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LAUNCH HAZARDS ASSESSMENT PROGRAM,
REPORT ON ATLAS/CENTAUR ABORT

SANDIA CORPORATION

PRIME CONTRACTOR TO THE
UNITED STATES ATOMIC
ENERGY COMMISSION
ALBUQUERQUE, NEW MEXICO
LIVERMORE, CALIFORNIA

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REPORT ON ATLAS/CENTAUR ABORT

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ABSTRACT

This report presents the analysis of the thermal and blast data from the aborted launch of the Surveyor mission Atlas-Centaur, March 2, 1965 launched from U.S. ETR.

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FOREWORD

The launch hazards assessment program is a continuing study of vital interest to the United States Air Force, National Aeronautics and Space Administration, United States Atomic Energy Commission, and other agencies that have an interest in or a responsibility to national aerospace programs.

The over-all basic objective of the launch hazards assessment program is the development of a reliable method of predicting the damage potential to be expected from a catastrophic accident to a missile or space vehicle on a launch pad.

Sandia Corporation (prime contractor to the Atomic Energy Commission) is responsible for the independent safety assessment of Systems for Nuclear Auxiliary Power (SNAP) for aerospace application. This responsibility covers the entire life of the SNAP from fabrication through terrestrial re-entry. Sandia Aerospace Nuclear Safety Division 9312 is responsible for ground test activities related to nuclear safety during transportation, ground handling, and launch. As a part of these activities this Division is conducting launch abort environment studies to define those hazardous characteristics which could affect the safety of a nuclear power supply.

Pan American World Airways (PAA), Inc., Guided Missiles Range Division, is the Range Contractor responsible for the operation of the Eastern Test Range (ETR) of the USAF National Range Division.

PAA Electro-Optics Section is responsible for the acquisition and reduction of data from launch pad accidents. These data are used by the ETR Range Safety Division to fulfill the requirements of the launch hazards assessment program.

The following joint report is based on data secured by a pad-abort measuring system which was designed and built as a joint Sandia/PAA effort because of the mutual USAF/USAEC interest in the launch hazards assessment program. This is the first time such measurements have ever been recorded, analyzed, and reported.

TABLE OF CONTENTS

	<u>Page</u>
FOREWORD	2
SUMMARY	5
Data Acquisition System	7
Characteristics of Measurements	7
Data Reduction Approach	9
General Launch Information	10
Launch Configuration	10
Meteorological Data	11
Events	11
Instrumentation Configuration for Atlas-Centaur Launch	11
Instrumentation Parameters	11
System Performance	16
Data Analysis (PAA Electro-Optics Section)	16
Pressure	16
Seismic	23
Thermal	28
Data Analysis (Sandia Engineering Dynamics Division)	28
Pressure	28
Thermal	43
Conclusions	43
Test Results	43
System Performance	48
System Sensitivity	48
System Operation and Maintenance	48
Data Reduction	48
APPENDIX A. PAD ABORT MEASURING SYSTEM DESCRIPTION	51
LIST OF REFERENCES	57

LIST OF ILLUSTRATIONS

Figure

1. Aerial View of Complex 36A, PAMS Sensor Location	8
2. Complex 36A, PAMS Pressure and Thermal Sensor Layout	12
3. PAMS Thermal Instrumentation at Complex 36A	14
4. PAMS Thermal Instrumentation at Complex 36A	15
5. Pressure Variations at Each Pressure Gauge	17
6. Damaged Cable, Pressure Gauge No. 4	18
7. Peak Overpressure versus Normalized Range	22
8. Peak Overpressure Isobars (3rd Explosion)	25
9. Overpressure and Impulse versus Range and Equivalent Yield Values versus Bearing (3rd Explosion)	26

LIST OF ILLUSTRATIONS (cont)

<u>Figure</u>	<u>Page</u>
10. Collapsed Doors under Launch Deck	27
11. Thermal Pulse	29
12. Test No. 205 Atlas Centaur Abort	31
13. Lox/RP-1 Tests $\approx$ 300 lb Mixtures	33
14. Shock Hugoniot for Plexiglas	34
15. Impedance Coupling of RP-1/Lox Detonation to Plexiglas	36
16. Impedance Coupling of RP-1/Lox Detonation to Air	37
17. Impedance Coupling of LH_2 /Lox Detonation to Plexiglas	39
18. Impedance Coupling of LH_2 /Lox Detonation to Air	40
19. Test No. 205 Atlas Centaur Abort	42
20. TNT Surface Burst 1000 lbs Hemispherical Charge	44
21. Temperature Data from PAMS Record of March 2, 1965	45
22. Calculated Temperatures for Launch Abort of March 2, 1965 and Comparison with PAMS Record (umbilical)	46
23. Temperature Data from PAMS Record of March 2, 1965	47
A-1. Variation of Overpressure and Dynamic Pressure with Time at Fixed Location	53
A-2. Pressure Sensor Layout	54
A-3. Thermal Sensor Layout	55
A-4. Thermal Pulse and Thermocouple Response	55

LIST OF TABLES

<u>Table</u>	
I. Pressure Gauge Schedule	13
II. Thermal Sensor Schedule	13
III. Pressure Readings for 1st Explosion	20
IV. Pressure Readings for 2nd Explosion	20
V. Pressure Readings for 3rd Explosion	21
VI. Pressure Readings for 4th Explosion	24
VII. Pressure Readings for 5th Explosion	24
VIII. Measured Data from Atlas-Centaur Abort Test No. 205	30

SUMMARY

The purpose of this report is to summarize as completely as possible all the information and analysis concerning the aborted launch of the Surveyor-Mission Atlas-Centaur, March 2, 1965. The information and analyses contained in this report will be used in conjunction with theoretical analysis, empirical data from planned tests, and additional data from field measurements to generate a model of an explosion to be expected from a catastrophic pad-abort. The data in this report are the first contribution of field measurements to the over-all data which are required to complete the explosion model.

