D44

N85-16933

MATHEMATICAL MODELS FOR SPACE SHUTTLE GROUND SYSTEMS

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ABSTRACT

MATH MODELS are a series of algorithms, comprised of algebraic equations and Boolean Logic. At Kennedy Space Center, math models for the Space Shuttle Systems are performed utilizing the Honeywell 66/80 digital computers, Modcomp II/45 Minicomputers and special purpose hardware simulators (Micro-Computers). The SGOS (Shuttle Ground Operations Simulator) operating system provides the language formats, subroutines, queueing schemes, execution modes and support software to write, maintain and execute the models.

Ground systems presented here consist primarily of the Liquid Oxygen (LO_2) and Liquid Hydrogen (LH_2) Cryogenic Propellant Systems, as well as LO_2 External Tank (ET) Gaseous Oxygen Vent Hood/Arm and the Vehicle Assembly Building (VAB) High Bay Cells.

The purpose of math modeling is to simulate the ground hardware systems and to provide an environment for testing in a benign mode. This capability allows the engineers to check out application software for loading and launching the vehicle, and to verify the Checkout, Control, & Monitor Subsystem (CCMS) within the Launch Processing System (LPS). It is also used to train operators and to predict system response and status in various configurations (normal operations, emergency and contingent operations), including untried configurations or those too dangerous to try under real conditions, i.e., failure modes.

INTRODUCTION

LAUNCH PROCESSING SYSTEM (LPS)

The Launch Processing System (LPS) at KSC consists of three primary subsystems: The Checkout, Control and Monitor Subsystem (CCMS), the Central Data Subsystem (CDS), and the Record and Playback Subsystem (RPS), (Figures 1 and 2).

CDS consists of four large Honeywell 66/80 Digital Computers (Systems A, B, C and D). Systems A and B are designated as Set 1 and C and D as Set 2. Set 1 and Set 2 are identical.

Within a Set the systems share mass storage and memory. The purpose of this is to facilitate switchover. Switchover is designed so the primary can switch to the secondary in case of a system failure (only during launch operations) utilizing the Real Time Data Management System (RTDMS).

Each system has dual processors and each processor can handle 1.2 million instructions per second. Each system has a mos memory of 1.5 million (36 bit) words and within a Set share an additional 1 million (36 bit) words of memory. Each set also shares 64 disk packs containing a total of over 12 billion (36 bit) words of storage.

SHUTTLE GROUND OPERATIONS SIMULATOR (SGOS)

Three operational modes exist for SGOS on CDS: (1) Real-time, (2) Remote Batch, and (3) Remote Terminal.

Real-time mode operates with any of the three Launch Control Center Firing Rooms. FR-2 is normally configured as the Ground Software Production Facility (GSPF), where model performances correspond to actual real world timing of events. It is here that GOAL Programs are de-bugged and verified, and engineering evaluation and training take place.

