A Fully Redundant On-Line Mass Spectrometer System Used To Monitor Cryogenic Fuel Leaks on the Space Shuttle

Timothy P. Griffin*, Guy R. Naylor, William D. Haskell
DNX-14, Dynacs Inc., Kennedy Space Center, FL 32899

Greg S. Breznik, Carolyn A. Mizell, and William R. Helms
NASA, Kennedy Space Center, FL 32899

Abstract

An on-line gas monitoring system was developed to replace the older systems used to monitor for cryogenic leaks on the Space Shuttles before launch. The system uses a mass spectrometer to monitor multiple locations in the process, which allows the system to monitor all gas constituents of interest in a nearly simultaneous manner. The system is fully redundant and meets all requirements for ground support equipment (GSE). This includes ruggedness to withstand launch on the Mobile Launcher Platform (MLP), ease of operation, and minimal operator intervention. The system can be fully automated so that an operator is notified when an unusual situation or fault is detected. User inputs are through personal computer using mouse and keyboard commands. The graphical user interface is very intuitive and easy to operate. The system has successfully supported four launches to date. It is currently being permanently installed as the primary system monitoring the Space Shuttles during ground processing and launch operations. Time and cost savings will be substantial over the current systems when it is fully implemented in the field. Tests were performed to demonstrate the performance of the system. Low limits-of-detection coupled with small drift make the system a major enhancement over the current systems. Though this system is currently optimized for detecting cryogenic leaks, many

other gas constituents could be monitored using the Hazardous Gas Detection System (HGDS) 2000.

Key Words: on-line mass spectrometry, real-time monitoring, Space Shuttle, gas monitoring, leak monitoring, process mass spectrometry

Introduction

The main engines of the Space Shuttles use cryogenic fuel (liquid hydrogen - LH_2) and oxidizer (liquid oxygen - LO_2). The fuel and oxidizer are stored in the external tank and feed to the engines during launch. To help ensure that no hazardous leaks are present in the Orbiters, the cryogenic systems are thoroughly leak tested before each launch. Because of the inherent hazards associated with large quantities of liquid hydrogen and liquid oxygen, the leak tests are performed with helium (He). This requires that helium in an air background be monitored during a large portion of the prelaunch testing. Resolution of helium is in the range of 1 part per million (ppm). After the external tank is filled with the cryogenic commodities, the levels of hydrogen (H_2), oxygen (O_2), and argon (Ar) in a nitrogen background are monitored. A new system was designed to monitor all of these gases (H_2, He, N_2, O_2, and Ar) and is called the Hazardous Gas Detection Systems (HGDS) 2000 [1,2].

There are currently a number of systems being used for each launch. The two that are the most critical are the Prime HGDS and Backup HGDS. These systems have proven to be invaluable in helping to ensure safe launches. The systems have their own sample delivery subsystems, including transport pumps and selector valves. In addition, both systems use mass spectrometers as the detector.

The systems were developed and installed in the 1970's. Since then two additional systems have been developed. They are the Hydrogen Umbilical Mass Spectrometer (HUMS)[3] and Portable Aft Mass Spectrometer (PAMS)[4]. The HUMS and PAMS systems enabled monitoring of cryogenic gases in a helium background and the ability to monitor low levels of helium in an air background, respectively. The new on-line mass spectrometer was designed to incorporate the requirements of all existing systems.

The major systems used for monitoring cryogenic fuel leaks before launch have been in service for over 20 years. For this reason the operators are starting to have problems keeping the units in operating order. While the systems are still supporting launches, they are becoming more difficult to keep operational for the duration of the launch. An additional operational problem is the age of the control electronics; it is becoming impossible to buy spares for many components. The current systems also fail to take advantage of mass spec and high-vacuum technology developments over the past few decades. Because it is crucial to continue monitoring these gases in support of Shuttle Operations, it was deemed that a new integrated system should be developed.

The HGDS 2000 has many features not incorporated in the current systems. The new system uses the latest high-vacuum and mass spectrometry technology for detecting the components of interest. Advances in computers and electronics will make more information available to the operators than with the older systems. In addition, steps were taken to ensure the systems are easy to maintain and repair. It is also expected that the reliability of the systems will be greatly increased. The new systems have incorporated redundancy on all major components. The only part of the system that will not be redundant is the sample lines that provide sample transport from the areas of concern to the mass spectrometer system. One sample line will feed both detection systems. All the systems use transport lines to bring samples from the Orbiter to the mass spectrometer. A depiction of the transport lines currently in use is shown in Figure 1. Notice that each system can monitor multiple locations, this method necessities a round-robin approach where each line is monitored for a set time before cycling to the next in the sequence.

