generated manifold pressure for predicting adjacent pressures could not be repeated in other flights without adjusting this offset.

To evaluate the robustness of these models, other LO_2 data from different missions was also examined. Table 2 gives a comparison of the pressure predictions using the primary predictive method (i.e. the manifold pressure was not used) relative to the base case. It was found that the pressure predictions worked well for all flights, with the only difference coming from offset differences between orbiters. Figure 3 shows how the prediction for the orbiter inlet pressure has a relatively constant error or offset using the same offsets as those used for STS50. This evaluation of LO_2 on different flights shows that the models developed are robust and should be applicable to all loadings once an offset is determined for the particular orbiter.

Table 2 Comparison of Predicted Pressures Relative to Measured Pressures for Various Shuttle Missions

Orbiter	Mission	Orbiter Inlet Pressure	17" Disc. Pressure	SSME#1 Pressure	SSME#2 Pressure	SSME#3 Pressure
Columbia	STS40	OK	OK	OK	OK	OK
Columbia	STS52	OK	OK	OK	OK	OK
Columbia	STS55	OK	OK	OK	OK	OK
Atlantis	STS37	0-1 psi low	0-1 psi high	6-7 psi low	4-5 psi high	1-2 psi high
Atlantis	STS44	0-1 psi low	0-1 psi high	6-7 psi low	4-5 psi high	1-2 psi high
Atlantis	STS46	0-1 psi low	0-1 psi high	6-7 psi low	4-5 psi high	1-2 psi high
Endeavor	STS47	7-9 psi low	7-9 psi high	3-4 psi low	1-2 psi low	3-4 psi high
Endeavor	STS49	7-9 psi low	7-9 psi high	3-4 psi low	1-2 psi low	3-4 psi high
Endeavor	STS57	7-9 psi low	7-9 psi high	3-4 psi low	1-2 psi low	3-4 psi high

It was found that in general the predicted level in the ET as a function of time was close to the actual level, however there were errors as would be expected. Although in some cases the predicted level would be several feet off from the actual level, the error itself was small since the geometry of the ET has such a rapidly decreasing cross sectional area as it approaches being full.