The first three sections of this report contain a general discussion of the system with which the measurements were taken, the characteristics of the measurements, and the reduction of these data. The fourth section describes the launch vehicle and presents all the relevant data (meteorological, time, etc.) at launch; it concludes with a sequence of events which starts at first vernier engine ignition and ends 1 hour later. The fifth section describes the instrumentation configuration and system performance during the accident. The sixth section reviews the analysis of the data, and the seventh section presents the conclusions and recommendations based on the results of this accident and on the experience gained in PAMS operation. A description of the Pad Abort Measuring System is given in Appendix A.

Figure 1. Aerial View of Complex 36A, PAMS Sensor Location

LAUNCH HAZARDS ASSESSMENT PROGRAM,
REPORT ON ATLAS/CENTAUR ABORT

Data Acquisition System

The pressure and thermal data contained in this report were acquired by the Pad Abort Measuring System (PAMS) located on Complex 36A at Cape Kennedy Air Force Station. PAMS characteristics can be found in Appendix A. The purpose of the PAMS is to measure the pressure and thermal environment generated by a launch abort occurring on or near a launch pad. Present coverage is as follows:

Pressure Range:	-10 psi to +20,000 psi
Pressure Rise Time:	100 microseconds
Temperature Range:	150 to 5200°F
Thermal Flux:	15 to 800 BTU/ft ² -sec
Thermal Rise Time:	1.0 millisecond to several seconds depending on sensor

The locations of most of the sensors are shown in Figure 1.

Characteristics of Measurements

The measurement philosophy of PAMS is based on defining the pressure and thermal characteristics of the source of energy created by an abort by working back from the measured environment it creates. Eventually data from aborted launches will be compared to the findings of theoretical and experimental studies being conducted by the AF Rocket Propulsion Laboratory under Project Pyro, a NASA/USAF study of the blast hazards of liquid propellants.

A reasonably accurate knowledge of the environmental characteristics of an aborted launch is required for evaluation of engineering materials, assemblies, and systems which might be exposed to the abort environment.

The source of pressure energy has been described by the equivalent yield of the detonation. This yield, which is the amount of high-explosive (usually TNT) which would have generated the observed pressures under similar circumstances, is used as an arbitrary standard. The equivalent yield concept is only the approximation of an actual event, because it is based upon an idealized spherical source of detonation. Many factors tend to modify the applicability of this concept in terms of symmetry, propagation, reflections, propellant mixing, and so forth. The net effect is that the value of the equivalent yield varies as a function of the bearing of the point of observation and, to a lesser degree, as a function of its range (Figure 8) page 25. Its value is also considerably affected by the amount of mixing of the propellant constituents.

Generally speaking, if the mixing is low, the yield will be low, and most of the propellant energy will be released as thermal energy.

The thermal energy source is best described by the resultant thermal flux and its history. The three modes of heat transfer, radiation, convection, and conduction, must be considered in taking measurements to define the thermal flux.

Data Reduction Approach

Pressure data reduction for analysis of the environmental characteristics of an aborted launch can be approached either from the standpoint of "effects analysis" or "phenomena analysis." Both approaches were used in the preparation of this report; PAA Electro-Optics Section's reduction of the pressure data is based on an "effects analysis," while Sandia's method was to apply the same pressure data to analyze both effects and theoretical phenomena.

The Sandia Blast and Earth Motion Division reviewed the "effects analysis" of PAA and agreed that the instrumentation system operation was as outlined in this report.

PAA data reduction approach consists of the following operations:

- (a) Reading the oscillograph strip charts and tabulating the values on all active channels.
- (b) Correlating the readings on separate channels to any particular event and segregating the readings by event (six different explosions were picked up by the PAMS sensors).
- (c) Deriving and tabulating the desired quantities from the measured values. These quantities include: isobars, impulse, yield, shockwave velocities (actual average values, theoretical average, and instantaneous values), and accuracies of the quantities obtained.
- (d) Plotting the significant quantities; determining by iteration actual centers of explosion and any fitting required for improved correlation and consistent interpretation of the measured events.
- (e) Presenting the final interpretation of the observations made and the necessary recommendations.

Item b, particularly in the pressure area, is a rather involved operation because there is no immediately obvious correlation between different channels: shockwave intensity and velocity are a function of the magnitude of the explosion. The explosion is not necessarily symmetrical and both intensity (pressure) and propagation velocity vary with distance and direction; hence, differences between arrival times for different events vary from data channel to data channel. Pseudo-events may also be introduced by reflections. The iterative processes required in Item d are also time consuming. Yet, the rare occurrence of such accidents does not warrant, for economic reasons, the use of computer routines.

The thermal data reduction methods are designed to provide the most useful thermal parameter (heat flux) for further analytical work. Heat fluxes as functions of time may be determined directly from the radiometer and calorimeter readings. Temperature data are obtained from the thermocouple systems which have been designed to provide a check point for the heat flux data.

The data reduction method is as follows. First, the heat flux data obtained from the properly calibrated radiometers and calorimeters are compared for consistency. If there is consistency, confidence that these data are correct is improved. If inconsistencies exist among the various heat flux readings, attempts are made to determine the causes and to obtain reasonably useful information.

Next, numerical descriptions of the thermal characteristics (thermal models) of the fast and slow-response thermocouples are determined. These thermal models are then made a part of a suitable heat transfer computer program which uses the heat flux obtained above as an input parameter. Outputs of this computer program are predicted thermocouple readings: temperatures as a function of time which should result from the input heat flux. These computer outputs are then compared with the corresponding thermocouple data. If reasonable agreement is found between the computer temperature predictions and the actual temperature data, there exists a high degree of confidence that the heat flux data are correct. Differing response time thermocouples are employed to allow a more precise determination of possible errors in the computer programs should satisfactory agreement not result.