Experimental

System Design

The overall system is composed of two independent detectors capable of monitoring all of the components of interest (i.e., H_2, He, N_2, O_2, and Ar). In addition to these five compounds the system has to be easily expanded to include additional compounds when needed. The system will use one set of sample lines while all major components will either be redundant or have backup systems (referred to in this document as redundancy). This redundancy will help ensure the system will be operational for the highest amount of time.

A sketch of the overall system is shown in Figure 2. The system will be made up of three parts – the sample delivery subsystem, detector subsystem, and control computer subsystem. This design is new because it is the first system to incorporate two detectors into one complete package. The design uses one transport pump to continuously draw samples from the points of interest. The detectors then draw off the amount of the sample that they need for detection. This method lets either detector monitor any sample line, even the same line.

Detector Subsystem

It was necessary for the detectors to not only monitor the gases that are of current interest (H_2, He, N_2, O_2, Ar) but it is also important that the detector system be able to be expandable to look at additional compounds. This flexibility will help ensure the HGDS 2000 system will meet the changing needs of the customer. This is extremely important with the development of new space vehicles such as the VentureStar.

After taking into account all of the factors associated with different detectors, the Stanford Research Systems (SRS) RGA 100 was deemed the best candidate for the HGDS 2000. It was found that the quadrupole mass spectrometer best meets all of the needs for this application.

The SRS RGA 100 is a single quadrupole mass spectrometer. The unit has an open source. The inlet and high-vacuum manifold were designed in-house during these tests and included two orifices for differential sample pressures. The control electronics, also called the head, interfaces to a personal computer via an RS-232 serial communications line. The calibration of the unit is held in nonvolatile memory by the head and automatically reloads upon power up.

Custom software (Visual C++) was written to control the operation of the RGA 100. The primary concern with writing custom software was the ability to easily interface to the mass spectrometer. Since the RGA 100 is easily interfaced with, only a few commands were needed to operate the unit. These commands were the single mass measurement (MR), noise floor (NF), calibrate all (CA), filament (FL), and multiplier high voltage (HV). An analog scan was also available but not used for these tests.

Sample Delivery Subsystem

The sample delivery subsystem is the part of the unit that draws the sample to the detectors. It can be seen as the circulatory system of the overall unit. A detailed drawing of the sample delivery subsystem is shown in Figure 3. Notice that the final design has included 8 continuously pumped lines and 7 lines that are only pumped when monitored. In addition, the design includes a primary transport pump and a backup transport pump. The Transport pump has the capacity to pull 9 standard liters per minute (L/min) down all 8 sample lines simultaneously. The flow down each sample line can be adjusted by means of vernier valves placed upstream of the transport pump but downstream of the analyzer.

The samples are transported down the 8 sample lines by the transport pump. A single line to be monitored is selected using sample valves that allow a portion of the transport flow to be drawn off to the mass spectrometer subsystem. The sample pump draws this sample past the inlet of the mass spectrometer. All of the exhaust ports are tied together and plumbed outside of the rack. The pressure to the inlet of the mass spectrometer is controlled via a feedback loop between a mass flow controller and pressure transducer.

The design also includes calibration lines for nitrogen and helium background gases. Two extra lines of each (nitrogen and helium) are included for future expansion.

Control Computer

The entire system is controlled via a remote computer operating custom software written in Visual C++. The software enables the user to input all desired commands and to monitor the health and status of the system. A local VME computer controls the system. This unit interfaces with various controllers in the system via Serial RS-232 communications. The Controller interfaces with users either through a local laptop terminal or a remotely located desktop terminal. These connections are Ethernet 100 BaseT. The user computers communicate with the local control computer that commands all of the necessary valves, pumps, and mass spectrometers. The connection between the computers is an independent, fully redundant network.

Experimental Design

Tests were run to examine the performance of the system. These tests examined the accuracy, limits-of-detection, drift, response time, and recovery time of the system. Before each set of experiments was run, the mass spectrometer was calibrated to give concentration readings in ppm.

