Level Sensor Shutdown for Liquid Rocket Systems

D. W. Dowell,* D. F. Giere,† R. F. McConnell,‡ and R. L. Donovan§
Martin Marietta Corporation, Denver, Colo.

An engine shutdown system has been developed for the Titan IIIB which affords a significant performance gain over a guidance generated command shutdown and eliminates the possibility of potentially severe and unpredictable dynamic loads associated with propellant depletion. The system consists of three liquid-level sensors in each propellant tank. The sensor uncover signals are individually timed out, then majority voted, to command engine shutdown at a time which leaves sufficient propellant on board to preclude depletion. A full-scale test program provided both the necessary confidence of system operation and data for the final timer analysis.

Introduction

TWO characteristics which emerge throughout the operational life of a space booster system are the search for increased performance capability and a continuing concern for fragile payloads. At some point these two factors arrive at cross purposes since the ultimate performance offered by permitting the propellant to deplete must be traded off against the generally adverse and unpredictable dynamic loads associated with this type of shutdown.

The dilemma of depletion lies not only with the generally violent behavior of the engine hardware but also with the multiple options which must be considered. Either propellant can exhaust first and, for booster systems which have outage control, a fair percentage of cases will be close to zero outage. This offers a multitude of possibilities representing various combinations of so-called simultaneous depletions, wherein either propellant can lead in the race for exhaustion by varying amounts, producing an unknown dynamic load situation which must be avoided in most cases.

Thus, the undesirable prospect of designing upper stages to accommodate a wide spectrum of dynamic loads, together with the potential damage to engine hardware, particularly for systems intended to be reusable, quite often results in a requirement to assure a command shutdown. Considerable data support the fact that command shutdown characteristics are generally benign and extremely repeatable.

The usual method for generating a command engine shutdown signal is by use of a preselected vehicle velocity. Although this guarantees a command shutdown in addition to a specified vehicle velocity, it requires that a significant amount of usable propellant be allocated as "margin" to cover the possibility of low booster performance. This margin is nonusable for a nominal booster and represents a significant performance penalty. On the Titan IIIB, which requires three-standard-deviation performance margin, the effect of sensor shutdown was approximately a 70% reduction in the quantity of nonusable propellant, representing a significant performance increase either in terms of payload capability or upper-stage propellant weight-on-orbit.

System Definition

The selection of level sensors as the primary signal source for the Titan IIIB shutdown system resulted from considerations of other alternatives, such as pressure sensors, a propellant utilization system, temperature probes, and sensed acceleration. These approaches all have limitations, which, together with the fact that the Titan system has used liquid-level sensors for instrumentation purposes for many years, strongly influenced their selection as the signal source. For system reliability, multiple sensors were imposed as a requirement. As a result, three level sensor probes are installed in the fuel tank and three in the oxidizer tank at identical height and as equally spaced as the structure permits. Remotely mounted controllers contain the level sensor circuitry required to provide a signal for a majority vote time delay (MVTD). The controller outputs are time delayed and majority voted to provide two redundant shutdown commands. The shutdown commands from the MVTD drive relays, which close the thrust chamber valve, leaving sufficient propellant on board to preclude depletion.

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*Unit Head, Propulsion System Analysis.

†Group Engineer, TIIIB/D Propulsion System Analysis.

‡Senior Engineer, TIIIC/E Propulsion System Analysis.

§Group Engineer, Power Conditioning.

Electronic System

Selective redundancy was incorporated throughout the Titan IIIB level sensor shutdown system to achieve maximum reliability with minimum system complexity. The single most important redundancy in the system is in the majority voting of the level sensor outputs. Because of the majority voting function, a single level sensor failure, either an erroneous cover or uncover indication, cannot cause an invalid shutdown command.