General Launch Information

Mission	Boiler Plate Surveyor
Missile Test Number	205
Location	Pad 36A, Cape Kennedy Air Force Station
Data Acquisition System	PAMS
Date	2 March 1965
Launch Time	1325:04 Z (Greenwich Mean Time)
Vehicle Type	Atlas Centaur

Launch Configuration

The Atlas stage has two booster engines rated at 165,000 pounds thrust each, one sustainer engine with 57,000 pounds thrust, and two vernier engines with 1000 pounds thrust each. The lift-off thrust is therefore, 389,000 pounds. The Atlas stage contained 76,923 pounds of RP-1 fuel and 176,995 pounds of liquid oxygen. The Centaur stage contained 5111 pounds of liquid hydrogen (including the hydrogen peroxide constituent) and 25,098 pounds of liquid oxygen. This stage has two RL-10 engines, each of which has a nominal thrust of 15,000 pounds.

Meteorological Data

Ground level temperature	68°F
Relative humidity	93 percent
Wind velocity (blockhouse)	14 knots
Wind direction	175° (out of the south)
Barometric pressure	1009.5 mb
Temperature inversion	None
PAMS recording time	1115 to 1426Z
PAMS test data	1325 to 1425Z

Events

1st vernier ignition	1325: 00.99Z
Sustainer ignition	00.99
2nd vernier ignition	01.05
Booster engines ignition	--
To	1325: 04.194
Lift-off	04.40
1st motion	04.637
Booster fuel pressure drop	05.00
Booster shut-off and pulsation until	05.80
Highest point of travel	06.01
RP-1 fuel line rupture	06.64
RP-1 contacts vernier and deflagrates (1st explosion)	06.92
RP-1 fuel tank splits (2nd explosion)	07.10 ± 0.05
Hydrogen detonates (3rd explosion)	07.472
Centaur stage lands on ground and burns	07.70
Another detonation	09.50 ±
Fireball - smoke transition	18 ± 1
End of major RP-1 fire on launch deck	1328: +
End of residual fire on launch deck (down to 170°F at thermocouple station)	1425: +

Instrumentation Configuration for Atlas-Centaur Launch

Instrumentation Parameters

(a) Pressure

The 12 pressure gauges were laid out as shown in Figure 2 (see also Figure 1).

Table I shows the full-scale pressure setting of each gauge together with its location coordinates (referenced to missile centerline).

Figure 2. Complex 36A, PAMS Pressure and Thermal Sensor Layout

TABLE I
Pressure Gauge Schedule

<u>PG Number</u>	<u>Full-Scale Setting (psi)</u>	<u>S/N</u>	<u>Range (ft)</u>	<u>Bearing (0° = South)</u>
1	10,000	6568	12.9	24° 03 ft
2	3,500	12147	12.7	6° 16 ft
3	750	10035	36.9	4° 27 ft
12	1	10004	75.7	25° 54 ft
4	300	10032	97.2	233° 28 ft
5	100	10783	145.2	147° 11 ft
6	50	10023	201.9	51° 29 ft
7	20	10013	231.1	320° 54 ft
8	10	10018	290.0	233° 50 ft
9	6	12142	476.9	144° 20 ft
10	2	10792	830.1	56° 41 ft
11	1	9997	1260.5	321° 35 ft

(b) Thermal

The twelve thermal sensors were mounted at two locations, six sensors each; each location contained four thermocouples, one radiometer, and one calorimeter (Figures 3 and 4).

One location was on the launch deck: range, 81 feet; elevation, 4 feet above launch deck; bearing, 28° (0° = south). The other location was on top of the umbilical, southeast corner: range, 37 feet; elevation, 150 feet above launch deck; bearing, 345°.

The type of thermal sensors and their full-scale settings are shown in Table II.

TABLE II
Thermal Sensor Schedule

<u>Channel No.</u>	<u>Full-Scale Setting</u>	<u>Sensor Type</u>
1	800 Btu/ft ² -sec	Radiometer
2	800 Btu/ft ² -sec	Radiometer
3	500 Btu/ft ² -sec	Calorimeter
4	500 Btu/ft ² -sec	Calorimeter
5, 10	4000°F	Tungsten-Tungsten/Rhenium Fast-response thermocouple
6, 9	4000°F	Tungsten-Tungsten/Rhenium Slow-response thermocouple
7, 11	2550°F	Chromel-Alumel thermocouple
8, 12	3200°F	Platinum-Platinum/Rhodium thermocouple

NOTE: 1, 3, 5, 6, 7, and 8 are on top of the umbilical; the others are on the launch deck.

Other system characteristics can be found in Appendix A.

Figure 3. PAMS Thermal Instrumentation at Complex 36A

Figure 4. PAMS Thermal Instrumentation at Complex 36A

System Performance

(a) Pressure

In most cases, the signals were clean and well defined although their amplitudes were sometimes too small to allow detailed interpretation. Because the sensitivity of the pressure sensors was set for maximum yield, a few of the sensors (specifically numbers 1 and 2) were not sensitive enough to pick up any intelligible signal; others had fairly small deflections. Typically, the noise level in PAMS is of the order of 1.67 percent of full-scale deflection; the recorded signals ranged from 2 to 10 percent of full scale with a few exceptions where an obvious trend allowed interpretation of data of less than 2 percent of full scale. Pressure gauge number 9, located in the path of the shaped-charge effect, had readings up to 41.5 percent of full scale. Finally, pressure gauge number 12, a high-sensitivity close-in gauge designed to monitor normal launch pressures, was saturated and overstressed by the pressures developed during the "third explosion"; however, this gauge provided excellent information until that time. This information included pressure variations resulting from the pulsations of the boosters (see "Sequence of Events" and Figure 5). The cable from pressure gauge number 4 was destroyed by fire prior to the arrival of the "third explosion" overpressures (Figure 6). Pressure gauge number 8 (same bearing as number 4) appears to have been affected by the thermal pulse resulting from the "second explosion" arriving simultaneously with the overpressure from the "third explosion." The latter was masked by the former; no reliable data could be obtained from this gauge.