Calibration

Three calibration gases were used to perform the calibration of the unit. The gas concentrations are listed in Table 1. The RGA 100 was setup as per the tests procedure before calibration of the unit. The procedure for the calibration was to select the zero gas, test gas, and then span gas. Each gas was allowed to flush the sample delivery system for 5 minutes. After flushing the system, the ion currents were measured and the average of 10 readings was recorded for the ions of interest (i.e., H_2, He, O_2, and Ar). The slope and offset were calculated using least squares fit of the Zero and Span gases. The concentrations for the experiments were calculated by using the slope and offset. The calculated concentration for the test gas was measured during the calibration to ensure the unit was functioning properly.

Accuracy, Limit-of-Detection

The system was calibrated prior to these tests. The gases were introduced into the system from lowest concentration to highest concentration (except Ar). The gas was then allowed to flush the system for 10 minutes before measuring the concentration. Calibration gases with the concentration mixtures listed in Table 2 were used for the tests. The RGA was setup as follows: NF=2, SIM=2, 4, 32, 40 Da, Faraday Cup.

Drift

The system was calibrated; no other calibrations were performed during the test. The Zero gas was continuously selected for 12 hours. At the end of the 1, 2, 6, and 12 hours, an average of 25 concentration readings was recorded. The Test gas was then selected for 5 minutes. The average of 25 concentration readings was then averaged and recorded. Zero gas was then selected until the next time sequence.

Response Times

Response times were measured by selecting Zero gas and then selecting Test gas. The time for the concentration reading to reach 95 % of the actual values was the response time.

Recovery Time

Recovery time was measured by selecting Span gas then selecting Test gas. The time required for the concentration reading to measure within 5 % of actual was called the Recovery Time.

Stabilization Time and Pressure Deviation

The procedure for the time studies was as follows:

1) Set both units to monitor line 1.
2) Wait until both have stable readings.
3) Change unit 2 to line 7.
4) Monitor maximum pressure and time necessary for pressure of unit 1 to stabilize.
5) Change unit 2 to line 1.

6) Monitor maximum pressure and time necessary for pressure of unit 1 to stabilize.

Results and Discussion

The results of the tests were very positive. The HGDS 2000 proved to be very stable. Many of the tests did not require a new calibration to be performed before running. The unit was found to be able to be calibrated once per day without major deviations.

Accuracy and Limits-of-Detection

The results of the Accuracy and Limits-of-Detection tests are listed in Table 3. The table lists the results for each of the individual tests. The average and standard deviation of the tests are also listed in the table. The actual (manufacturer stated) levels are included for comparison. Notice that all of the values fall within 10 % of reading except 100-ppm values. The high errors are attributed to air and water in the lines. The lines were tygon tubing. It has been shown that air and water diffuse through the tygon making low-level values difficult to accurately monitor. The 25-ppm lines were stainless steel. The dashes (-) indicate where no data were collected.

From these results it is clear that the system can monitor less than 25 ppm of hydrogen and oxygen. However, because of the difficulties in obtaining known values at lower levels, no experiments where run with values less than 25 ppm. In order to meet the detection limits for H_2 an O_2 close attention had to be paid to mass-to-charge tuning of the instrument. When the peak height was too large (lower limit-of-detection) high-end linearity suffered. However, when the peak height was decreased for better linearity the limits-of-detection worsened. This interaction necessitated tuning, which was not optimal for either case (low-level detection or high degree of linearity). It was found that with minimal practice the tuning could be accomplished without any major difficulty. It was deemed worth the effort of tuning to eliminate the need for the electron multiplier and the instability associated with it.

Drift

The data obtained for the zero drift are listed in Table 4. The table includes the data obtained for the tests along with the average and the acceptable drift tolerances for each test. Notice that the only values that are problematic are associated with He and O_2. Again, this is attributed to water in the system. Notice that the values all drift down with time, which corresponds to the water concentration. The dashes (-) indicate where no data were collected.

The data obtained for the test drift study are listed in Table 5. The table includes the data for each test along with the averages. Notice that all the values are extremely small.

Response Time

The response time was measured to be less than 10 seconds for each component.