Additional system reliability is obtained by use of redundant relays, cross-strapping of the MVTD output shutdown commands, and use of an enable command obtained from the guidance system. A block diagram of the shutdown system is shown in Fig. 1. The following observations can be made relative to system reliability: 1) No single relay failure can cause either the MVTD or the thrust chamber valve to be activated without a valid enable command from the guidance system; hence, a premature shutdown is prevented. 2) No single relay failure can prevent either the MVTD or the thrust chamber valve from being activated once an enable command

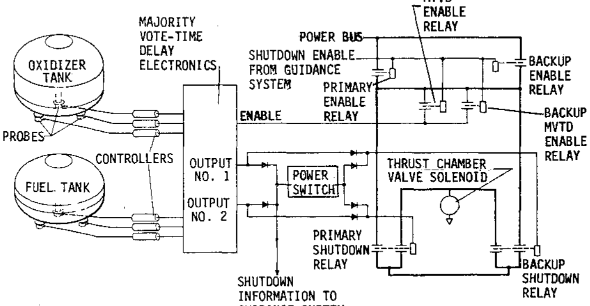

Fig. 1 Shutdown system schematic.

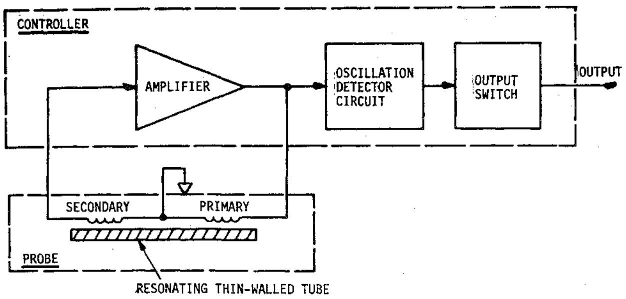

Fig. 2 Level sensor circuitry.

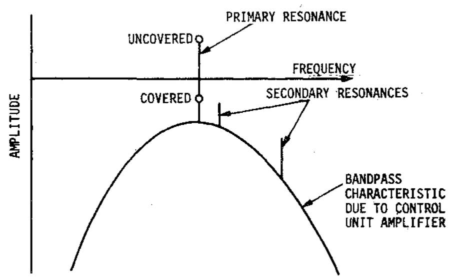

Fig. 3 Level sensor resonance characteristics.

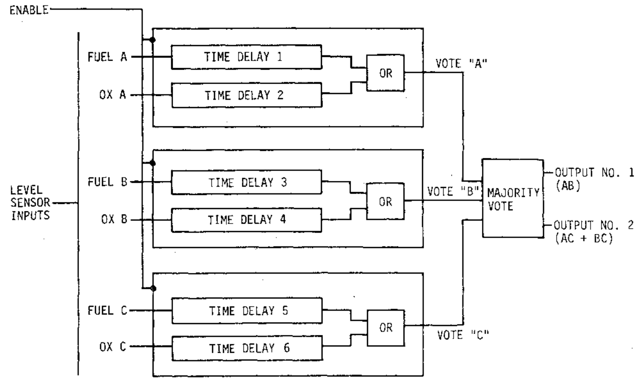

Fig. 4 Majority vote time delay schematic.

is received from the guidance system; hence, a failure to shutdown is precluded. 3) No single relay failure can prevent a shutdown signal to the thrust chamber valve, even if a single level sensor failure has also occurred (single MVTD shutdown command output). A failure to shutdown is again precluded.

The enable command from the guidance system energizes the primary and backup shutdown enable relays and the primary and backup MVTD enable relays. Without the enable command present, the MVTD cannot issue a shutdown command, and the thrust chamber valve solenoid cannot be energized. The MVTD contains two outputs which, taken together, constitute a complete majority-voted shutdown command. Each output represents a partial majority vote of the redundant level sensor input signals. If the three level sensors in a propellant tank are designated as A, B, and C, MVTD output No. 1 represents the votes A and B and output No. 2 represents A and C or B and C. The MVTD outputs are cross-strapped, with diode logic and a power switch, such that the presence of either output will assure drive to both the primary shutdown relay and the backup shutdown relay.