Post-test recalibration of all pressure sensors showed no change in their sensitivity greater than 3 percent with the exception of PG number 3, the sensitivity of which changed 6 percent; PG number 7, 17 percent; and PG number 5, 20 percent. Pressure gauges numbers 2 and 12 were permanently damaged. Most gauges had their sensitivity increased by the amounts indicated.

Reasonable agreement exists between PAMS pressure data and data from BRL self-recording blast gauges. Numerous passive indications of pressure levels (broken glass, collapsed walls, and doors) confirm the pressure distribution developed from the PAMS data.

(b) Thermal

Five thermocouple channels gave good data. Two thermocouple channels gave questionable data. One thermocouple was defective and could not be replaced for lack of spares. The two radiometers and the two calorimeters were left disconnected because of a system incompatibility which created spurious oscillations in the thermal channels. The interface problem which is in the DC amplifiers is being worked on by the amplifier manufacturer under the guidance of PAA and Sandia electronics engineers.

Data Analysis (PAA Electro-Optics Section)

Pressure

Figure 5 is a composite hand tracing of the pressure variations at each of the active pressure gauges. The traces are spaced on the ordinate as a function of their distance (range) from nominal ground zero. The approximate time scale of the original oscillogram was 8 inches per second. Actual data reduction was made from oscillograph records run at 40 inches per second for all pressure gauges except 3, 7, and 9 which were run at 160 inches per second.

Figure 5. Pressure Variations at Each Pressure Gauge

Figure 6. Damaged Cable, Pressure Gauge No. 4

Inset A shows the pressure variations at PG number 12 during booster pulsation and shutdown.

Inset B shows a break in PG number 12 trace; this can be reasonably interpreted as another explosion in spite of the excessive stress damage to this gauge during the "third explosion." The amplitude value is probably unreliable.

(a) Tabulated Raw and Reduced Data

The pressure readings have been segregated into five tables according to which explosion gave rise to the pressures observed. Only those gauges which gave any readings for a particular explosion are listed in each table. The unlisted gauges may be considered as damaged or not sensitive enough to have been activated.

The second column is for the range (or distance) of each gauge from nominal ground zero. A number is sometimes shown in parentheses below the nominal range and is equal to the actual slant-range to the center of explosion as derived from arrival times or as observed on photographic documents.

The overpressure accuracy in the fifth column is the reading accuracy equal to plus or minus one tenth of a minor division (1 minor division = 0.1 inch) on the oscillograph records for values above noise level (which is approximately plus or minus one quarter of a minor division).

The impulse (ninth column) is equal to the area under the pressure pulse.

The normalized range $(Z)^1$ (tenth column) is read off the curve shown in Figure 7 once the peak overpressure is known. The eleventh column is the value of the actual range at which the peak overpressure was observed divided by Z . The third power of this value is the equivalent yield or weight of TNT, the detonation of which would have generated the observed pressure at the given range.

The last three columns are related to shockwave velocity. The "PG number" column defines the two gauges between which the average velocity was computed by dividing the distance between the gauges by the difference in arrival times of the shockwave at the two gauges.

The value of the computed average velocity is shown in the fourteenth column.

The theoretical instantaneous velocity¹ presented in the fifteenth column is based on the weight of TNT at the normalized range (column twelve) and has no measured counterpart.

Table III gives the values observed in connection with the "1st explosion." This explosion was caused by RP-1 fuel spilling and igniting upon contact with one of the vernier engines. The explosion has the character of a deflagration since shockwave velocities are barely supersonic.

The explosion center is estimated to be 5 feet off missile centerline in a northwesterly direction and approximately 10 feet above the launch deck.

Table IV is concerned with the "2nd explosion" which was again a deflagration even milder than the first one. It was set off when the first-stage fuel tanks were engulfed by the flames of the first explosion. Only PG number 12 recorded any readable values.

Table V lists the values observed during the third and major explosion, a true detonation, which occurred when the hydrogen ignited.

TABLE III
Pressure Readings for 1st Explosion

1 Press. Gauge #	2 Range (ft) () = Range Adjusted to Ground 0	3 Bearing (0° = South)	4 Pressure			7 Arrival Time 1325: (Z)	8 Duration msec	9 Impulse psi-msec	10 Normalized Range Z ft/lb ^{1/3}	11 W ^{1/3} (r/Z)	12 Yield W lb TNT	13 Shockwave Velocity (ft/sec)		
			psi	Accuracy ±psi	Noise Level ±psi							Press. Gauge	Actual Average Value	Theoretical Instantaneous Value
12	75.7 (80)	25° 54'	0.3 -0.1	0.007	0.017	06.990 7.011	20 16	3 -0.8	80	1.0	1.0	0-12	1170	1138
7	231.1 (236)	320° 54'	0.7 -0.3	0.13	0.33	07.139	23	8.1 -7.5	42	(5.6)	176	0-7 12-7	1080 1070	1151
9	476.9 (472)	144° 20'	0.4 -0.2	0.04	0.1	07.336 0.3585	22.5 21.5	4.7 -1.8	64	(7.4)	406	0-9 12-9	1132 1130	1141
10	830.1	56° 41'	0.13	0.02	0.05	07.668	32	4.2	145	5.74	190	0-10 12-10	1110 1102	1133
11	1260.5 (1266)	321° 35'	0.04	0.007	0.017	08.055	33	0.13	330	(4.84)	53	0-11 12-11 7-11	1115 1115 1122	1130