Remote Batch mode is initiated from a user's remote terminal. There is no interaction between the model and user once the "job" is submitted, and processing occurs at a much faster rate than real-time rate. All timing, however, is relative and kept consistent with real world activity. For example, in filling a tank with liquid in real time it may take 30 minutes, but in Batch Mode this time may be shortened to 1 minute, while preserving consistency throughout the entire model. Output from a Batch run can be printed or saved in mass storage.
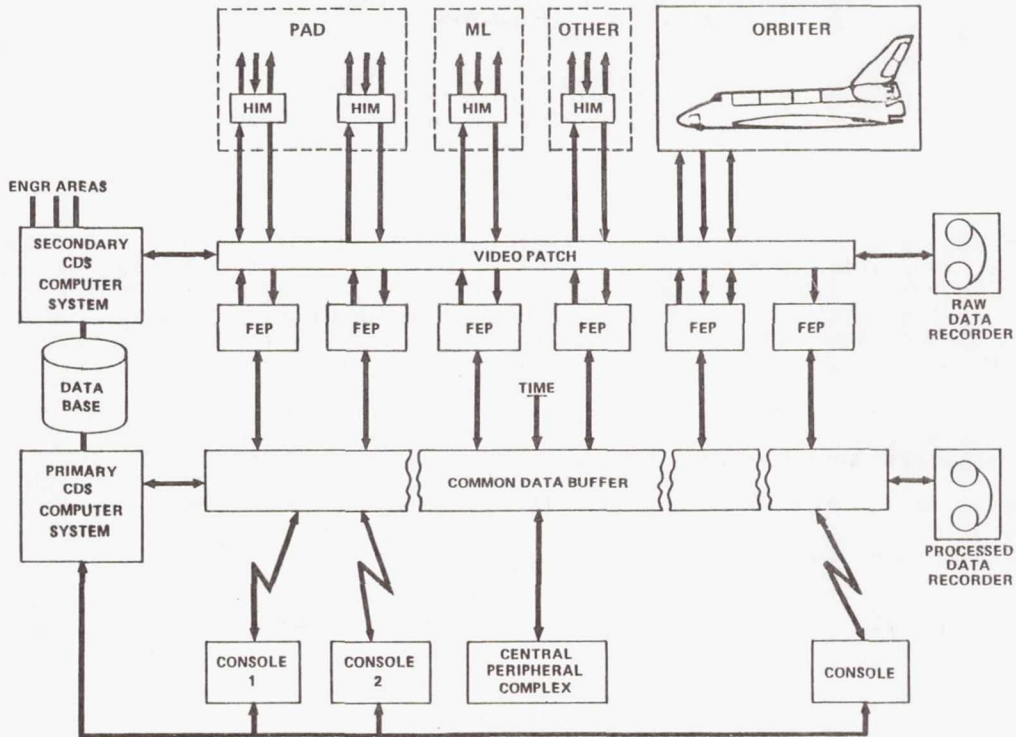
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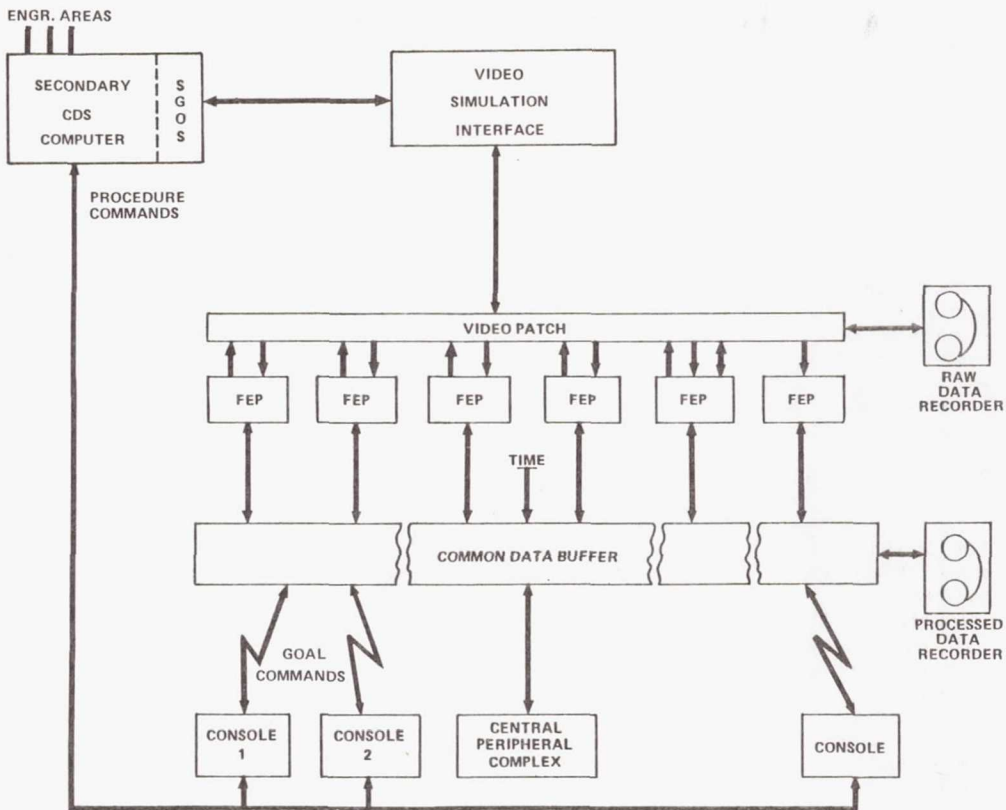Fig 1.- Hardware relationships for LPS/CCMS.

Fig 2.- CCMS/SGOS relationships.

Remote Terminal Mode (non-real time) is used for creating source files of models, procedures, and data banks. Compilation of models and procedures is done via Terminal Mode. The model can also be executed in Terminal Mode, but the output is directed back to the user's terminal, where an interactive session can occur.

