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COMPUTER CONTROLLED VENT AND PRESSURIZATION SYSTEM

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COMPUTER CONTROLLED VENT AND PRESSURIZATION SYSTEM

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ABSTRACT

The paper illustrates how the Centaur space launch vehicle airborne computer, which was primarily used to perform guidance, navigation, and sequencing tasks, was further used to monitor and control inflight pressurization and venting of the cryogenic propellant tanks. Computer software flexibility also provided a failure detection and correction capability necessary to adopt and operate redundant hardware techniques and enhance the overall vehicle reliability.

INTRODUCTION

A digital computer formerly used only for guidance, navigation and sequencing tasks is now used on the Centaur stage of the Atlas/Centaur and Titan/Centaur space launch vehicles to manage pressurization and venting of the propellant tanks. Special needs of cryogenically fueled vehicles of this type are illustrated along with the equipment developed to manage the pressurization and venting requirements. Full scale ground testing of the Centaur stage further pointed out the need for a better way to overcome hardware related problems. Techniques used in ground testing were later used as a basis to conceive a software system to enhance and simplify the hardware systems for the pressurization tasks. Use of the computer also yielded other advantages. Failure sensing and correction techniques were later considered and found to be within the capabilities of the computer. Computer flexibility features and effects on the aspects of redundancy, accuracy, and reliability are also presented.

The concept of computer control of propellant tank pressures is significant, and may parallel the needs of other pressurization control systems. Users of the techniques described here may benefit from the new flexibility brought about through software systems. Adopting techniques described may yield benefits of failure detection through software, greater accuracy, and repeatibility never before thought possible.

The paper presents [illegible] definition of the Centaur vehicle, its specialties and peculiar needs posed by the cryogenic propellants used for propulsion. Background on the conception and development of such a system will be described. The equipment used for the computer controlled vent and pressurization system (CCVAPS) is described along with the techniques finally incorporated to perform the required tasks. The system is described conceptually without failure detection and a final section is dedicated to the failure detection and correction features.

CENTAUR SPACE LAUNCH VEHICLE

Centaur Definition:

The current Centaur D-1 space launch vehicle is an improved version of the Centaur high energy upper stage which began operational use with an Atlas booster in 1966. See figure 1. Further development began in 1969 to integrate the improved Centaur stage with the Titan booster. See figure 2. Consequently the Centaur performs today with either of these boosters.

Atlas Centaur vehicles have been used for interplanetary ventures such as, Surveyor, Mariner, and Pioneer and orbital missions such as OAO, Intelsat and ATS. Titan/Centaur, however, having a greater payload capability, has been charged with interplanetary missions, such as the helios and Viking spacecraft, which were launched during the past year.

The Centaur on-board computer was previously used primarily for guidance, navigation and sequencing tasks. Growing needs of preflight calibration of the guidance and navigation systems created a need for a larger and faster computer. A new generation computer was considered and finally incorporated as part of the D-1 Centaur. With the new computer came the use of its expanded capabilities to do many other vehicle tasks. In addition to the tasks of guidance, navigation and sequencing, the computer was assigned the following new duties: Centaur and booster stage sequencing, telemetry formatting, digital auto pilot, propellant utilization or engine mixture ratio control, monitoring of propellant usage for attitude control engines, monitoring helium usage for tank pressurization, preflight testing and management and control of the propellant tank venting and pressurization requirements. This latter system now used for pressurization and vent control and identified as the Computer Controlled Vent and Pressurization System (CCVAPS) is the subject of this paper.

Propellant System Description:

The propellants used by the Centaur stage are liquid hydrogen and liquid oxygen. The low temperature liquified gases require special handling not only on the ground but also in flight. The temperatures of the propellants and the environments created by the mission profiles make it necessary to tailor each flight in terms of pressure versus time.

The propellant tanks are configured as shown in figure 3. They are thin-wall pressure stabilized tanks that are structurally maintained through proper pressurization. Pressures are raised and maintained with a helium pressurization system supplemented by boiloff of the cryogenic liquids. Venting to reduce pressure is accomplished with vent valves which vent the ullage gas overboard when required.

Pressurization and Vent System:

A schematic of the pressurization and vent system is shown in figure 4. The elements used to control the functions of venting and pressurization are also shown. Components used for pressurization are the high pressure helium storage bottle, solenoid operated pressurization valves, orifices, pressure sensing transducers and the vent valves.

The pressurization and vent system is used to condition the Centaur vehicle propellants prior to engine start and to protect the vehicle against structural problems related to over or under pressurization.

Pressurization to predetermined levels is physically accomplished by a metered injection of helium gas, from high pressure (3000 psia) bottles, through orificed pressurization valves into the propellant tanks. The actual pressure feedback control process will be discussed in greater detail in a subsequent section.

Venting of the propellant tanks is accomplished by independent control of the two position solenoid operated vent valves. When the valves are in the relief mode they **regulate** within a preset control pressure range. When the valves are switched to the closed mode venting is inhibited regardless of indicated tank pressure. Pressures within the propellant tanks may be reduced from values above reseat pressure to reseat pressure by commanding the valve to its relief or open mode. Intermediate pressures of any value above reseat may be maintained by alternately switching the vent valve operating mode between open relief and closed as a function of sensed propellant tank pressures.

Ullage Rocket System:

The ullage rockets are four low thrust hydrogen peroxide engines which are mounted on the aft bulkhead. See figure 3. They provide the forces necessary to position propellants at the aft end of the propellant tanks under low gravity coast conditions. Figure 4 shows an output from the sequence control unit which operates the ullage rocket system.

The engines are fired continuously and a bi level thrust, depending on the propellant management mode, is controlled by firing either 2 or 4 engines. Switching of alternate pairs of engines is also performed midway through the settled coast period to offset the probability of an engine out failure. Control is not jeopardized by an engine out problem and stability is maintained by the pitch, yaw, and roll attitude control engines.

PECULIAR CENTAUR NEEDS

Propellant Conditiong:

The liquid oxygen and liquid hydrogen propellants are fed to the engines through hydrogen peroxide powered, turbine driven boost pumps. Both propellants must be subcooled just prior to starting the boost pumps to prevent cavitation within the pumps.

To obtain subcooled propellants, the tanks are vented to pressures corresponding to vapor pressures of the bulk liquids. Venting is permitted for a sufficient period of time to allow for saturation conditions to occur. The tanks are then repressurized to predetermined levels. The conditioning vent and pressurization levels were based on data obtained from past flights and from ground testing of Centaur at the Plum Brook test facility of NASA in Sandusky, Ohio.