Level Sensor

Ultrasonic liquid-level sensors have been used on the Titan IIIB launch vehicle for years as flight instrumentation. The sensor consists of two components: a sensing element, or probe, mounted in the propellant tanks with the active portion immersed in propellant, and a remotely located controller connected to the probes. The controller contains the necessary circuitry for probe operation, and the probe and controller together represent an electromechanical oscillator. The probe is the feedback element in the oscillator, while the controller contains the oscillator amplifier plus signal conditioning circuitry to detect the oscillation and deliver the switched output signal.

The probe circuitry consists of a loosely coupled transformer (Fig. 2). The primary and secondary coils are magnetically coupled through a resonating, thin-walled, magnetostrictive tube that is physically common to both coils. The resonating tube is also mechanically coupled to the probe tip. When the probe is out of liquid, an oscillating signal on the primary coil will produce mechanical motion in the thin-walled tube. This mechanical motion in turn generates an emf in the secondary coil, which increases the secondary signal to a level greater than would be observed if mechanical motion in the tube were not present. An electrical resonant peak is observed in the transmission characteristic at the frequency at which the probe thin-walled tube enters mechanical resonance. When the probe is submerged, the liquid medium dampens the tube resonance by absorbing energy at the probe tip. The signal transmission around the probe-controller loop (Fig. 3) becomes less than unity and no oscillation is produced or, if an oscillation is initially present, it will decay. When uncovered, the probe resonant peak increases approximately 20 dB from its covered value. The signal transmission around the loop becomes greater than unity and the probe oscillates. The presence of the oscillation is detected and an output signal issued. In addition to the primary resonance, the probe construction also permits secondary, or parasitic, resonances of varying magnitudes, as shown in Fig. 3. To prevent these parasitic resonances, or harmonics of the fundamental resonance, from causing a false oscillation, the controller amplifier has a bandpass characteristic centered at the fundamental resonance of the probe. To distinguish between a valid uncover oscillation and extraneous ringing, the circuitry also contains a 50-msec delay between uncover sensing and output issuance.

Majority Vote Time Delay Assembly

The MVTD assembly provides the time delay and majority voting functions. A block diagram is shown in Fig. 4. The assembly contains an individual time base for each sensor input signal, and it is the time delayed sensor signals that vote. By providing the time delay function before the vote function, a capability for individual sensor time delay adjustment is achieved, and close sensor location matching is not required. The capability to calibrate for a characteristic sensor uncover sequence is also available. The MVTD time delays are obtained by decoding digital counters driven by fixed-frequency clocks. Depending on the decoding arrangement, any time delay can be obtained from zero delay to the maximum delay required to fill the counter registers. The counter decode which sets the time delay is implemented in the MVTD by a wire patching arrangement installed in patch plugs mounted on the unit. Time delay modifications can be made by a substitution of the patch plugs, permitting field adjustment of the time delays for individual launch vehicles.

The MVTD design incorporates several features, in addition to the majority voting function, which protect against erroneous level sensor signals. These features are: an enable command, an input delay, and an input latch. In the Titan III application the enable command is issued by the guidance system several seconds prior to anticipated level sensor uncover. Hence, any inadvertent sensor uncover signals due to vibration and shock inputs at liftoff or staging will be ignored. The enable command is a continuous signal, rather than a pulsed input, and the MVTD is, therefore, incapable of being enabled by any type of transient condition early in the flight sequence. Additional protection against erroneous uncover signals is provided by an input delay circuit which