Engineering Displays, Full Trace, and selected Variable Column Trace and Plotting are available in both Terminal and Batch modes.

Real-time also supports a logging capability similar in nature to the non-real time Full Trace, recording every change that occurs within the model, i.e., every calculation which produces a change in value or external stimuli which produces a change.

SYSTEMS MODELED AND PURPOSE

The types of systems involved in KSC Ground Math Models at LC39 are:

1. Cryogenic Fluid Networks (LO_2 and LH_2)

2. Electrical Power Distribution Systems

3. Mechanical Devices, GOX Vent Arm and Hood

4. Pneumatic Actuators and Gaseous Supply Pressures and Purges

Areas Modeled are:

1. Vehicle Assembly Building (High Bays)

2. Mobile Launch Platform (MLP)

3. Pad Terminal Connection Room (PTCR)

4. Launch Pad 39, Storage Areas and Burn Pond

An End-to-End Nodal Analysis is necessary for modeling the cryogenic fluid networks, therefore, the LO_2 and LH_2 External Tank and Flow Path through the Orbiter are also modeled as part of the Ground System Models.

The main purpose of the math models at KSC is the checkout and verification of the Ground Operations Aerospace Language (GOAL) programs[5] designed to automatically load and launch the Space Shuttle. The programs must control and respond to the math model exactly as they would to the real hardware.

At this point it would be helpful to discuss model fidelity. Model fidelity is the degree of accuracy and completeness with which a model simulates the real world. There are, then, two distinct model forms, namely: imitators and predictors.

An imitator is a model which is as complete as it must be, but is blind to any other conditions or anomalies. Coding in this fashion allows for computer processor efficiency, faster-running models, use of less file space, and easier maintainability. The main drawbacks are its limited scope and flexibility. An imitator is based mainly upon empirical data.

A predictor is a model which can be written using (in addition to empirical data) real physical equations relating flows, pressures, temperatures, etc. Coding in this fashion is usually more difficult, and in most cases requires more computer time. The obvious benefits are accuracy and flexibility in testing new operational techniques, and accurate predictions of system response in abnormal and failure mode configurations.

As it turns out, KSC models are a hybrid of these two forms, stressing predictive qualities in areas of fluid networks and associated calculated phenomena, and an imitative analysis in areas such as electrical power and pneumatics, where exact replication is unnecessary.
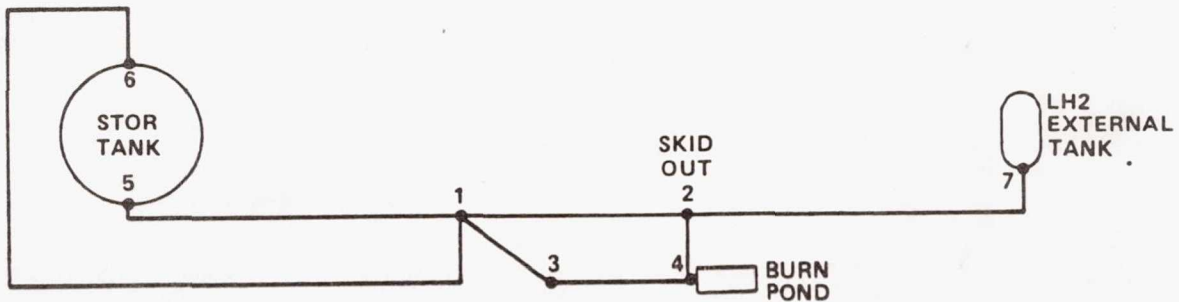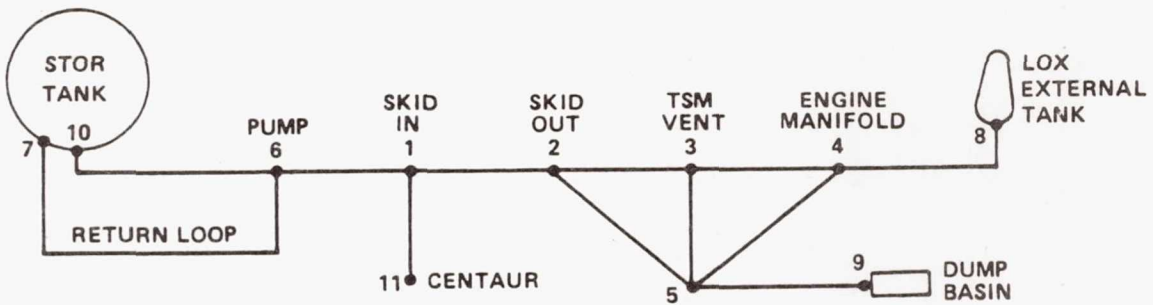
FLUID NETWORKS