Propellant Positioning:

Propellants are positioned in the bottom of the tanks under low gravity conditions by the application of low level thrust from the ullage rockets. Propellants in their settled position ready the vehicle for either an engine start or for a propellant tank venting sequence. Propellants are clear of vents so as not to vent liquid and the boost pump sumps are filled with liquid.

For long coasts when it is not feasible to settle propellants continuously, a zero gravity coast technique is used wherever propellants are allowed to drift freely throughout the propellant tanks. When pressures rise to levels sufficient to initiate a vent cycle the ullage rockets are fired to position the propellants away from the vents. Thereby only gases and vapors are expelled during a vent routine.

CONTROL EQUIPMENT FOR PROPELLANT SYSTEMS

Digital Computer System:

The digital computer unit (DCU) is a stored program random access core memory type of machine. Memory capacity is over 16 thousand words of 24 bits each. The flight program may only be loaded into a select portion of memory with special laboratory equipment. This special loading feature was specifically designed to protect approximately 12 thousand words of memory dedicated to the flight program and telemetry formats. Once loaded into protected memory the flight program may not be changed unless special laboratory equipment is used under rigidly controlled conditions. The remaining portion of core is accessible and is used for prelaunch testing, calibration and storage of temporary constants.

The software is constructed in modular fashion to reduce lead time in flight program design and for quick system response. Each module is an entity in itself. As previously mentioned, modules exist for sequencing, telemetry formatting, steering, stability, propellant management, hydrogen peroxide and helium monitoring, and pressurization and venting control. All of the modules are under the control of a program executive. Operation of each module and communication between each of the modules for transfer of information is handled through the program executive. The task modules may be scheduled by the executive at different frequencies during the flight. They also may be turned off or on for different phases of flight.

Thus, the digital computer has proved to be an ideal tool for the task of pneumatic system management and control. It has sufficient capability to detect, monitor, and maintain all the needs with great flexibility. Software flexibility replaces the inertia involved with tailoring a hardware system to match more increasingly complex missions. Overall flexibility is enhanced and so is reliability.

Control System Output Equipment:

Figure 4 shows the DCU and how it is interfaced for its input and output functions. Determinations made internal to the DCU by any of the modules that requires a sequence change are passed on to external systems through the sequence control unit. The sequence control unit is essentially a bank of relays which receives its commands for switching from the DCU.

The computer outputs all venting and pressurization commands through the sequence control unit. Relays of the SCU operate the propellant settling ullage rockets, the solenoid operated vent valves and the appropriate pressurization solenoid valves to maintain complete control of the pressures within the propellant tanks. The computer controlled vent and pressurization system module of the flight program is scheduled to perform either of the vent or pressurization tasks by the sequencer module of the computer. Digital to analog converters which are part of the computer, provide the final feedback of information on tank pressures and system performance back to the CCVAPS module within the computer. These elements shown in figure 4 comprise the total closed loop control system for propellant tank venting and pressurization.

COMPUTER CONTROL OF PRESSURIZATION AND VENTING

Computer Controlled Vent and Pressurization System:

The computer controlled vent and pressurization system (CCVAPS) used for the Centaur launch vehicle is schemetically shown in figure 4. The system is comprised of the digital computer, the sequence control unit, the vent system, the pressurization system, and the pressure sensing system.

The CCVAPS controls and maintains tank pressures by operating vent valves and pressurization valves in response to sensed tank pressures. The digital computer monitors pressures prior to the sequence control unit relays.

Figure 4 shows how pressures within the propellant tanks are fed back to the digital computer for control purposes. Information gathered by the pressure transducers is relayed to the computer through analog to digital converters which are a part of the computer. The computer uses this information to exercise control over the venting and pressurization requirements of the control program.

Pressure measurements are made with redundant transducers as shown in figure 5. These transducers work in conjunction with the computer software program to determine the adequacy of the pressurization system performance. They also provide a check on the performance of the measuring devices themselves. Methods of failure detection and correction are discussed in a later section.

The basic control modes are pressurization and venting. A flow diagram in figure 6 shows the two modes of pressurization and venting control. When the CCVAPS program is called on by the sequencer to perform it does so at one of three processing rates. For pressurization, the program is processed 25 times per second. Venting is processed at 5 times per second during propellant settling preceding an actual vent and at 0.5 times per second during the vent.

Each step of the computer program flow diagram will be discussed to illustrate how the computer manages and maintains the propellant tank pressures within the desired limits.

Pressurization System Control By Computer:

Entry into the pressurization portion of the flow diagram is made prior to each engine start and at times before spacecraft separation. Logic references exist to select pressurization levels consistent with engine start and tank structural requirements dependent upon the particular mission. Shortly after the vent valves are closed by the sequencer portion of the flight program, the CCVAPS program is sequenced into operation. Initial tank pressures are sensed by the propellant tank transducers and passed on to the computer through the analog to digital converters for pressure calculations.

An example of the pressurization before engine start is shown in figure 7. The computer adds the delta pressure increase requirement shown for engine start to the initial pressures observed. This pressure is compared to a maximum allowed valve closing pressure and the lower of the two pressures is used for control. Pressures calculated are used for raising and maintaining propellant tank pressures at the proper levels by issuing discretes as shown in the flow diagram (Figure 6).

The pressurization increase requirements are a function of several variables: the net positive suction pressure needed for the boost pumps, size of propellant tank ullages, rate of sensing tank pressures, pressure rise rates after commanding pressurization valves closed and thermal effects causing pressure overshoots after valve closure. In addition pressure overshoot and undershoot about the programmed deadband must also be defined. Typical values selected are as shown in figure 7.

The flexibility of the computer control system simplifies changes to be made to tailor each vehicle flight to its special requirements.

Venting System Control By Computer:

Entry into the vent portion of the flow diagram, figure 6 is made between each engine firing of multiple burn missions and precedes the pressurization sequence before the second and subsequent engine starts. Pressure readings are taken over predetermined intervals of time and averaged as shown in figure 8. The average pressure is then compared to a vent initiation pressure chosen for venting the propellant tank in question. After the average pressure has exceeded the initiation pressure a vent sequence is started.