TABLE IV
Pressure Readings for 2nd Explosion

1 Press. Gauge #	2 Range (ft) () = Range Adjusted to Ground 0	3 Bearing (0° = South)	4 Pressure			7 Arrival Time 1325: (Z)	8 Duration msec	9 Impulse psi-msec	10 Normalized Range Z ft/lb ^{1/3}	11 W ^{1/3} (r/Z)	12 Yield W lb TNT	13 Shockwave Velocity (ft/sec)		
			psi	Accuracy ±psi	Noise Level ±psi							Press. Gauge	Actual Average Value	Theoretical Instantaneous Value
12	75.7	25° 54'	0.27 -0.1	0.007	0.017	07.1615 0.1730	12 19	1.6 -1.0	86	0.88	0.68	0-12	1230	1137

TABLE V
Pressure Readings for 3rd Explosion

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Press. Gauge #	Range (ft) () = Range Adjusted to Ground 0	Bearing (0° = South)	Pressure			Arrival Time 1325: (Z)	Duration msec	Impulse psi-msec	Normalized Range Z-ft/lb ^{1/3}	W ^{1/3} (r/Z)	Yield W lb TNT	Shockwave Velocity (ft/sec)		
			psi	Accuracy ±psi	Noise Level ±psi							Press. Gauge	Actual Average Value	Theoretical Instantaneous Value
3	36.9 (62)	4° 27'	-10 96 33* -10 101 ⁽¹⁾ 35*	5.1	12.7	07.4765 0.5035	15.0 1.0	-75 48 17* -1	2.8 4.2*	13.2 (14.8)*	2300 (3250)	0-3	2000	1930
12	75.7	25° 54'	0.1 -0.1 0.1 1.87 ⁽²⁾	0.007	0.017	0.4895 0.4915 0.4940 0.4970	2.0 2.5 1.2 (2)	0.05 -0.1 0.06	175 175 (2)	0.43 0.43	0.08 0.08	3-12	1860	1480 ⁽²⁾
5	145.2	147° 11'	4.5 -1.5 (a)	0.6	1.5	0.5440 0.5750	31.0 29.0	70 -22	11.5	12.7	2080	0-5 3-5	2000 1610	1268
6	201.9	51° 29'	3.74 (b) (superimposed on a) 1.15 (a) 2.25 (b) (superimposed on a) 1.73	0.34	0.85	0.6035 0.6115	44 2	83.5	12.5	16.1	4200	0.6	1530	1245
7	231.1	320° 54'	1.0 0.13 (a) 0.33 (b) (superimposed on a) 1.73	0.13	0.33	0.6360 0.6525	29 4.5	36.5	17.5	13.2	2300	0-7 3-7	1410 1460	1201
8	290.0	233° 50'	1.0 0.07 (a) 0.17 (b) (superimposed on a) 1.73	0.07	0.17	0.660 0.6525	Noisy (Pulse masked by thermal pulse from 2nd explosion.)		32	9.06	742	6-8	1540	1161
9	476.9	144° 20'	2.6 -0.13 0.92 -0.3	0.04	0.10	07.8175 0.8183 0.8188 0.8720	0.8+54.5 0.25 2.0 65.0	30.1	16 34	29.8 14	26500 2750	0-9	1380	1211
10	830.1	56° 41'	0.56 -0.06	0.02	0.05	08.1480 0.2020	53 25	14.8 -0.75	49	16.9	4850	0-10	1225	1147
11	1260.5	321° 35'	0.17 -0.054	0.007	0.017	0.5420 0.6410	99 110	8.5 -3.0	118	10.7	1240	0-11	1180	1134

NOTE: *Value corrected for face-on effect. (1) Probable reflection off umbilical tower. (2) Gauge Overstressed: No valid overpressure data at this point and beyond.

Figure 7. Peak Overpressure versus Normalized Range

The center of explosion was estimated to be on the missile centerline about 50 feet above the launch deck. Because of this geometry, the close-in gauges (number 3 was only one that gave readings) were subjected to face-on rather than side-on pressures. Face-on pressures take into account the interaction between the shockfront and the structure, while side-on pressures are independent of such interaction and are thus directly comparable to one another. Therefore, the pressure readings for PG number 3 were corrected for the face-on effect, and the corresponding side-on values are shown marked by an * below the observed values. The second reading shown is probably a reflection from the umbilical. This double pulse also appears on PG numbers 7 and 9.

PG number 12 shows the fine structure of the shockfront just prior to being overstressed.

Table VI is for an explosion picked up by pressure gauges numbers 3, 7, and 10 approximately 30 milliseconds after the third explosion.

Another explosion and possibly its reflection were picked up by PG number 3 at 23 milliseconds after the fourth explosion (Table VII).

Finally the explosion picked up by PG number 12 and shown on the composite trace (Figure 5) about 2-1/2 seconds after the abort started was not tabulated because amplitude readings on PG number 12 are not considered reliable at this point in time.

(b) Plotted Reduced Data

Figure 8 gives a representative over-all effect of the third and most powerful explosion. The lines of equal pressure represent the maximum peak overpressure levels reached in the vicinity of the launch pad as a result of the third explosion. These isobars were derived by interpolation from the pressures recorded by the pressure gauges. The yields noted on the isobar graph are fairly consistent along each of the four radii on which the gauges are located (see Figure 9) with the higher yields in the southwesterly and northwesterly directions. The pressure distributions were verified by passive indications such as broken glass, collapsed doors, and damaged masonry work² (Figures 8 and 10). The shaped-charge effect observed in the northwesterly direction is attributed to the missile splitting in that direction, atmospheric heating, and to a reflection from the umbilical tower.

Figure 9 shows the plots of overpressure and impulse values versus range along the four gauge axes for the third explosion. Each of the overpressure curves is annotated with the corresponding values of equivalent yield. The yield values shown in parentheses are the ones calculated, assuming a surface burst instead of an air burst. Stated differently, had the same force explosion occurred on the ground instead of at some height, the observed overpressures would have been approximately 60 percent higher.