Recovery Time

The recovery time was measured to be less than 20 seconds for He, O_2, and Ar while being less than 2 minutes for H_2. It was expected that the recovery time would be greatest for H_2 because of the decrease in compression ratio of the turbo-drag pumps for the lighter gases. There are two orders of magnitude difference in the compression ratios between nitrogen and hydrogen. Steps are being taken to help improve the conductance through the high-vacuum region and thus improving the recovery time of hydrogen.

Stabilization Time and Pressure Deviation

The time necessary for the sample pressure to stabilize when the second unit left the same line are listed in Table 6.

The information in Table 6 was repeated, only the pressure of Unit 2 was monitored (see Table 7).

Notice from Tables 6 and 7 that the maximum stabilization time is 9 seconds. These studies were run to determine what the maximum pressure deviations are with line changes. Unit 1 was held constant on line 1 while Unit 2 was changed from line 1 to 7 then back to line 1. The results are in Table 8.

Conclusions

The mass spectrometer was deemed to be the best method for detection of the compounds necessary for the HGDS 2000. In addition, scanning mass spectrometers enable future expansion of the systems with minimal modifications. The mass spectrometer that is being designed into the HGDS 2000 is the SRS RGA 100. The system gave outstanding performance in the areas of accuracy and limits-of-detection. In addition, the system was extremely stable and required minimal calibration.

The sample delivery system worked extremely well. The response times for the system are less then 10 seconds after a line is selected. Minimal effects were seen while monitoring a line when the second unit is cycled on or off of the monitored line. The unit as designed has redundancy/backup capabilities for all critical components including power supplies. While the sample delivery system was designed as a complete system, a single side can be used at a time. This ability enables the unit to be run in case of complete failure of a system.

The prototype HGDS 2000 has supported four Space Shuttle launches working in parallel with the older systems. A data comparison between the new system and the old systems has proven very favorable. Modifications to the MLP's are under way for the permanent installation of the HGDS 2000 to be the primary launch support equipment in the spring of 2002.

Acknowledgments

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References

1. Griffin TP, Naylor GR, Haskell WD, Curley C, Hritz RJ, Breznik GS, Mizell C. Hazardous gas detection 2000. NASA Technical Briefs 2001.
2. Griffin TP, Naylor GR, Mizell C. A multiple detector sample system for remote gas monitoring. NASA Technical Briefs 1999.
3. HUMS NTR.
4. Griffin TP, Naylor GR, Lingvay L, Adams FW, Mizell C. Portable aft mass spectrometer. NASA Technical Briefs 1999.

	H_2 (ppm)	He (ppm)	O_2 (ppm)	Ar (ppm)	N_2
Zero	0	0	0	0	bal
Test	500	500	500	100	bal
Span	5000	5000	5000	1000	bal

Table 1. SRS Calibration Gases.

Bottle	H_2	He	N_2	O_2	Ar
1	0	0	Balance	0	0
2	25		Balance	25	
3	100	100	Balance	100	500
4	500	500	Balance	500	100
5	1000	1000	Balance	1000	5000
6	5000	5000	Balance	5000	1000
7	10000	1000	Balance	10000	10000

All data are ppm.

Table 2. SRS Linearity Test Values (ppm).

	H_2	O_2		H_2	He	O_2	Ar		H_2	He	O_2	Ar
Run 1	21.9	23.0		91.5	79.4		493.6		494.9	472	456.8	98.1
Run 2	24.2	23.1		93.0	78.1	70.0	493.4		496.0	473.8	459.4	101.5
Run3	24.0	23.3		98.6	102	91.7	427.6		521.9	512.0	461.15	101.7
Average	23.4	23.1		94.4	86.4	80.8	471.5		504.3	485.93	459.1	100.4
Sigma	1.25	0.12		3.8	13	15.3	38		15.3	22.6	2.2	2.0
Actual	25.0	25.0		101	101	96	500		503	501	501	101
Δ	-1.6	-1.9		6.6	14.6	-15.2	-28.5		1.3	-15.1	-41.9	-0.6

	H_2	He	O_2	Ar		H_2	He	O_2	Ar		H_2	He	O_2	Ar
Run 1	898	947	889	4948		5074	5121	5087	1014		11108	10674	10877	10398
Run 2	1038	1007	929	5130		5029	5163	5021	1008		11064	10748	10804	10719
Run3	1069	1036	931	4421		-	-	-	-		9909	9333	9612	8509
Average	1001	997	916	4833		5052	5142	5054	1011		10694	10252	10431	9775
Sigma	91	45	23	368		32	30	47	4		680	796	710	1096
Actual	1000	1020	972	5000		4923	5056	4965	1000		10100	9910	9990	10200
Δ	1	-23	-56	-167		123	86	89	11		594	342	441	-425

All data are ppm.