FLows and Pressures

Accurate modeling of fluid networks has proven to be essential for cryogenic propellant loading. The fluid network shown in Figure 3 is for LH_2 and LO_2. This is known as a nodal analysis, in which a node represents an exterior source or sink point, and interior points (points at which there is a fluid branch). The theory behind a nodal analysis is conservation of mass, or continuity, in which the sum of the flows into an interior node equals the sum of the flows out of that node. The boundary conditions must be known or calculated, and the internal admittance between nodes must also be known or calculated. A series of n simultaneous equations in n unknowns can be generated. The unknowns we are solving for are the pressures at the nodes. The flows are the dependent variables, and once the pressures are solved for the flows are calculated. IN SGOS, the "CALL FLOW" statement provides the format for easily setting up and solving any fluid network. Specifically, at boundaries where a source or sink exist, a pressure must be input at that node. The interior admittances, called G-numbers or Flow Constants, follow the inverse rules as electrical resistances where admittances in series sum as:

$$1/G^2_t = 1/G^2_1 + 1/G^2_2 + 1/G^2_3 --- + 1/G^2_n$$

LH2 NODAL ANALYSIS

LO2 NODAL ANALYSIS

Fig 3.- LH2 and LO2 fluid network nodal analysis.

and admittances in parallel sum as:

$$G_t = G_1 + G_2 + G_3 + \text{---} \, G_n.$$

However, the larger the value of the G-Number, the greater the flow. The flow constant was initially based on historical data and design information. It is simply a constant that is a function of the C_v of the valve, the density of the fluid flowing through it and admittance of the plumbing between nodes. Originally the solution for flows and pressures was obtained by using an iterative calculation similar in nature to the Runge-Kutta method. First a nodal analysis of the network is drawn, then the pressures at the ends or boundaries are calculated. The G-numbers are calculated along with the head pressures between the internal nodes. Once all the known quantities are computed, the flow rates are calculated using the flow equation:

$$Q = G\sqrt{P_2 - P_1 - HP_{21}}$$

where Q = Flow rate in gal/min
 G = Flow constant
 P_2 = Upstream pressure
 P_1 = Downstream pressure
 HP_{21} = Head pressure between P_2 and P_1

The flows are iterated to increment the pressures to that the sum of the flows into each interior node equals the sum of the flows out. This method used enormous amounts of CPU time and the accuracy was very limited.

SGOS developed the "Call Flow" routine in the Spring of 1981. This new method of computing flows and pressures used the same basic flow equation and nodal analysis as before as well as the Law of Conservation of Mass.

Given boundary conditions of known pressures, and interior G's and head pressures, solve (iterate) for the pressures at the interior nodes first and then compute the flows. The method of computing these interior pressures uses a piecewise linear approximation for the vector square root function. Convergence is achieved in one (50 millisecond) model cycle as opposed to hundreds of cycles before which at best only approached convergence.

The Flow Solver is processed in the SGOS executive, and is done with maximum efficiency, rather than having all the calculations performed in the model itself. The ease of formatting the fluid network and the reliable accuracy the flow solver achieves, has made true predictors out of the LO_2 and LH_2 models.

During actual vehicle loadings, Flows, and Pressures were recorded. This data was used to re-compute more accurate flow constants, which then reflected all the dynamics in the system. Typical items that contribute to the flow constant between two nodes are: valves, orifices, pipes and plumbing, filters, and the fluid medium itself (viscosity/density). One additional consideration, vitally important, to be calculated and input to the fluid network calculation is the fluid head pressure.

Head Pressure in the format for the "CALL FLOW" is input as a negative number when computing Flow from a lower elevation to a higher elevation. Knowledge of the system in terms of elevations of various nodes must be known, as well as the volume of liquid contained in various segments of pipe between nodes. This is necessary when filling or draining segments of pipe to allow realistic head pressure rise rates as the pipe fills up. When flowing "downhill" head pressure is added to the nodal pressure, and will increase the flow rate. When flowing "uphill" the head pressure is added to the nodal pressure and is used to reduce the flow rate.