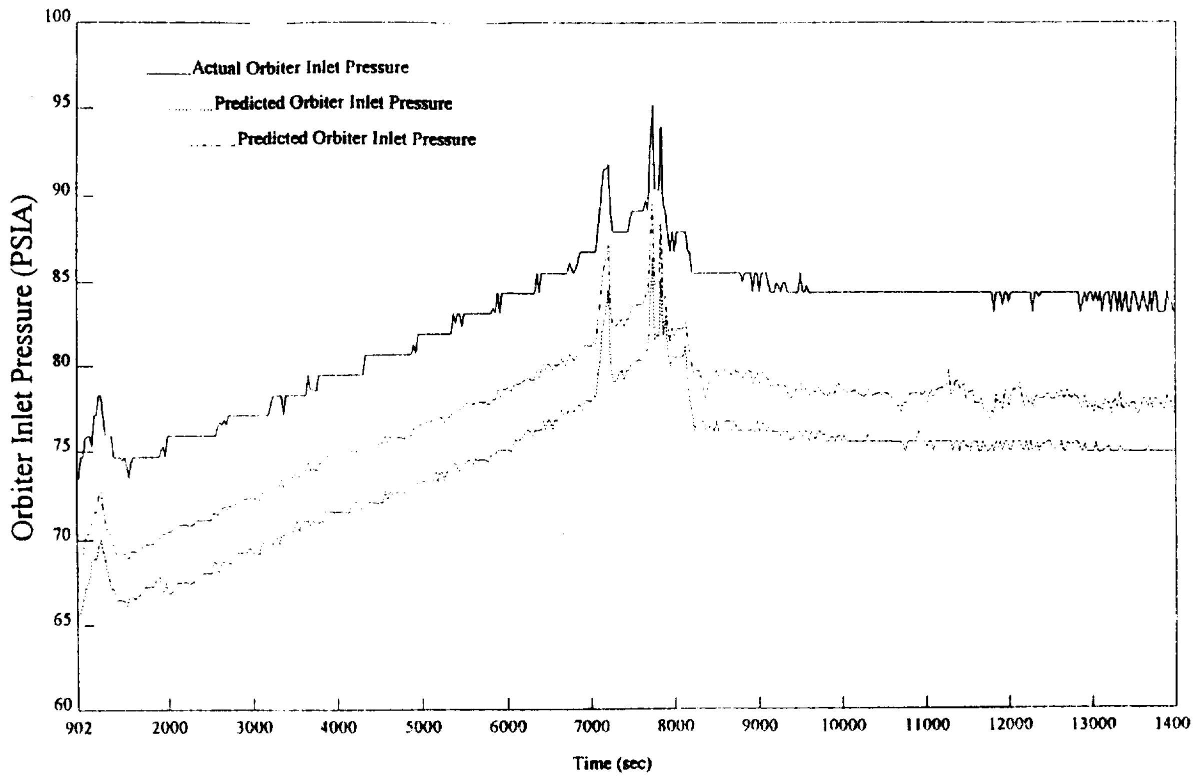

Figure 3 Predicted versus Actual Orbiter Inlet Pressure for STS57

To illustrate this, the difference in height between the 98% level sensor and 100% level sensor is greater than 3.5 feet, or roughly 7% of the height, while the volume of this section is only approximately 2% of the total volume.

Predictions were also generated for the temperatures in the orbiter section. For most of the fast fill phase the temperatures stay relatively constant and change only small amounts. Once the flow of LO_2 is decreased during the topping and replenish phases, all temperatures begin to rise and then ultimately come to a new steady state. This was modeled by performing a linear expansion of equation 3 and assuming that the dynamic response of the temperature can be modeled as a first order with time delay transfer function where the flow rate is assumed to be the only input variable effecting the output variable temperature. The response to the flow rate disturbance input can be seen in Figure 4. Although the model prediction has some error from the simplifications, it does seem to reasonably capture the dynamics.

MODELING FOR THE CASE OF LO_2 REVERT FLOW (DRAIN BACK)

As a separate case, an attempt was made to model the revert flow condition which occurs during a launch scrub. Data from STS71 was obtained for the entire drain period. No attempt was made to model temperatures for this case as only pressure predictions in the orbiter were evaluated. The cause for the scrub on this flight, was the failure of a fuse which had some of the key ground