Table 3. Linearity Data.

1 hr					2 hr					6 hr					12 hr				
Run	H2	He	O2	Ar	Run	H2	He	O2	Ar	Run	H2	He	O2	Ar	Run	H2	He	O2	Ar
1	-1.8	-16.2	-2.2	-0.3	1	0.5	3.5	-5.7	-0.6	1	1.8	-15.0	8.5	1.8	1	-3.4	0.6	-15.9	-2.1
2	1.2	0.0	-4.0	-0.1	2	-2.3	-1.6	-14.3	-2.1	2	0.4	1.6	-7.0	-2.3	2	-	-	-	-
3	-2.5	0.8	-13.0	-0.0	3	-	-	-	-	3	-2.0	1.0	-14.3	-0.3	3	-	-	-	-
aver	-1.0	-5.1	-6.4	-0.2	aver	-0.9	0.9	-10.0	-1.3	aver	0.0	-4.1	-4.3	-0.3	aver	-3.4	0.6	-15.9	-2.1

All data are ppm.

Table 4. SRS Zero Drift Data.

1 hr					2 hr					6 hr					12 hr				
Run	H2	He	O2	Ar	Run	H2	He	O2	Ar	Run	H2	He	O2	Ar	Run	H2	He	O2	Ar
1	-3.9	-10.0	-7.0	0.0	1	-1.0	-3.7	-6.7	0.0	1	-21.0	-11.5	-9.8	4.0	1	1.5	21.5	18.5	4.7
2	-12.6	1.7	-11.0	1.1	2	-13.4	6.5	-12.2	2.1	2	-2.9	19.8	-17.5	3.7	2	-	-	-	-
3	-7.3	-3.1	-	-	3	-7.9	-2.3	-	-	3	13.5	23.2	5.0	3.6	3	-	-	-	-
4	-	-	-	-	4	-	-	-	-	4	-6.8	-2.3	-	-	4	-	-	-	-
aver	-7.9	-3.8	-9.0	0.6	aver	-7.4	0.2	-9.5	1.1	aver	-4.3	7.3	-7.4	3.8	aver	1.5	21.5	18.5	4.7

All data are ppm.

Table 5. SRS Test (500 ppm) Drift Data.

Run	Time (s) Line 1 -> Line 7	Time (s) Line 7 -> Line 1
1	6	8
2	7	9
3	6	9
Average	6.33	8.67

Table 6. SDS Settle Times Data.

Note: Both units were set at 400 Torr and line 1 was selected for both. Unit 2 changed lines. Unit 1 was monitored.

Run	Time (s) Line 1 -> Line 7	Time (s) Line 7 -> Line 1
1	8	6
2	7	7
3	8	6
Average	7.67	6.33

Table 7. SDS Maximum Stabilization Time Data.

Run	Press (Torr) Line 1 -> 7	Press (Torr) Line 7 -> 1
1	20	17
2	21	17
3	21	17
Average	20.67	17

Table 8. SDS Maximum Pressure Deviations Data.