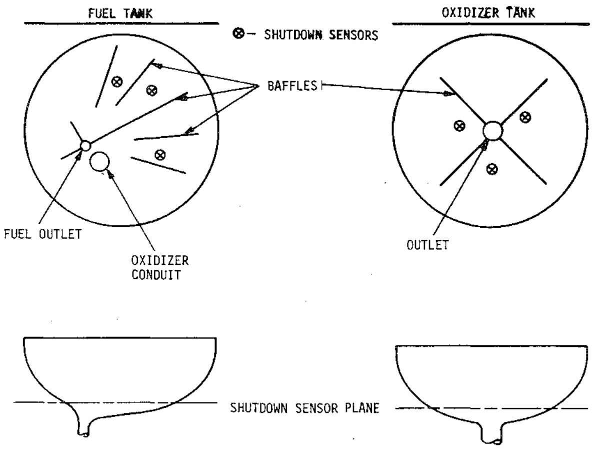

Fig. 5 Stage II shutdown sensor locations.

requires the presence of level sensor uncover signals for 10 msec before the MVTD will respond. Once the signal is present for 10 msec, it is identified as a valid uncover signal and the MVTD will latch, providing a proper time delay vote irrespective of subsequent level sensor cover indications.

In keeping with the emphasis on reliability provided by the majority voting function, the MVTD electronics is also fully redundant. No single point failure internal to the MVTD will cause a premature shutdown command or prevent issuance of a valid shutdown command. Although a single majority vote shutdown command is provided by the MVTD, this command is issued as two redundant outputs, as shown in Fig. 4. Each output represents a partial majority vote, but taken together, both outputs provide a complete majority vote. A failure to indicate uncover by one level sensor would prevent the issuance of one, but not both, of the redundant shutdown commands. In the system relay logic, these commands are cross-strapped such that either one will provide redundant drive to the engine thrust chamber valve. In addition to the shutdown command, the MVTD also provides flight telemetry and ground monitors for the six level inputs, the two shutdown command outputs, and the status of the internal logic. An unfavorable indication from any of these monitors prior to lift-off will cause an automatic "hold."

Outflow Tests

Preliminary analyses, together with certain propellant tank structural and fabrication considerations, resulted in the location of the Stage II sensors as shown in Fig. 5. It should be noted that the sensors in the fuel tank are nonsymmetrically located. This was due to the unusual tank outlet and baffle configuration, and it was recognized that this could add to the general concern regarding the propellant outflow characteristics at the time the sensors uncover. This fact, plus the overall flight critical nature of the sensor shutdown system, required that test data be provided on the operation of sensors in both Stage II tanks under simulated flight conditions. The data were also important in defining the final timer settings. The Stage I sensors are located much higher in the tanks, in positions near sensors which have flown on past Titans. For this reason a Stage I test was unnecessary.

One of the major factors affecting the propellant remaining in the tank at the time of level sensor uncover is surface layer distortion due to the dynamic effects of terminal propellant drain. Surface distortion is caused by nonuniform fluid velocities across the tank cross section. This effect is represented graphically in Fig. 6. Other factors present which may cause premature or delayed uncover signals from the level sensors are wetting of the sensors and combinations of temperature and pressure which may produce hot surface layers, bubbling liquid, or localized cavitation at the probe.

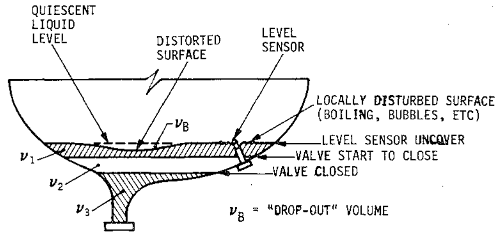

Fig. 6 Reconstruction of surface characteristics. ν_1 = volume outflow at steady state conditions from level sensor uncover signal to shutoff valve first movement. ν_2 = volume outflow during shutoff valve closure. ν_3 = volume remaining in the tank after shutdown.

Baffles effectively eliminated vorticity as a contributor to surface distortion.