There are several limitations to the SGOS CALL FLOW statement which can be treated "outside" of the general matrix of simultaneous equations. These limitations are: fluid inertia, water hammer, non-continuous fluid networks (as when a segment of the network is drained), isolated interior networks, check valves and one-way flow, and pumps between interior nodes. Detailed discussion of these items is outside the scope of this paper; however, these problems have been overcome in the cryogenic models.

Volumes

Volumes of tanks, canisters, and pipes are needed in order to provide a realistic and accurate model. The volume of liquid in a tank at a source or sink node is computed by integrating, using a time constant, the net volume that exists in the tank - beginning with its initial volume and incrementing by adding or subtracting the flow rate from that node. The SGOS "CALL INTGRL" statement is very useful for this purpose. "CALL INTGRL" provides the format where an integrand can be summed to at a fixed but selectable rate of from 10 times per second to once every 10 seconds. A one second update is normally used, but a number of special cases need faster or slower iteration rates.

Volumes of pipes between nodes can be computed based on segment length and diameter, that fill and drain based on flow rates. Imaginary or pseudo wet/dry liquid sensors at each node triggers the calculations.

Temperatures

In most instances, temperature dynamics is done mostly for display purposes. A stagnant or empty segment of the fluid network will start off at an ambient temperature of 73^0 F. As cryogenic fluid enters a segment of the network, rapid boiling occurs and gaseous propellants will move downstream, causing a pre-chilldown. At this point, we start calculating temperatures colder until actual liquid (based on tests) would reach the location of a temperature probe. When the liquid volume reaches a probe, the temperature is assumed to be that of LO_2 or LH_2 at the Boiling Point. Very little change in temperature will occur thereafter. When the line is drained, the temperature will begin to rise. This rate may be rapid, unless the line is vacuum-jacketed.

One notable exception where temperature fluctuations are pronounced, dynamic and critical is the feedline temperature in the LO_2 system, which forewarns a geyser condition if redline criteria are exceeded. Due to head pressure in the feedline, this creates a very dynamic temperature profile during loading.

ELECTRICAL SYSTEMS

Power supplies are usually modeled in discrete terms. Power is either on or off, and sub-busses automatically receive power when the supply is turned on. Fuses are not modeled, but, in certain instances, circuit breakers are. Voltages and currents are assigned as constants based upon hardware data. These systems are handled rather simply, with very little dynamics involved. Every Function Designator will have a power bus assigned to it, and when the power is off that "FD" will read its powered-off value. Back-up batteries are also modeled, along with a limited amount of dynamics involved with threshold Zener Diode Systems.

PNEUMATIC, GASEOUS SUPPLIES AND PURGE SYSTEMS

Gaseous supplies are treated as inexhaustable reservoirs which supply GN_2 or Helium. Generally, these supplies are for purge systems and pneumatically actuated values. Modeling of these systems typically uses discrete logic, depending upon whether supply valves are open or closed. Dynamics are involved when a regulator is modeled using the line pressure as a feedback to the regulator to provide more or less regulator opening. Another case involving dynamics is when a purge flows through a heater where heater temperature is a function of a cool purge flowing through it. All pneumatic values are modeled to require a specified minimum supply pressure to operate. Helium bubbling in the LO_2 feedline is modeled to provide a realistic temperature gradient profile. This will influence the head pressure in the feedline.

It is noteworthy to mention that for the LH_2 system, helium is always used when cryogenic hydrogen may be present, due to the fact that the boiling point of helium is lower than that of LH_2. If GN_2 were used in contact with LH_2, the nitrogen would form GN_2 ice. In the LO_2 system both GN_2 and Helium can be used since GN_2 stays gaseous at liquid oxygen temperatures. For economy, GN_2 is generally used with LO_2.

MECHANICAL SYSTEMS

The ET GO_2 Vent system consists of a heated purge and a hinged cantilevered truss assembly supporting a conical shaped plenum chamber (which also is hinged). It is moved to a docking position with the ET nose cone to provide an environment for warming the nose cone while venting GO_2, which prevents ice build-up on the ET. The simultaneous motions of the arm and hood, primary and secondary drives, presented an interesting challenge in designing the math model.