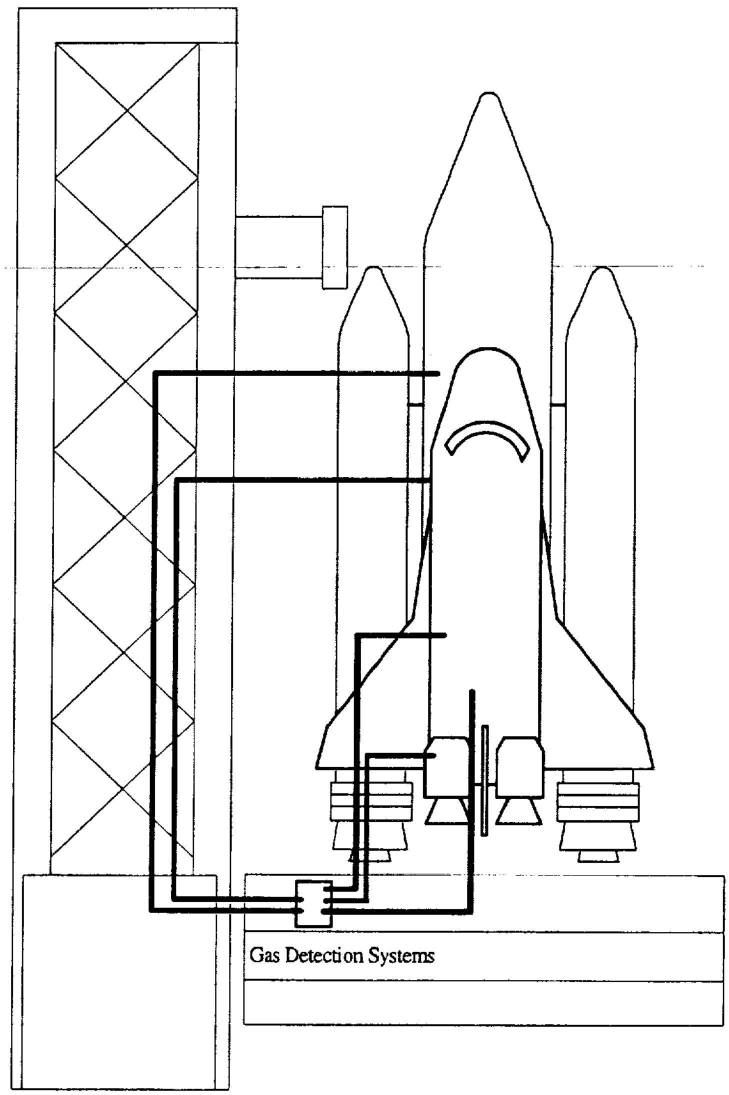

Figure 1a. Depiction of Transport Line Locations

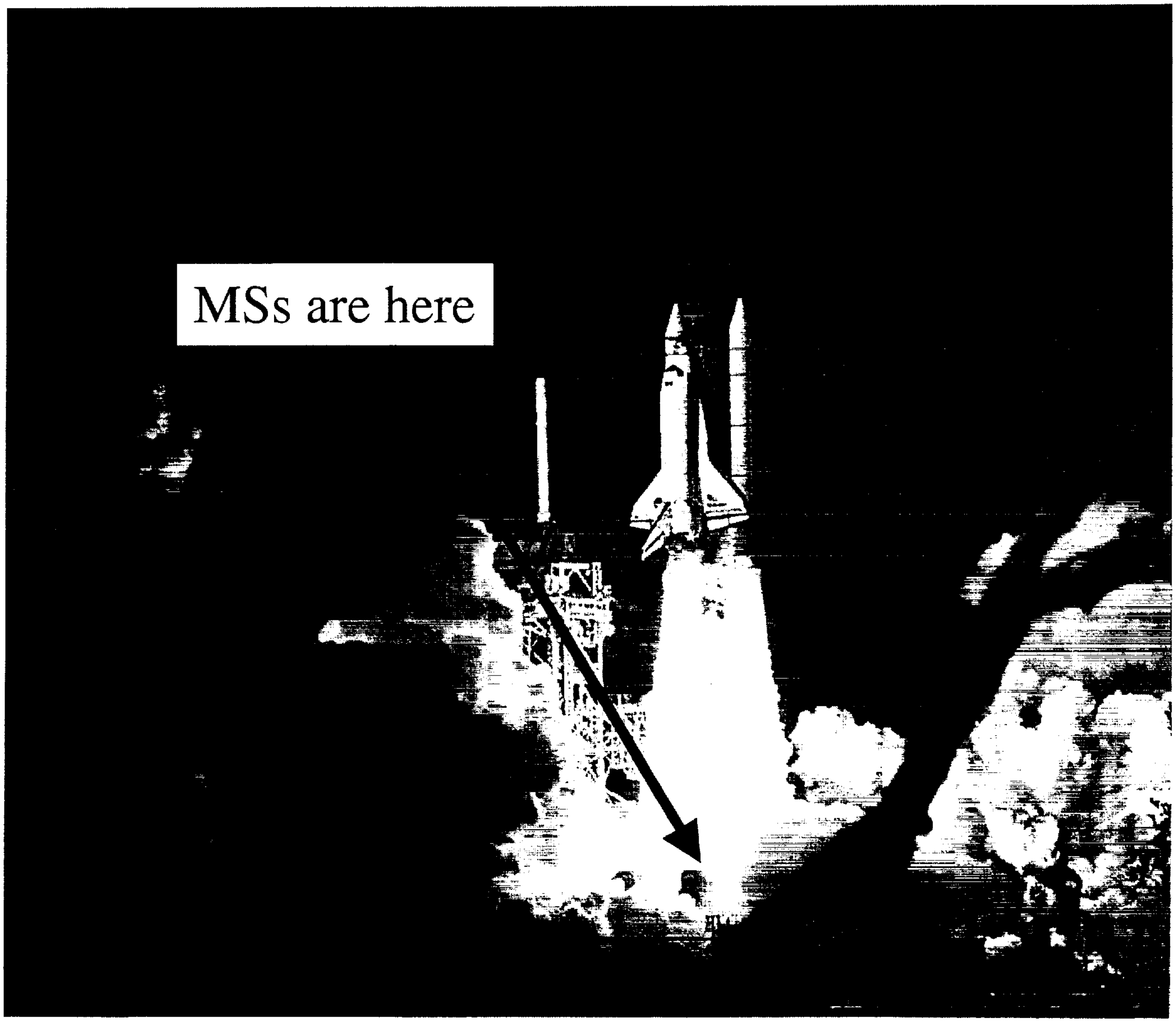