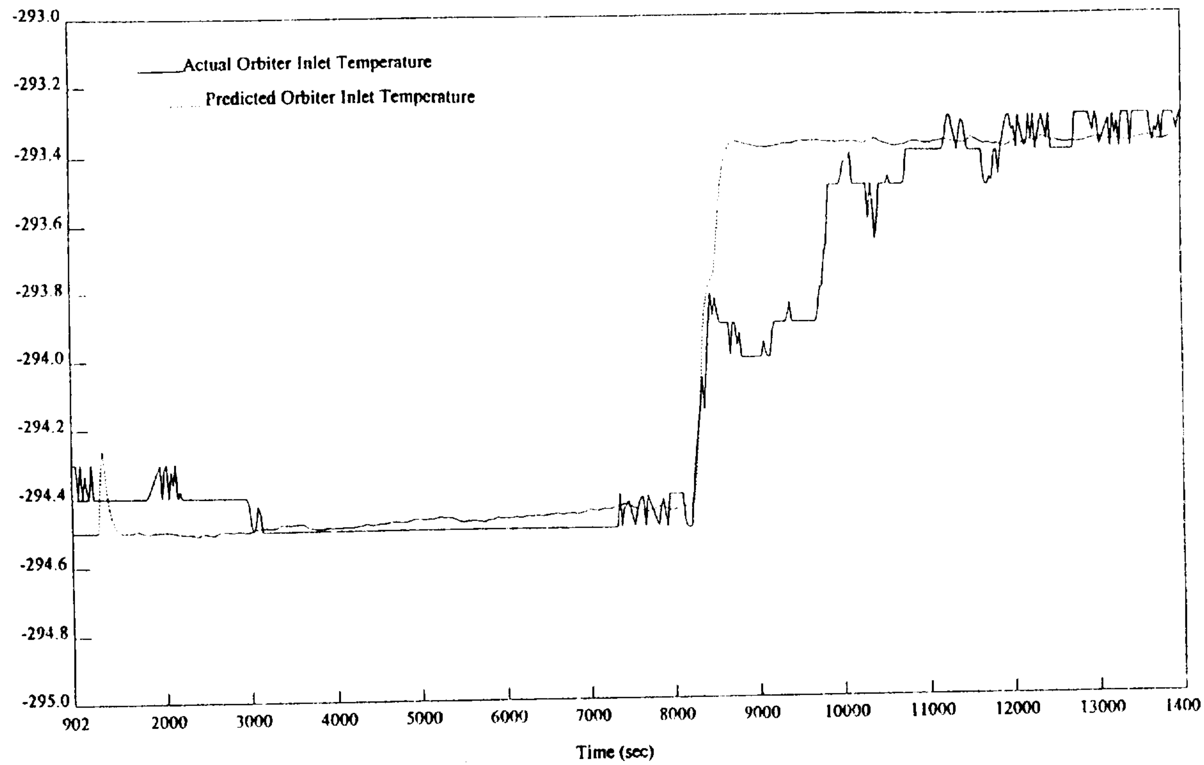

Figure 4 Predicted versus Actual Orbiter Inlet Temperature for STS50

measurements and valve state indicators. As a consequence the flow of LO_2 which was drained back to the storage tank was based on the measurements between the orbiter inlet pressure and the bypass pressure. A flow coefficient for this section of pipe was determined by iteration in a fashion similar to that outlined above. By having the integrated level and the actual level match at the times given by the data at which the 5% and 98% levels were reached.

In addition to the above analysis on the ET level, it was found that the pressures on the orbiter could also be predicted accurately once the appropriate offsets were included. Figure 5 shows the shuttle main engine #2 predicted and measured pressures as illustration of this fact. Although not shown, the orbiter inlet prediction had considerable error initially, due to the fact that the PV10 valve was actually closed during this period. This caused the actual pressure to drop, however once the valve was reopened the pressure prediction became valid.

INTEGRATION OF THE PREDICTIVE MODELS INTO PAT

The ultimate goal of this work was to use the predictive models which were developed using VisSim, in Rockwell's Propulsion Advisory Tool (PAT). PAT is a program written in G2 which is used by Rockwell for launch support. G2 is a graphical oriented programming tool which gives the user the ability to use rules, objects or procedures for software development. It is relatively user friendly, made evident by the fact that of the ten week period in the summer fellowship, only the last three weeks of the summer program were spent working on PAT.