Reaction to vent initiation is dependent upon conditions at the time of detection. If in a state of zero gravity coast, ullage rockets are commanded to start to settle propellants. Should this be the situation, and should tank pressure still rise, venting will occur at pressures just above the initiation limit until the propellant settling period is over. At completion of the prescribed propellant settling period, venting is initiated. During the venting interval pressures are regulated within a 1.0 psi band with the minimum pressures just above the vent valve reseat pressure. After the vent period is completed pressure averaging is again resumed until further venting is needed or until the vent enable period chosen is completed.

The sequencing and techniques described are the particular ones chosen for the needs of most missions. Variations to the techniques described are only limited by the imagination. Many variations could have been used.

Pressurization and Venting Technique Development:

Variations in pressurization and venting techniques were developed using full scale testing methods. Tests were conducted on a full scale thick walled Centaur type tank and finally on the Centaur tank itself. Full duration rocket engine firing tests with the Centaur vehicle at altitude conditions were run at NASA's Plum Brook Test Facility of Sandusky, Ohio. Pressurization of the propellant tanks for these tests was accomplished using conventional hardware. Pressure switches were used to control solenoid operated pressurization valves. This method of pressurization worked well, but the system lacked flexibility as the pressurization requirements were changed in the course of the test program. Procurement of new pressure switches would have caused a schedule slip so an alternate method of pressurization control was developed.

The pressure switch was essentially replaced by an electronic comparator. The pressure transducer output voltage was compared to a voltage representing the desired pressure switch setting (set point). The comparison output was then used to drive relays which operated the solenoid valves. Pressurization was then regulated by the opening or closing of the valves.

Use of these set point and feedback principals eventually set the way for use of the digital computer. The fast sensing and reaction capabilities of the computer established the feasibility for development of the CCVAPS system.

FAILURE DETECTION AND CORRECTION TECHNIQUES

Techniques used for failure detection and correction were made possible as a result of the speed of the computer. Data sampling at a rate of 50 times a second provides a rapid detection of errors between a given control and reference pressure at any instant. Therefore upon sensing an error it was possible to switch to a spare transducer for control in a short interval of time. This type of failure detection and correction provides valuable redundancy in system control. Similarly, valve failure detection can be achieved by observation of the pressurization effects after commanding a valve open or closed, and if a vehicle failure is detected a switchover can be made to a redundant valve.

Pressurization Valve Failure:

A pressurization valve failure is essentially detected by computer observation of pressure rise and pressure decay rates after a pressurization valve is commanded open or closed. Once the computer has determined the desired pressurization valve closing pressures it issues commands through the sequence control unit to open the pressurization valves. See figure 5. Pressure in the tanks increases and as it does the computer monitors these pressures so that the pressurization valves may be commanded closed when the previously calculated pressure is reached.

During the pressurization, the rate at which the pressure is rising is observed. See figure 9. Should the pressure rise not occur or be too slow it is assumed that a pressurization valve has failed to open fully or not at all. A detection of failure to open for two consecutive cycles, requires that the prime pressurization valves, see figure 5, be closed and that the backup valves for each tank be used for all further pressurization.

If the valve does open properly and the proper pressure rise rate is detected, pressure will continue to rise until the desired valve closing pressure is reached. When this pressure is reached a command is sent to the SCU to close the valve. The duration between the time of detection and the closing of the valve allows more pressurant into the tank and results in some expected overshoot. An allowance for the overshoot in pressure has been made in the original calculation of valve closing pressure. Closing pressure is derated by the amount of expected overshoot. If pressure increases to a value above the allowance for overshoot and the overpressure is confirmed by two consecutive compute cycles, then switch over is made to the backup pressurization valve system.

The bands of acceptable overshoot and undershoot allowed before the backup pressurization system is called upon to perform is shown in figure 9. As stated earlier, both propellant tanks are involved in the switch to the redundant system after a failure in the pressurization system is detected. Figure 5 shows the configuration of the pressurization valves for both systems

The failure test of pressure rise with time after initiation of pressurization is in effect only until the tank in question reaches valve closing pressure for the first time. See figure 9. If by chance a propellant tank transducer failure should be detected during the initial pressurization before arriving at the first valve closing a second test is made. The second test is a pressure rise rate test and is reinitiated at the exact time the spare transducer is introduced for control. The same criteria used at pressurization start is used for the second test. If the pressure reaches closing pressure before the second test is completed, it is cancelled. Overshoot and undershoot tests remain in effect.

After tank pressures have risen to valve closing pressure values and after the expected overshoot, tank pressure will decay primarily due to thermal effects upon the pressurant gas. When tank pressure drops below the valve closing pressure and beyond by the predetermined deadband of operation, the pressurization valves open again. Deadband limits for valve opening and closing are stored as data just as other predetermined limits and parameters.

Each tank then independently continues this cyclic mode of control until instructed otherwise. Any change in pressurization level parameters, failure detection limits or timing is handled through the sequencing module of the computer. A new codeword is issued by the sequencer module and is then interpreted by the CCVAPS module. By codeword the CCVAPS module detects information leading to direction on which valves are to be used, for pressurization and venting, and which set of constants are to be used for that particular portion of the flight.

<u>Pressure Transducer Failure:</u>

Propellant tank pressures are measured by transducers using the "pair plus a spare" concept of redundancy. Figure 5 shows the three transducers in each propellant tank which are used to provide the computer with system pressures data.

One transducer is used for control, the second for reference, and the third for substitute control should a discrepancy be detected between the first and second transducer.

Transducer failure detection is performed whenever the CCVAPS module is turned on for venting or pressurizing the propellant tanks. Two types of failure detection tests are made to determine if the primary or reference transducer has failed. One test measures the absolute difference in pressures measured between the primary and reference transducer at all times. An exception is during the first step of pressurization from the time the pressurization valves are commanded open until the propellant tank reaches valve closing pressure. A second test is made during the first pressurization step by comparing the two instantaneous values of pressure increase from the initial pressure at the start of pressurization.

Judgment for failure detection is based upon the magnitude of the transducer difference readings for both tests described. The failure detection also requires there must be two consecutive out of tolerance conditions. After a failure has been detected, control is switched to the spare transducer. In addition the program modifies the closing pressure value it previously calculated for the propellant tank in question. The valve closing pressure would be incremented by the allowable failure detection pressure differential.

Figure 10 illustrates a specific situation where the control transducer No. 1 was just within detection limits and then drifts out of tolerance during a pressurization cycle. Switching control from transducer No. 1 to transducer No. 3 requires an incrementation to compensate for loss in pressure by an amount equal to the detection limit.