MODEL DEVELOPMENT

DATA COLLECTION: FEEDBACK TO MODEL THROUGH STS-1

Sources for model data include:

1. The original schematics and specifications

2. Discussions with engineers about operating parameters

3. Consulting with vendors on specific hardware items, and actual test data during system operation. After a hardware test (such as a tank loading) or an actual launch, a quantitative analysis is done on the data collected, and is compared to model output. From this analysis we can provide accurate empirical data and write more comprehensive equations for further model development. When new operating techniques are employed during a simulated loading, model predictions can also be verified by test data later.

ADVANCED DEVELOPMENT: STS-2 THROUGH STS-5

Advanced development has included continual feedback from hardware testing and launch data. Hardware modifications have also been fairly regular throughout each flight, and model dynamics have been heavily impacted. A "New Standards and Guidelines for Math Models" (KSC-80K00009) has instituted numerous convention and fidelity conformities. This was necessary in order to coordinate and make common, models written by all KSC and Vandenberg Air Force Base contractors. This has also specified the identification of all Ground and Vehicle interfaces, and all system interfaces to be recorded in the "Math Model Interface Definition Document" (MMIDD).

FUTURE DEVELOPMENT: STS-6 AND BEYOND

Model enhancements will dominate this effort, along with sustaining engineering for hardware modification. The most significant hardware change was the development of the Martin Marietta Light Weight External Tank. STS-6 was launched April 4, 1983, with the first lightweight tank. At the time of this writing, STS-7 is scheduled for launch in mid-June and will have successfully completed its mission a week before this conference.

Future plans include the installation of a Centaur stage in the Orbiter cargo bay, which will be fueled with LO_2 and LH_2 simultaneously with the External Tank. This will present a new challenge for modeling as the LO_2 and LH_2 fluid networks will be modified to accommodate this space vehicle. At present, the first Centaur launch, STS-38, is scheduled for May, 1986.

Study plans are under way at Martin Marietta for Shuttle derived vehicles, Advanced Space Transportation System (ASTS), which include an aft cargo carrier (ACC) or shroud on the External Tank, with a cargo carrying volume greater than that of the Orbiter Cargo Bay.

Launch Complex 39B should be in operation by January 1, 1986, and the first launch will be STS-36, in February, 1986. Pad-A & B at KSC will be very similar, requiring only slight model changes. Mobile Launch Platforms (MLP) 1 and 2 are in use now with some hardware differences, and MLP-3 is being processed at this time.

Vandenberg models were patterned after KSC models, with some hardware differences inherent to VAFB. Their first launch (1V) is scheduled for October, 1985. Plans are for KSC to operate with OV99, OV102 and OV104 and VAFB to operate with OV103.

The next major event for math models at KSC will be in June, 1983, with the implementation of the expanded model capability project also known as BIG SIM. Currently, the largest master model which can be built is approximately 227K words. It may be possible that BIG SIM will expand that size 2 or 3 times. This new capability will allow for an integrated test of a launch countdown model with all consoles supporting. Also this will greatly increase GSPF support time by allowing more users to operate the model simultaneously (restricted only by the processor's capability). This will greatly reduce the GSPF's down time, because at present each of several smaller master models must be loaded, which can take several hours, during which time there is no model support. Once a large 700K master model is loaded and running, it can support continuously, with changes necessary only to update the master model. Changes will not be necessary for scheduling purposes.

With the large master models it will be necessary to streamline all existing models, to write more efficient code, and to understand how model segments are ranked, queued and executed. Caution should be exercised in attempting to make a model segment run faster, while at the same time, not adding more of a burden to the model executive processing.

CONCLUSION

Math modeling presents a unique opportunity to intimately blend engineering/hardware knowledge with computer technology. Since a model must perform identically as the hardware, a very broad knowledge is gained by the modeler in both the hardware and the software. Within the environment of operations and maintenance, this author has found model research and development to be challenging and satisfying.

In closing, I would like to quote from Kenneth P. Timmons, Michoud Division Vice President and General Manager, at an address to 300 members of the Louisiana Tech University Engineers Association in Ruston, Louisiana, March, 1983:

[3]"In your generation, which saw polio conquered and man landing on the Moon, I believe the greatest advance is the ability to model events, states and phenomena and to process these models in small fractions of seconds in large capacity computers.

Engineers have contributed to these achievements and will continue to make us part of the technological triumphs - such as the Space Shuttle - today."

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