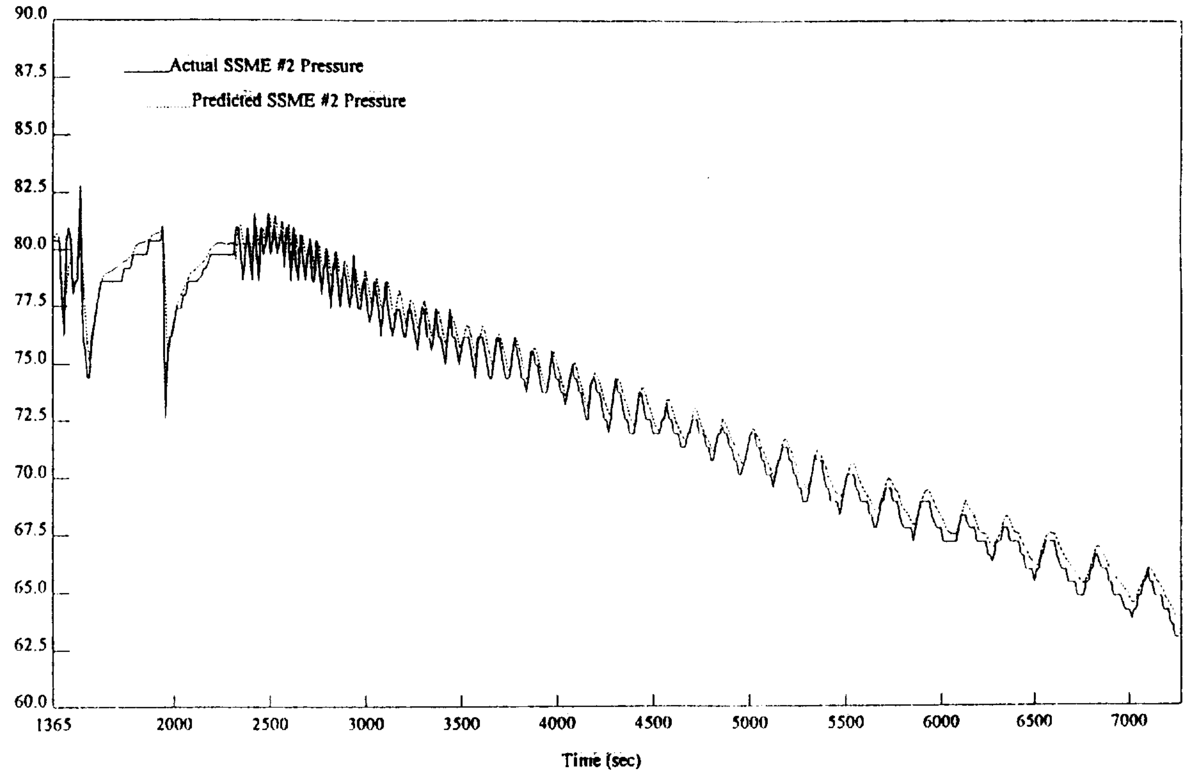

Figure 5 Predicted versus Actual SSME#2 Inlet Pressure for STS71

Due to the lack of time, all models were not added to PAT, several aspects of the model development were included, in particular pressure and flow predictions in key sections of the orbiter. The model components which were included in PAT were found to work well as they were evaluated using data from a recent LO_2 loading.

Generic functions were written in G2 for both flow prediction and pressure prediction and placed into a workspace. (i.e. G2 window) The workspace containing these functions in their native G2 language, along with some rules for the different loading phases are shown in Figure 6. Since many of the predictions in VisSim use simple first order filters, this capability was also included in PAT. Figure 7 illustrates the effect of the digital filter applied to the flow rate measurement from the LO_2 pumps.

CONCLUSIONS

The work which has been performed the past two years under the NASA Summer Faculty Fellowship has shown that a block diagram based simulation language such as VisSim can be used to rapidly develop robust predictive models. While additional work could be done to improve the robustness and predictive abilities of the models, the development effort has been largely successful. Furthermore, it has also been demonstrated that the results of the model development can also be incorporated into existing software with relative ease and similar success.