The explosion pattern was asymmetrical, ranging from 1100 pounds TNT equivalent to 4800 pounds clockwise from northeast to southwest with a shaped charge effect to the northwest with an equivalent yield of 25,000 pounds of TNT.

Seismic

A letter from the U. S. Coast and Geodetic Survey to PAA Facilities Engineering stated that no seismic signals resulting from the abort were detected by the seismic station at Cape Kennedy.

The absence of ground movement is another confirmation of the low-yield character of the explosion.

TABLE VI
Pressure Readings for 4th Explosion

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Press. Gauge #	Range (ft) () = Range Adjusted to Ground 0	Bearing (0° = South)	Pressure			Arrival Time 1325: (Z)	Duration msec	Impulse psi-msec	Normalized Range Z ft/lb ^{1/3}	W ^{1/3} (r/Z)	Yield W lb TNT	Shockwave Velocity (ft/sec)		
			psi	Accuracy ±psi	Noise Level ±psi							Press. Gauge	Actual Average Value	Theoretical Instantaneous Value
3	36.9 (50)	4° 27'	81 36*	5.1	12.7	07.5370	1.0	40 18*	30 4.1*	12.3 (12.2)*	1860 (1820)*			2700 1986*
7	231.1	320° 54'	0.8 -0.4	0.13	0.33	0.6645 0.6665	2.0	0.8 -3.2	38	6.07	225	3-7	1515	1154
10	830.1	56° 41'	0.16	0.02	0.05	08.2280	6.0	0.5	125	6.65	295	3-10	1150	1134

*NOTE: Value corrected for face-on effect.

TABLE VII
Pressure Readings for 4th Explosion

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Press. Gauge #	Range (ft) () = Range Adjusted to Ground 0	Bearing (0° = South)	Pressure			Arrival Time 1325: (Z)	Duration msec	Impulse psi-msec	Normalized Range Z ft/lb ^{1/3}	W ^{1/3} (r/Z)	Yield W lb TNT	Shockwave Velocity (ft/sec)		
			psi	Accuracy ±psi	Noise Level ±psi							Press. Gauge	Actual Average Value	Theoretical Instantaneous Value
3	36.9	4° 27'	34 61 -10	5.1 5.1	12.7 12.7	07.5605 0.5625	1.0 1.0 0.25	17 30 -1	4.2 3.3	8.8 11.2	685 1410			1949 2409

Figure 8. Peak Overpressure Isobars (3rd Explosion)

Figure 9. Overpressure and Impulse versus Range and Equivalent Yield Values versus Bearing (3rd Explosion)

Figure 10. Collapsed Doors under Launch Deck

Thermal

Figure 11 is a composite plot of the temperatures observed on the launch deck and at the top of the umbilical. It can be noted that channels 6 and 9 have similar shapes with the exception of time duration; the channels were recorded with medium-response thermocouples which had the same delay characteristics and which were located on the launch deck and at the top of the umbilical. It is concluded that the thermal histories at both locations were very similar except for duration.

The initial millisecond of the actual temperature trend is reproduced in real time by channel 5, which was obtained from the fast-response thermocouple located at the top of the umbilical. There was no similar thermocouple on the launch deck.

Channel 12 was recorded on the launch deck by a slow-response platinum-platinum/rhodium thermocouple with a maximum temperature range of 3200°F. This channel remained saturated at 3200°F for 50 seconds after which it showed gradually decreasing temperatures for 1 hour; at that time it registered 170°F. The validity of the data is questionable since it is doubtful that temperatures remained above 2000°F for more than a few seconds. The heat transfer characteristics of the sheath shielding the thermocouple which gave channel 9 is such that the actual peak temperature reached on the launch deck was not registered. The temperature recorded after the initial peak was representative of temperatures at that time.

The fireball size was determined from motion picture records. It was an ellipsoid with a 300-foot minor axis, 800-foot major axis, and a 450-foot height.

Data Analysis (Sandia Engineering Dynamics Division)

Pressure (D. M. Webb)

The motion pictures show that the first explosion occurred immediately upon the missile's impact with the launch pad. The explosion represented an increase in the combustion, apparently due to propellant spillage, rather than a high order detonation. The second explosion occurred somewhere above the base of the missile and was a high order detonation. Judging from the time sequence of the pressure pulses, this detonation occurred about 1325:07.485, which corresponds approximately to the time PAA specifies for the third explosion. This high order detonation is considered by this author to have originated from the RP-1/Lox mixture. Following this detonation was another high order detonation that propagated into the expanding fireball.

The multiple explosions and detonations complicated interpretation of the measured pressure data. A means had to be devised to determine which measurements represented the principal shock wave. A tabulation of the peak pressures as measured is shown in Table VIII. First of all, the pressures shown in Table VIII labeled as having a long rise time can be discounted since they are not true shock waves but rather were pressure waves resulting from a subsonic flow situation in a high-temperature environment. These subsonic pressure pulses may have been generated by the detonation of the liquid hydrogen. Apparently the principal air blast came from the detonation of the RP-1 rather than the LH_2 although the LH_2 detonation was probably slightly more intense. Detonation properties of the two propellants will be covered in more detail later in the report.