CONCLUDING REMARKS

This paper describes the space launch vehicles using the new computer controlled vent and pressurization system. It has shown that the special needs of the cryogenically propelled Titan/Centaur and Atlas/Centaur vehicles are complex and have been relieved by the incorporation of the on-board computer for control of the venting and pressurization tasks. An explanation of the control equipment and the methods employed to use them are included. Also explained are the techniques used for programmed control and failure detection of pressurization system and pressure sensing hardware. The application of this versatile control concept would also lend itself to a wide range of applications in industrial or other non-aerospace systems.

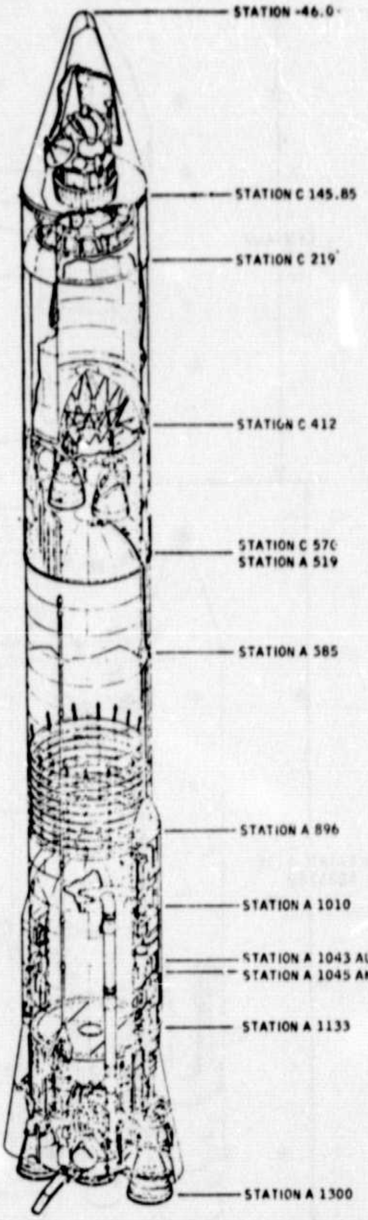

Fig. 1-Atlas Centaur Booster

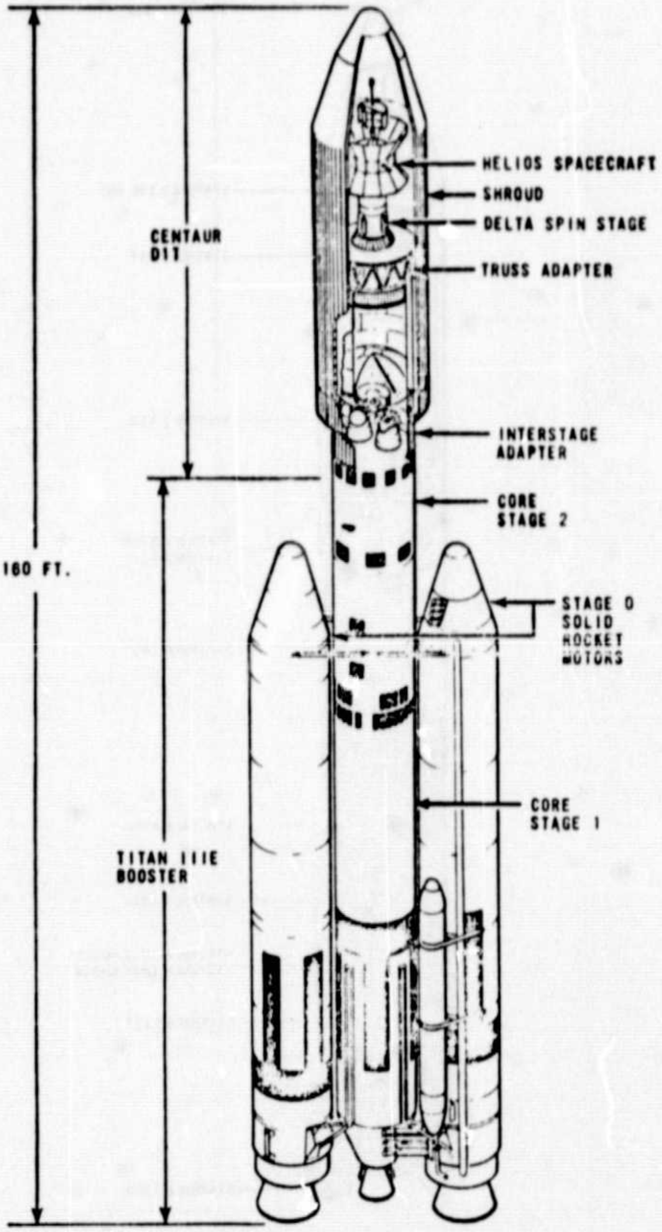

Fig. 2-Titan Centaur Booster

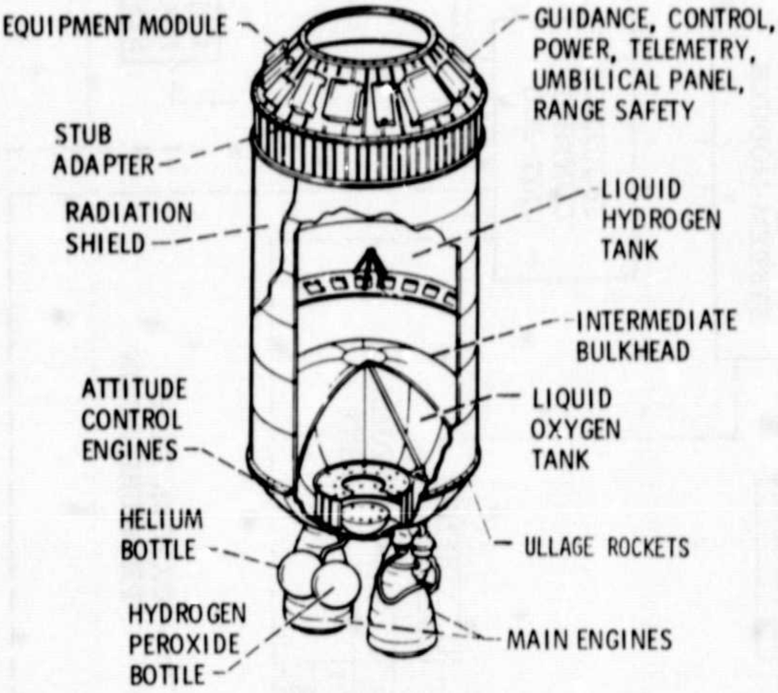

Fig. 3-Propellant Tank Configuration

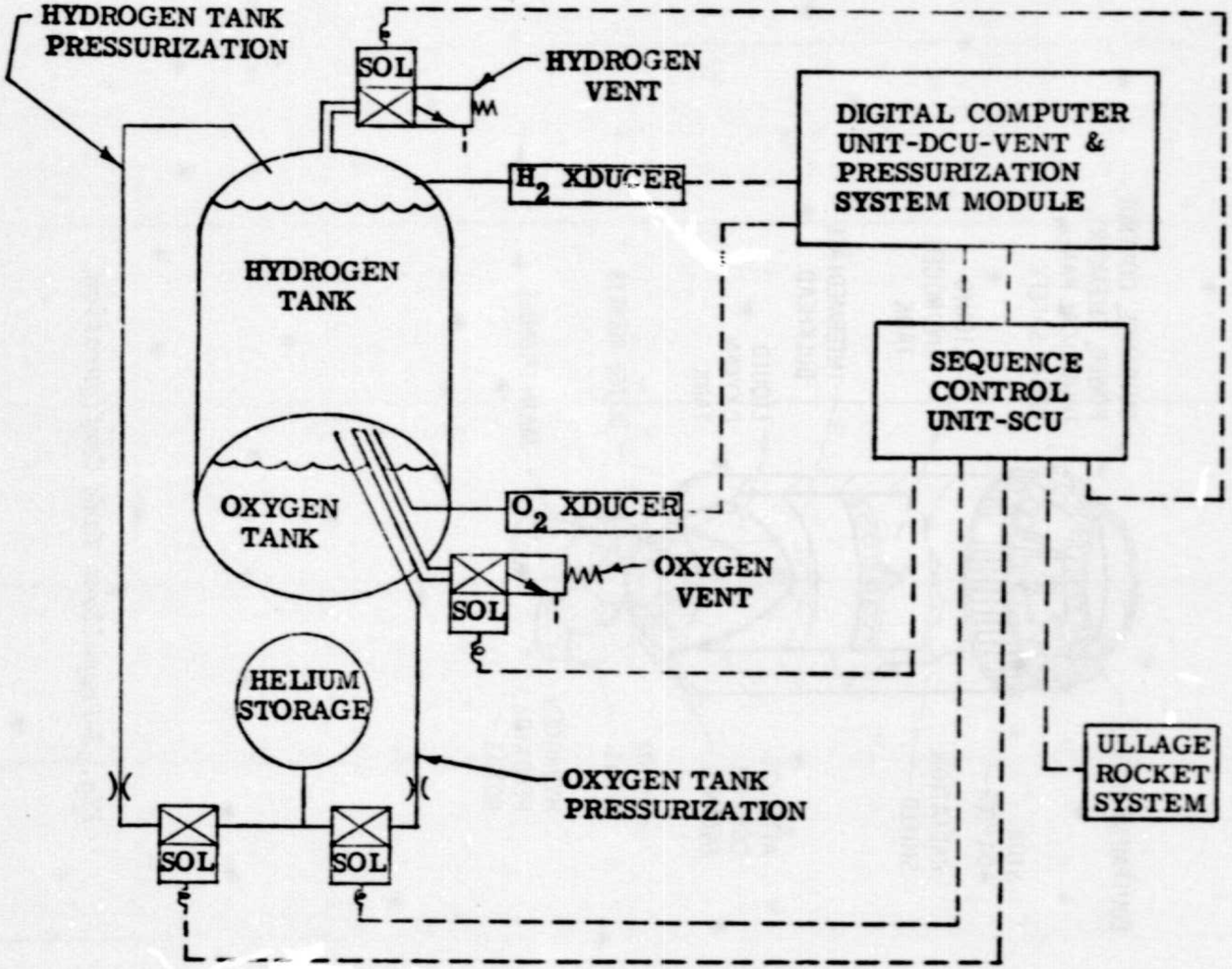

Fig. 4-Schematic of Computer Controlled Vent & Pressurization System (CCVAPS)