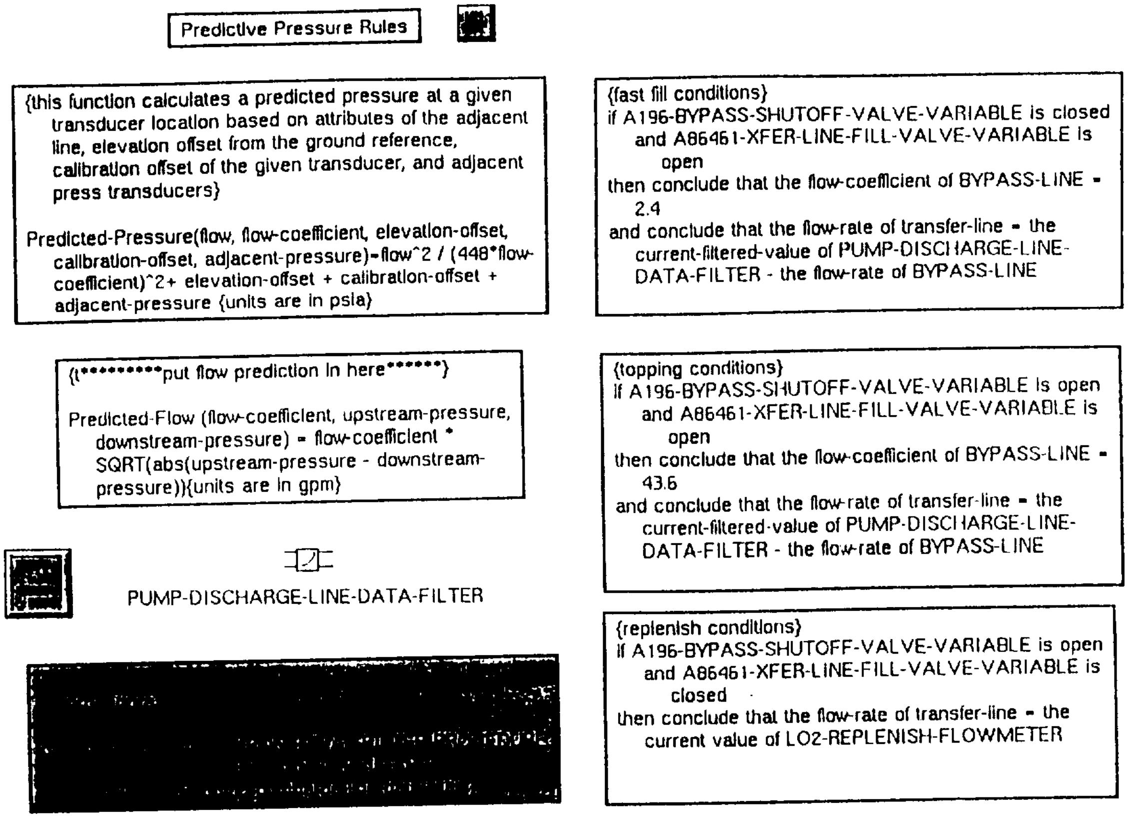

Figure 6 G2 Workspace Containing Predictive Rules and Procedures

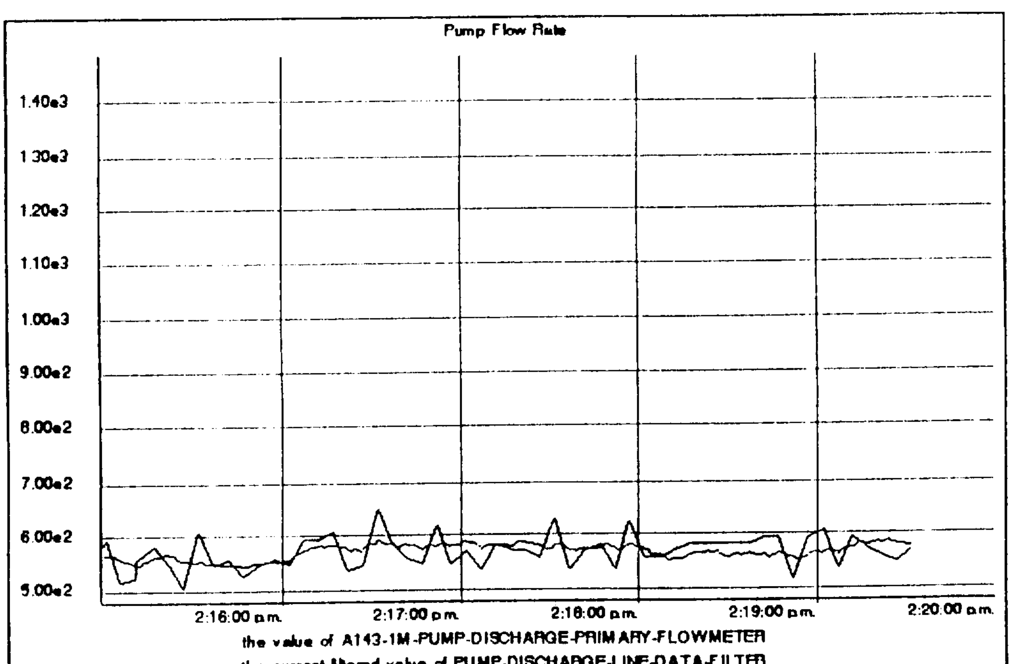

Figure 7 Comparison of Filtered and Actual LO_2 Flow Rates