Two primary objectives were identified for the outflow test program. The first objective was to determine the mean and dispersed quantity of propellant remaining in the tank at the time each of three sensors uncovered under simulated flight conditions. A second objective was to determine the individual signatures and relative timing between the three sensor output signals. The test approach selected to satisfy these objectives was to outflow actual propellants (Aerozine-50 and nitrogen tetroxide) from flight-type tanks under simulated flight conditions. Propellant quantity in the tank at the time of level sensor uncover was reconstructed from the quantities ν_1, ν_2, ν_3 illustrated in Fig. 6. The difference between the total of these three volumes and the quiescent volume determined from static height-volume calibrations of the tank represents the amount of "drop-out" or "bias" which must be accounted for in the analysis.

Test Modeling

Flight surface layer distortion was simulated through the Froude number relationship (ratio of inertial to body forces) as given by

$$\mathrm{Fr} = V^2/aL$$

where: Fr = Froude number, V = flow velocity (fps), a = acceleration /ft/sec^2), L = characteristic dimension (ft). By letting Fr_A = actual or flight Froude number and Fr_M = model or test Froude number and equating: $\mathrm{Fr}_A = \mathrm{Fr}_M$, or

$$V_A^2/a_A L_A = V_M^2/a_M L_M$$

Now, using the identities $\dot{W} = \rho A V$ and substituting

$$\dot{W}_A^2/\rho_A^2 A_A^2 a_A L_A = \dot{W}_M^2/\rho_M^2 A_M^2 a_M L_M$$

where: $\dot{W}$ = flow rate (lb/sec), ρ = density (lb/ft^3), A = area (ft^2).

If test conditions are controlled such that the test liquid density equals flight liquid density and test tanks are full scale, having the same internal configuration as flight hardware, the following relationship results

$$\dot{W}_A^2/a_A = \dot{W}_M^2/a_M$$

Solving for $\dot{w}_M$

$$\dot{W}_M = (a_M/a_A)^{1/2}\,\dot{W}_A$$

Since $a_M = lg$, the flight surface layer distortion can be achieved by modeling test flowrates through the following relationship:

$$\dot{W}_{\text{test}} = \dot{W}_{\text{flight}}/(a_{\text{flight}})^{1/2}$$

Maximum flight propellant flowrates were simulated in conjunction with minimum flight acceleration at the time of level

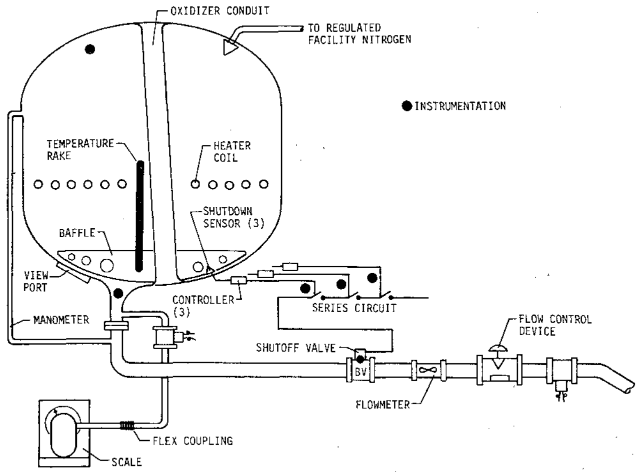

Fig. 7. Fuel outflow test configuration.

sensor uncover to maximize dropout effects and localized cavitation potential at the level sensors.

Flight tank gas pressures and liquid temperatures were simulated in the test. A stratified liquid temperature profile was constructed in the propellant prior to each outflow to simulate flight aerodynamic and autogenous pressurant gas heating effects on the propellant. Liquid temperature profiles were constructed from Titan III Stage II propellant depletion cases. This temperature profile changes the quality of the top surface layer, possibly affecting the actual probe sense point. The stratified liquid temperature profile was also required to maintain the validity of the Froude number modeling of the test flowrates by providing actual flight propellant liquid densities.

A series of seven fuel and seven oxidizer outflows was defined with controlled run-to-run repeatability of test conditions. Sensor installation and internal tank structure were identical with the flight configuration. System checkout and calibration runs were also defined to obtain height-volume relationships for each tank and to calibrate the propellant control and measuring devices.