Figure 11. Thermal Pulse

The measurement of gauge Number 12 can also be discounted. This gauge, which was designed to measure low pressure from a successful launch, was overdriven by the strong shocks. Gauges 1 and 2 were insensitive to these pressures, and 4 failed completely. From the author's point of view, nonrepresentative measurements can more easily be detected by plotting shock front velocity minus the local speed of sound versus distance from the detonation. Hence, the shock velocity was computed from the measured pressures using the usual Hugoniot equations. A plot of the data in this form is shown in Figure 12. The data plotted as "x" were considered the result of a shock wave; the data plotted as "⊗" were considered the result of a subsonic compression wave. The considered representative points were joined by a solid curve. The point at 36.9 feet was not considered because of its significant departure from the trend of the other points, and, because it was near the detonation point, it probably measured some reflected pressure instead of pure free-stream overpressure. The first peak from gauge number 7 also did not fall on the curve and was discounted because it did not seem to follow the general trend. No justification for the existence of this peak can be found. The measurement of gauge number 9 was slightly above the curve. Instrumentation accuracy is considered the reason for the deviation on this measurement. The data, of course, lend themselves to several possibilities of joining the points, but the curve chosen seems the most plausible. The general shape and slope of the curve was verified by plotting data from a controlled Lox/RP-1 test³ in the same format as Figure 12. This plot is shown in Figure 13. The shape of the curves even for different mixture ratios are essentially the same. One final point further establishes validity of the curve in Figure 12. If the measurement of gauge number 3 at 36.9 feet had been considered representative, then the slope of the curve upon extrapolating to the missile interface would imply that the detonating properties of the Lox/RP-1 were similar to TNT. Such is not the case, as will be shown in the analysis that follows.

TABLE VIII

Measured Data from Atlas-Centaur Abort
Test No. 205

<u>Gauge No.</u>	<u>Horizontal Range (ft)</u>	<u>Azimuth</u>	<u>Time (Z)</u>	<u>Overpressure (psi)</u>
1.2 (insensitive)				
4 (failed)				
3	36.9	4° 27'	1325:07.503	50
12	75.7	25° 54'	1325:06.93	0.35
			1325:07.163	0.20
			1325:07.498	1.65 (saturated)
			1325:07.530	1.0
5	145.2	145° 11'	1325:07.544	5.0
6	201.9	51° 29'	1325:07.604	3.5
			1325:07.611	3.0 (long rise time)
7	321.1	320° 54'	1325:07.634	2.2
			1325:07.651	3.0
			1325:07.692	1.5 (long rise time)
8	290	233° 50'	1325:07.626	0.75 (long rise time)
9	476.9	144° 20'	1325:07.820	1.5
10	830.1	56° 41'	1325:08.148	0.50
11	1260.5	321° 35'	1325:08.54	0.15

Figure 12. Test No. 205 Atlas Centaur Abort

Figure 12 shows the curve extrapolated to a range of 5 feet, which is actually the radius of the missile. This represents the interface between the propellant detonation and the induced air shock. Air shock over-pressures reach a maximum at this point, with the exception of reflected pressures. Therefore, the determination of this point is an important one. The impedance match or the induced air pressure may be computed, provided the detonation properties of the propellant are known. Melvin A. Cook of the Inter-mountain Research and Engineering Company has performed tests to determine these properties.⁴ Using plexiglas as an interface material and measuring shock front and detonation front velocities with streak camera techniques, the detonation pressure of the propellant could be computed. The results of Cook's tests are given below:

Propellant Mixture	U_g (mm/ μ sec)	P_g (kb)	D (mm/ μ sec)	P_P (kb)
LH ₂ /Lox	3.4	20	2.3	8
RP-1/Lox	3.1	13	2.24	11

U_g = shock velocity in plexiglas

P_g = pressure induced in plexiglas

D = detonation velocity of propellant mixture

P_P = detonation pressure of propellant mixture

The propellant mixtures were given as a mole ratio of two for LH₂/Lox and a 22/78 (weight) ratio for the RP-1/Lox. Mixture densities were given as 0.40 gm/cc for the LH₂/Lox and 1.04 gm/cc for the RP-1/Lox. The report qualified the above values by stating that there was a possibility of some deviation from the given mixture composition ratios and densities.

Evaluation of Cook's results revealed a major error in his analysis causing all of the computed detonation properties to be incorrect. Unfortunately, the error was caused primarily by an incorrect Hugoniot for plexiglas. Recent work by R. A. Graham⁵ of Sandia Corporation results in a well-defined plexiglas Hugoniot in the low-kilobar region, ≈ 3 to 20 kilobars. A plot of Graham's data is shown in Figure 14. The Hugoniot curve of plexiglas may be compared to the calibration of a pressure gauge. The Hugoniot equation of state is simply:

$$P = \rho_o u U$$

P = shock pressure

ρ_o = undisturbed density

u = shock particle velocity

U = shock front velocity or
detonation velocity

In order to determine pressure, it is necessary to measure only one parameter, either shock (detonation) velocity or particle velocity, when the Hugoniot of a medium is known. Reference 4 chose to measure shock velocity in the plexiglas and detonation velocity of the propellant mixture. Knowledge

Figure 13. Lox/RP-1 Tests $\approx$ 300 lb Mixtures

Figure 14. Shock Hugoniot for Plexiglas

of these two velocities permits the computation of the plexiglas pressure and the pressure of the detonating shock wave. The measured shock velocity in plexiglas resulting from the detonation of RP-1/Lox was 3.1 mm/ μ sec. The detonation velocity of this propellant was 2.24 mm/ μ sec. The Hugoniot of the plexiglas shows a pressure of 8.85 kilobars, which is the interface pressure of the plexiglas and RP-1/Lox. Both pressure and particle velocity across this interface are constant at the instant of contact. The interface pressure is not detonation pressure. The Hugoniot of the propellant is not known, but the slope of the Hugoniot is known, which is $\rho_o D$ (see Figure 15). Because the impedance match across an interface is simply the intersection of the Hugoniot with the isentrope of the impeding material, the isentrope can be approximated by reflecting the Hugoniot (the negative slope).⁶ The approximated isentrope shown in Figure 15 is drawn from the plexiglas-RP-1/Lox interface until it intercepts the positive slope of the propellant Hugoniot. This intersection represents only one point on the RP-1/Lox Hugoniot and is the detonation pressure or the Chapman-Jouguet (C-J) pressure. Once this C-J pressure is determined, then other means may be used to determine the propellant's isentrope. The impedance match between the detonating propellant and air is again a function of the detonating velocity and pressure. This interface condition is also determined by the Hugoniot-isentrope intersection. The Hugoniot of air is well known, so this presents no problem. The reflected Hugoniot of the propellant will not suffice for this situation, because the isentrope cannot be considered linear for this large a pressure differential. W. E. Deal, LASL, has developed an equation for computing the isentrope of a detonating medium:⁷