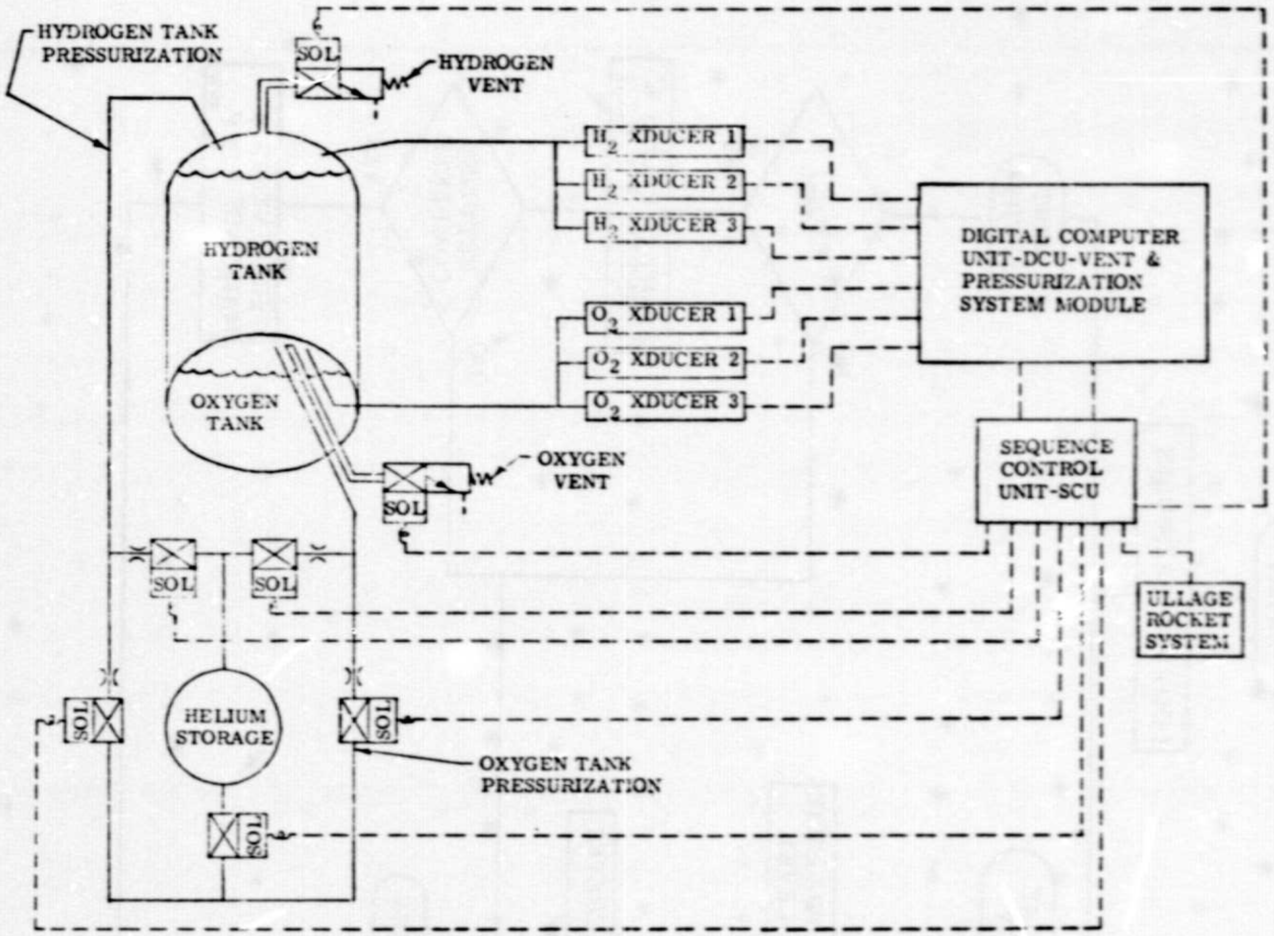

Fig. 5- Schematic of Redundant Computer Controlled Vent & Pressurization (CCVAPS)