Test System

The outflow test hardware included full-scale flight configuration fuel and oxidizer tanks, flight configuration level sensors and controllers, propellant outflow plumbing and control devices, and propellant quantity measurement devices. A schematic of the overall test configuration for the fuel tank showing major system components and instrumentation is presented in Fig. 7.

Liquid heat exchangers were installed in each tank above the outlet baffles to heat the propellant bulk and liquid surface layers to the required conditions prior to each outflow. A viewport located in the bottom of each tank at the plane of the level sensor probes was used to evaluate the extent of liquid surface layer distortion and determine surface layer quality at the time of sensor uncover. Photographs of surface conditions were obtained through this viewpoint during each outflow. The viewport was scribed with calibration marks to provide a height-volume correlation as a backup method for reconstructing the quantity of propellant remaining the tank.

Actual flight configuration level sensors, cables, and controllers were used to supply the signal to close the outflow shutoff valve. The shutoff valve circuitry was designed to require inputs from all three controllers prior to closing the shutoff valve. A drain-and-weigh technique was used to determine the volume of propellant remaining in the tank after each outflow.

Testing

In general, all of the test conditions and objectives were successfully met. Seven fuel and seven oxidizer outflow runs

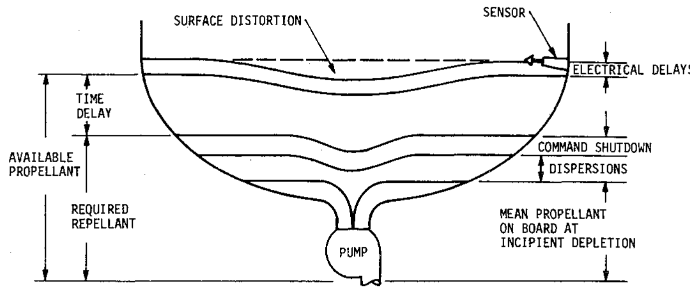

Fig. 8 Available and required propellant.

were obtained within the established tolerances on target parameters. Individual level sensor uncover signatures showed no indication of a particular sensor leading or lagging the others in either the oxidizer or fuel tank by an amount great enough to require individual electronic patching. No evidence of bubbles, foam, or significant surface layer disturbance was noted from a review of motion pictures films taken through the viewport at the time of level sensor uncover. The following conclusions were derived from the test: 1) Test results indicate that approximately 0.4 ft^3 of "dropout," i.e., loss of usable propellant, exists in either tank at the proposed probe location. 2) Dispersions in level sensor uncover times were small and system repeatability was exceptionally good. 3) The nonsymmetrical location of probes in the fuel tank does not have a significant effect on relative sensor uncover times.

System Analysis

Once the location of the shutdown sensors was verified, it was necessary to determine the time delay between sensor uncover and issuance of the engine shutdown signal. This is the time needed to consume the difference between the propellant available at the beginning of the timer run and the propellant required on board at issuance of the shutdown signal to assure a command, rather than a depletion, shutdown transient. A ground rule for the analysis was that the time delay must be short enough to assure a command shutdown for the three-standard-deviation smallest difference between the available and required propellant, as shown in Fig. 8. The available propellant is the quiescent propellant volume below the level sensor point minus any propellant lost due to surface distortion and electrical delays.

Defining the required propellant involved a tradeoff between vehicle performance and the probability of depletion. The least conservative technique considered for guaranteeing a command shutdown would issue the shutdown signal causing chamber pressure (P_c) to drop at incipient propellant depletion. The most conservative approach would issue the shutdown signal at an earlier time so that command shutdown would be complete at incipient propellant depletion. In this "zero overlap" condition, the shutdown transient would always be a pure command shutdown. Between these two extremes are all the cases for which depletion begins during the command shutdown transient. Consultation with the engine manufacturer (Aerojet Liquid Rocket Co.) resulted in a decision to ensure "zero overlap" to guarantee prevention of the indeterminate dynamic loads typical of depletion shutdown.