Figure 1b. Location of HGDS 2000 During Space Shuttle Launch

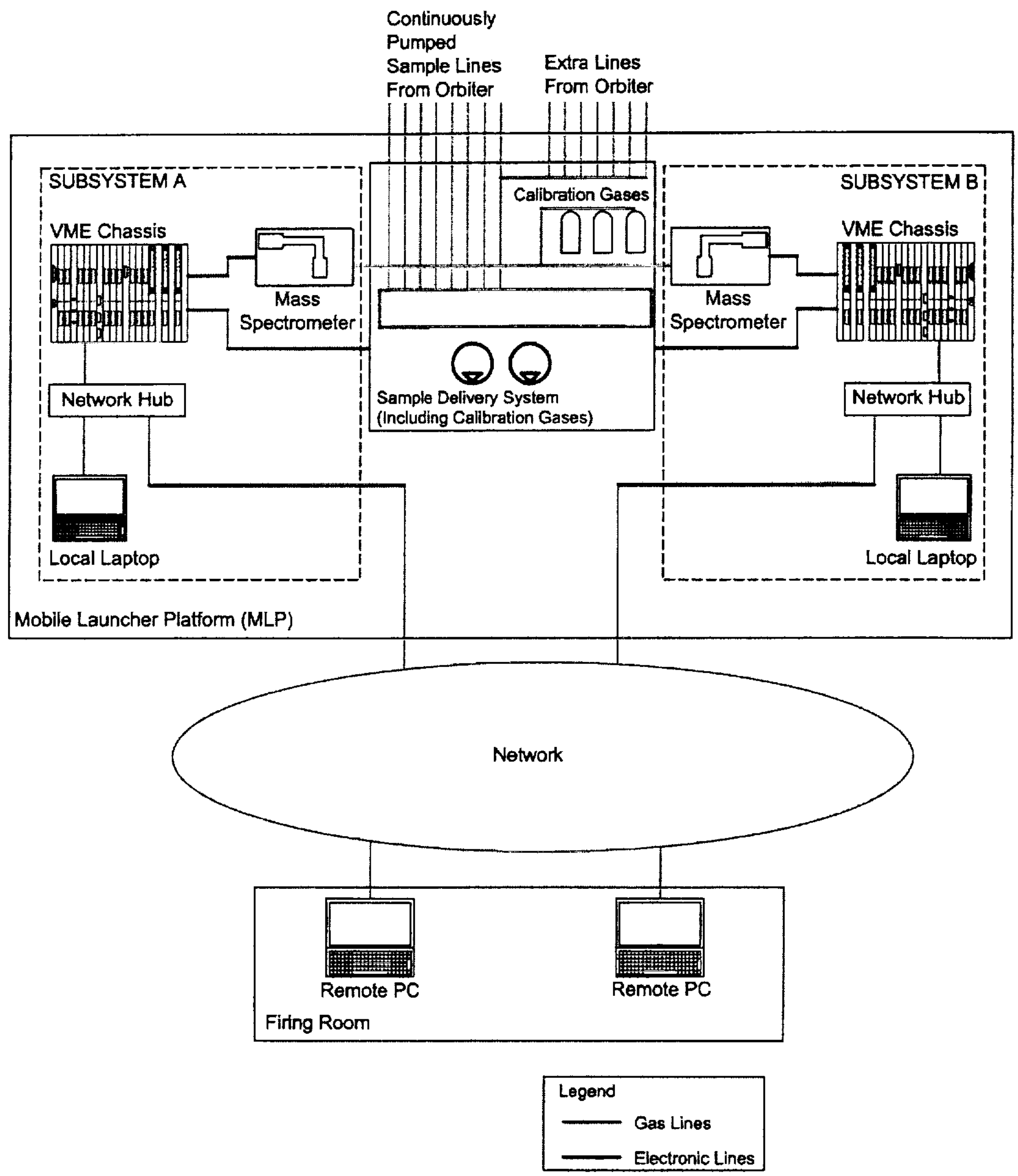