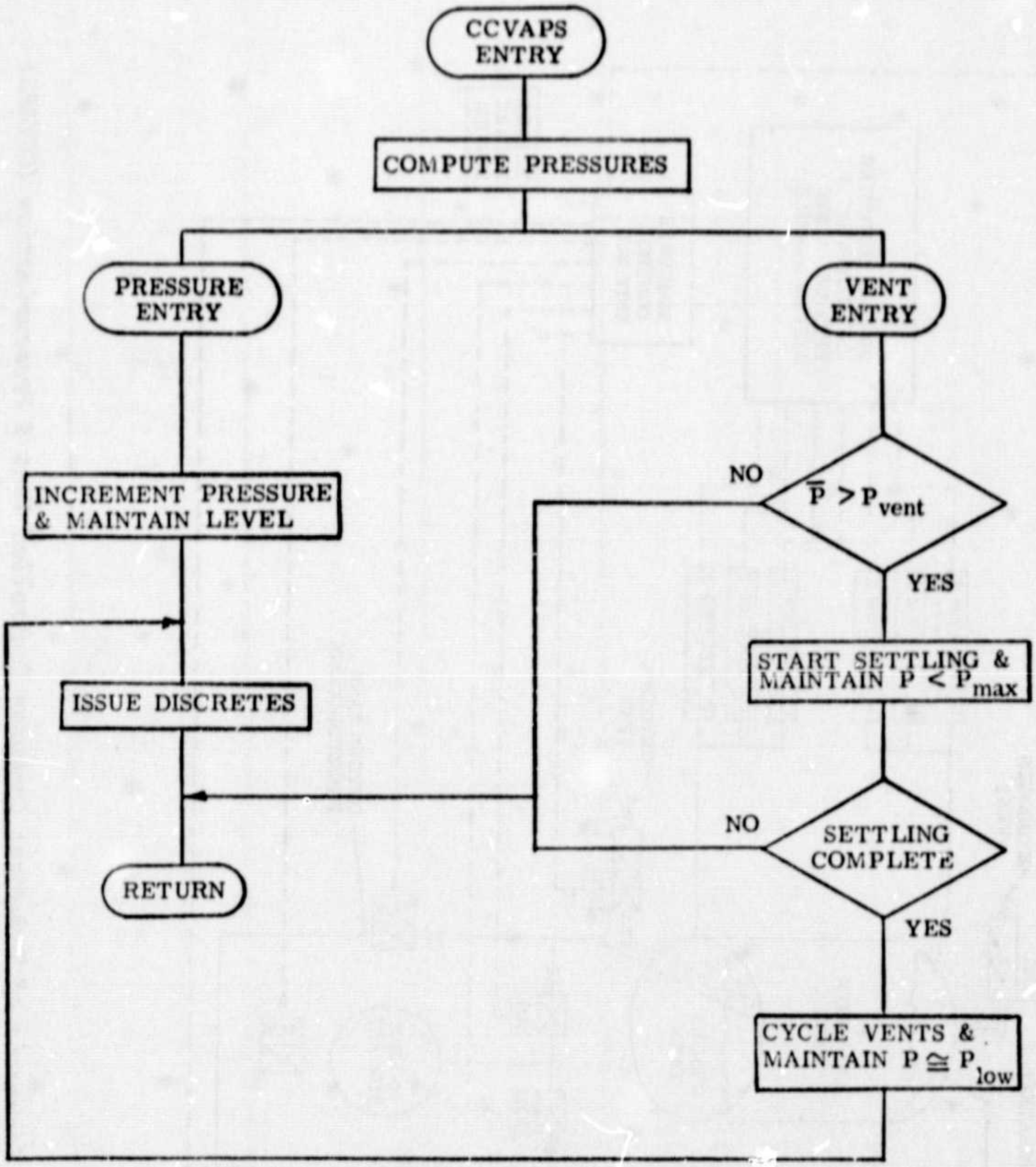

Fig. 6-Computer program Flow Diagram

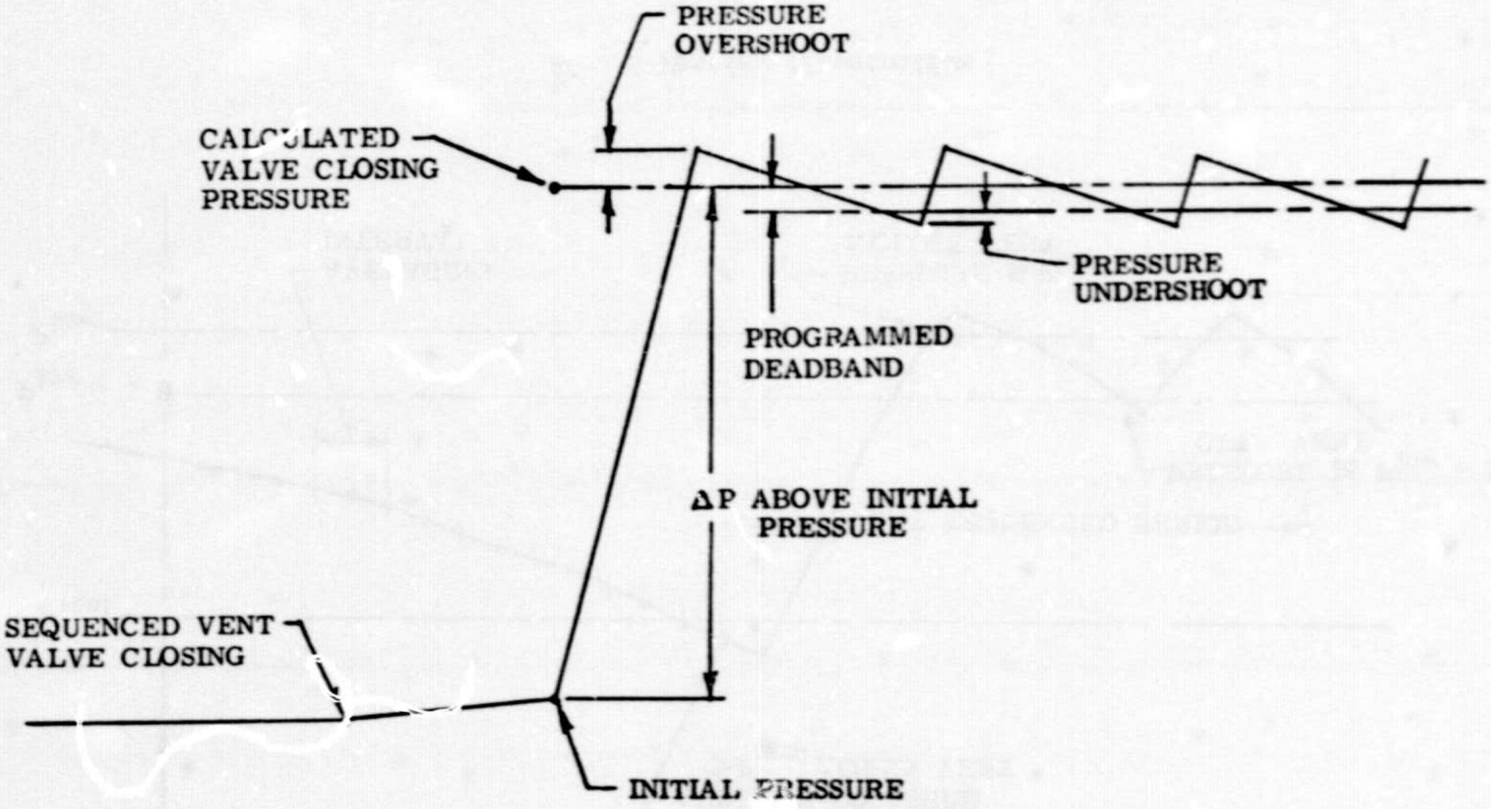