Required and Available Propellant

Defining the required propellant consisted of calculating the mean propellant on board at the beginning of depletion, the mean command shutdown consumption for each tank, and the amount of propellant necessary to allow for each of the identified uncertainties in the system. The results are discussed next.

Incipient depletion is defined as the point at which engine chamber pressure first drops from its steady-state value

Table 1 Time delays

	Stage I fuel	Stage I oxidizer	Stage II fuel	Stage II oxidizer
Net available propellant (lbm)	1785	5191	261	313
Required propellant (lbm)	921	1016	243	178
Difference (lbm)	864	4175	18	135
Propellant flow rate (lbm/sec)	595	1191	117	210
Time delay (sec)	1.452	3.505	0.154	0.643

(characteristically referred to as "P_c corner"). The technique used to determine the amount of propellant on board at P_c corner in each tank consisted of an evaluation of data from 55 Titan III flights. For each flight, the volume at a level sensor located low in the tank was known. Propellant flowrate between the uncover of that sensor and P_c corner was calculated from engine data, yielding the propellant remaining at P_c corner.

The time delay for each tank is the same for all vehicles; therefore, propellant must be reserved to allow for the expected range of volumes below the shutdown sensor due to variations in manufacturing. A height-volume calibration is performed on each Titan propellant tank using water, and the volume dispersions used in the analysis were determined from these data.

The delays and the corresponding dispersions of each element of the electronic system are the same for all tanks and must be expressed in terms of propellant weight using appropriate values of nominal and dispersed engine flowrate. The timer used in the system was assumed to have an accuracy of $\pm 3\%$ of the setting. This produces a different value for each tank and again is expressed in terms of propellant weight.

The command shutdown consumption is the propellant consumed between engine receipt of the shutdown signal and complete closing of the thrust chamber valves. The mean and dispersed values shown in the table were defined by Aerojet Liquid Rocket Co., based on engine acceptance test data.

Sensor error includes the repeatability characteristics of a sensor responding to a slowly moving liquid surface together with the added dispersions due to the velocity and variable quality of the liquid surface under flight conditions. For Stage I, the sensor error was estimated from a review of flight data from the Gemini launch vehicle which flew with two level sensors located at the same height.

The Stage II sensor error was determined quantitatively in the outflow test. This test also indicates that on Stage II a bias, as well as a dispersion, exists in the response of the sensor to the passing liquid surface. This is believed to be due to liquid surface distortion at the level sensor plane and is accounted for in the analysis in the "available" propellant calculation.

The total propellant requirement to assure no depletion is defined to be the mean $+3\sigma$ propellant requirement. The mean is the sum of the mean P_c corner propellant and command shutdown consumption. The 3σ propellant requirement is the rss of all the system dispersions.

The available propellant is the amount of propellant in each tank at the time the MVTD begins the time delay. It is the volume between the sense point plane of the shutdown sensors and the engine injector, minus propellant lost due to electrical delays and distortion of the liquid surface at the sensors.

Time Delay

The desired time delay is the time required for the engines to consume the difference between the avilable and required propellants. The time delays are summarized in Table 1.

Conclusions

A system which guarantees predictable and smooth command shutdown for liquid rocket engines, and at the same time provides performance capability comparable to that obtained with depletion, has been described. The shutdown system is thought to have applicability for other space boosters or missile programs, and an attempt has been made here to describe the design and operational factors which must be considered in outlining any such development effort.

The MVTD, developed specifically for this program, represents an unique design and offers possible potential for other application, unrelated to a shutdown system, where a requirement for a highly reliable, flight-qualified, lightweight timer system exists.

Although primarily designed as a flight critical shutdown system, the shutdown level sensors also provide a high-quality instrumentation capability which will enhance the postflight analysis of the propulsion system on the launch vehicle.