Figure 2. Overall Block Diagram of the HGDS 2000.

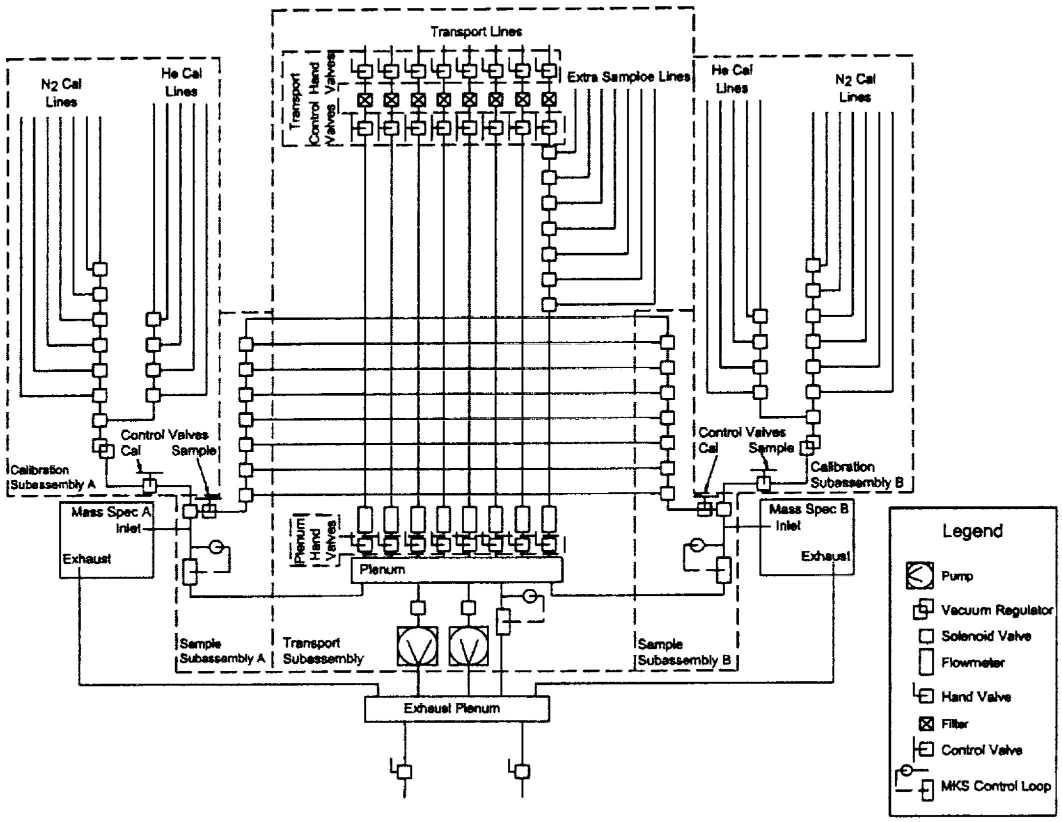

Figure 3. Sample Delivery System of the HGDS 2000.