Fig. 7-Pressurizaion Illustration

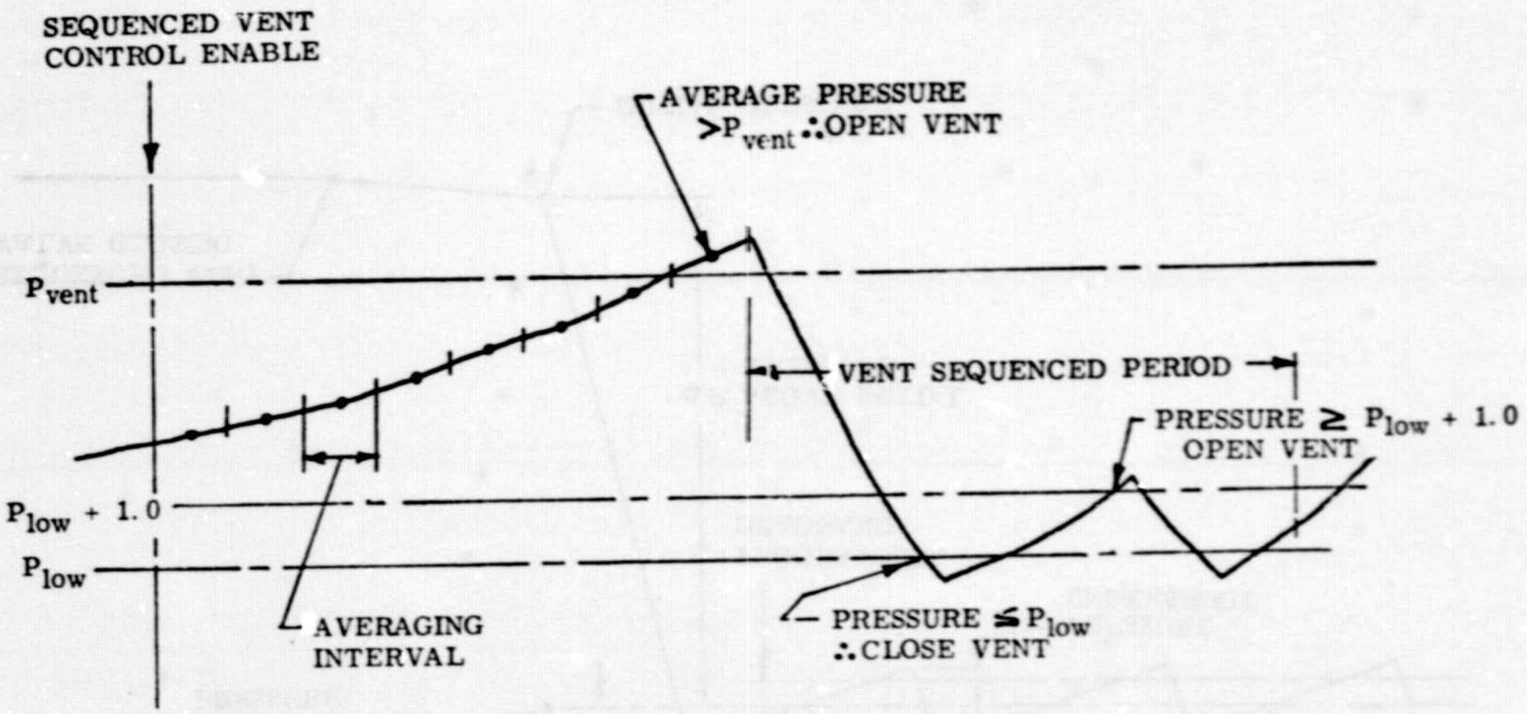

Fig. 8-Venting Illustration

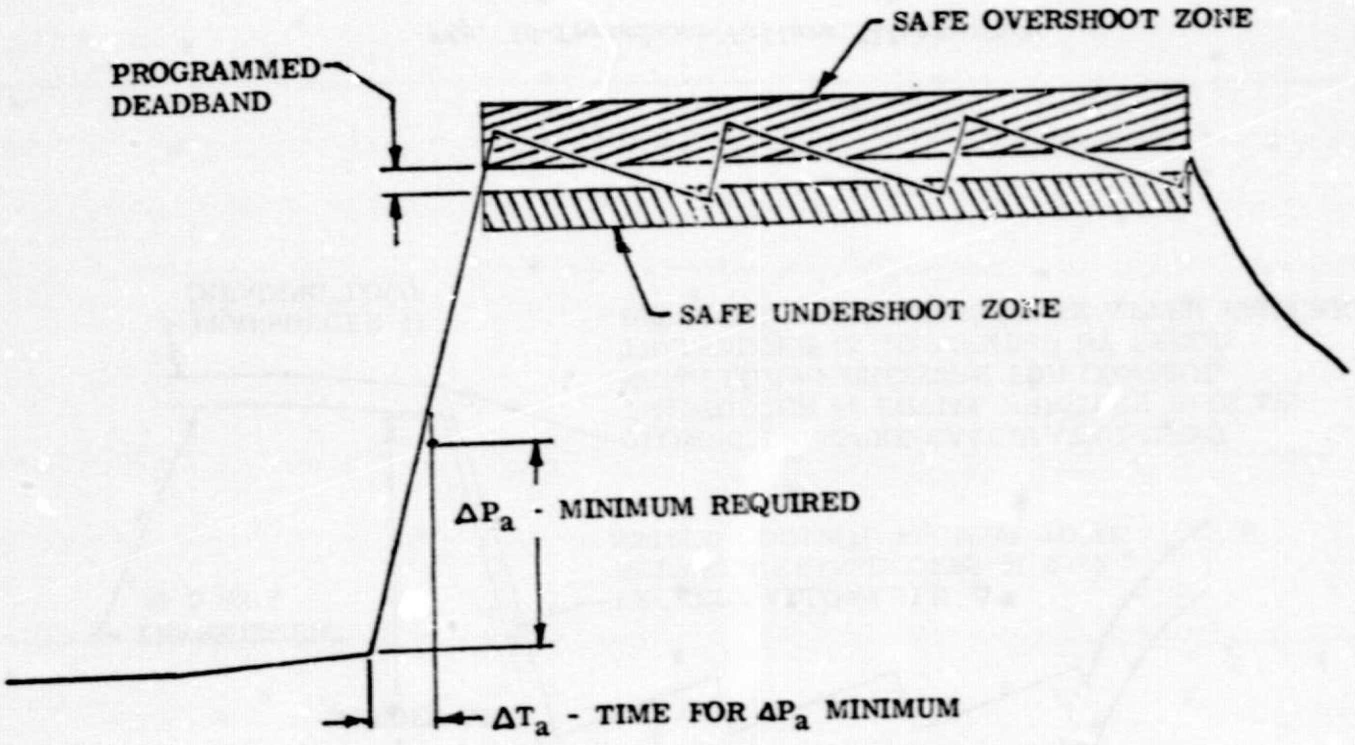

Fig. 9-Valve Failure Illustration

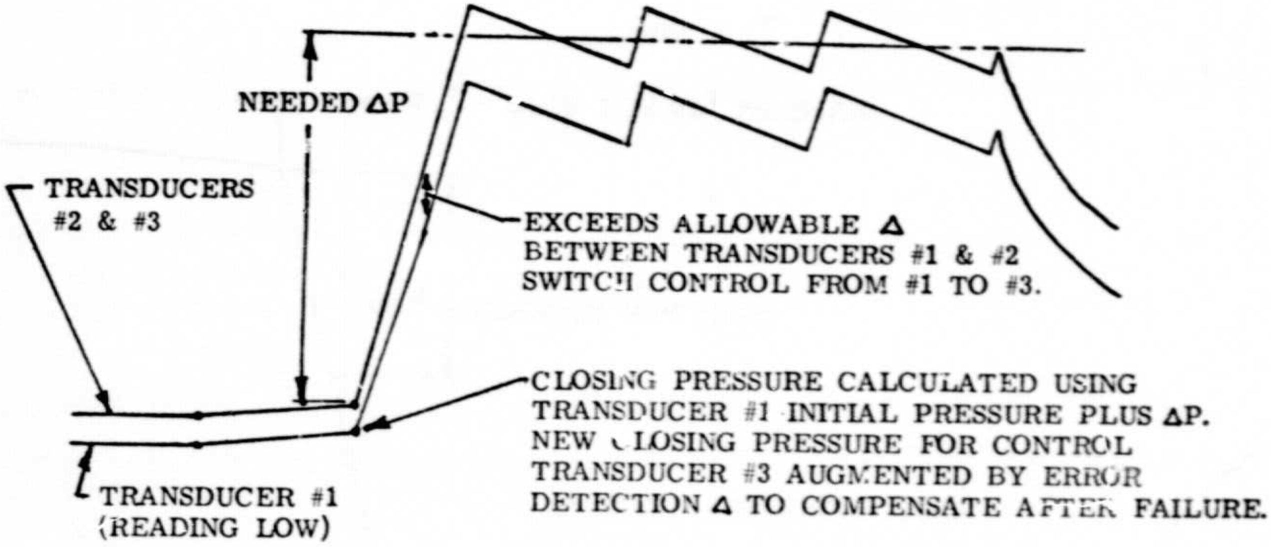

Fig. 10-Transducer Failure Illustration