$$u_p = \left[\frac{P_{cj}}{\rho_o \alpha D_p} \right] \left[1 + \alpha - \left(\frac{P}{P_{cj}} \right)^\alpha \right]$$

$$\alpha = \frac{\gamma-1}{2\gamma}$$

The particle velocity, u_p , was computed as a function of pressure, P , and is plotted in Figure 16. Also shown in Figure 16 is a plot of the air Hugoniot. The intersection of these two curves gives the pressure induced into the air which should theoretically be the pressure at the outer radius of the missile. This, of course, assumes that the missile skin is thin. The detonation properties of the RP-1/Lox and its effects are summarized below.

Detonation of RP-1/Lox

Detonation velocity = 2.24 mm/ μ sec
 Detonation pressure = 7.2 kilobars
 Initial density = 1.04 gm/cc

Plexiglas Interface

Induced velocity = 3.1 mm/ μ sec
 Induced pressure = 8.85 kilobars
 Initial density = 1.18 gm/cc

Figure 15. Impedance Coupling of RP-1/Lox Detonation to Plexiglas

Figure 16. Impedance Coupling of RP-1/Lox Detonation to Air

Air Interface

Induced velocity	= 1.285 mm/ μ sec = 4210 ft/sec
Induced pressure	= 16.8 bars (ΔP = 229 psi)
Initial density	= 1.225×10^3 gm/cc

The air interface shock condition at the missile radius is shown in Figure 12 as a function of shock velocity minus sound speed. This solution does no more than approximate the missile abort situation.

The LH_2 /Lox will now be analyzed in the same manner as the RP-1/Lox to determine its explosive potential. Cook performed the same tests on liquid hydrogen as on the RP-1, but with less success. Many shots were fired, but only one shot gave any readable data. The results were marred by the existence of multiple shocks induced into the plexiglas pressure gauge and the delayed initiation of the LH_2 /Lox mixture. Cook observed three shocks in the plexiglas: 2.7, 3.3, and 3.4 mm/ μ sec. This author noted several shocks, but only one was clearly definitive, 3.03 mm/ μ sec. The velocity of 3.4 mm/ μ sec which Cook claimed was induced in the plexiglas by the detonating LH_2 /Lox does not seem logical from the point of view of the quoted low density of the mixture. Furthermore, it was not possible to analytically obtain an impedance match from Cook's results. Using a shock velocity in the plexiglas of 3.03 mm/ μ sec and a detonation velocity of 2.3 mm/ μ sec, a solution could be obtained when a LH_2 /Lox mixture density of 0.61 gm/cc was assumed. This solution is shown in Figure 17. The pressure at the plexiglas- LH_2 /Lox interface was about 8.2 kilobars, and the detonation pressure was about 5.55 kilobars. Computing the isentrope by the method of Reference 7, a solution was found for the air- LH_2 /Lox interface (Figure 18). The induced air shock pressure was 25.5 bars, or an overpressure of 355 psi. A summary of the LH_2 /Lox detonation properties and its effects are shown below.

Detonation of LH_2 /Lox

Detonation velocity	= 2.3 mm/ μ sec
Detonation pressure	= 5.55 kb
Initial density	= 0.61 gm/cc (assumed)

Plexiglas Interface

Induced velocity	= 3.03 mm/ μ sec
Induced pressure	= 8.2 kb
Initial density	= 1.18 gm/cc

Air Interface

Induced velocity	= 1.58 mm/ μ sec = 5180 ft/sec
Induced pressure	= 25.5 bars (ΔP = 355 psi)
Initial density	= 1.225×10^{-3} gm/cc

The computed LH_2 /Lox-air interface shock condition at the missile radius is shown in Figure 12 as a function of shock velocity minus the sound speed. Here again, this solution must be accepted only as a rough approximation of the conditions of the actual missile abort.

Figure 17. Impedance Coupling of LH₂/Lox Detonation to Plexiglas

Figure 18. Impedance Coupling of LH_2/Lox Detonation to Air

The conclusion stated earlier in this report was that the principal blast was produced by the RP-1/Lox propellant. The theoretical analysis shows that the LH_2/Lox has a slightly greater explosive potential. Even if the theoretical analysis is acceptable as being representative of the abort conditions, a comparison of the quantity of propellants involved would indicate the total blast potential. The propellant quantities of the Atlas and Centaur are shown below.

<u>Atlas - 1st Stage</u>	
RP-1	76,923 lbs
Lox	<u>176,995 lbs</u>
Total	253,918 lbs
<u>Centaur - 2nd Stage</u>	
LH_2	5,110 lbs
Lox	<u>25,098 lbs</u>
Total	30,208 lbs

The quantity of the charge is indicative of the blast propagation characteristics, not the detonation characteristics. As shown above, the Atlas had about eight times the total propellant as the Centaur. Films taken of the abort showed that the Atlas was first to rupture and first to burn and that it appeared to detonate shortly after rupture. The films also showed a strong shock propagating from the missile before the fireball had grown to an estimated 50 feet. This shock did not appear to originate 60 to 70 feet above the pad. When the fireball had grown to about 200 feet (estimated), another detonation occurred. This author thinks this was the detonation of the LH_2/Lox . The propagation from this detonation showed up as subsonic pressure waves at stations 5, 6, and 7. The waves were subsonic because of the high sound speed in the fireball.

From the shock propagation characteristics established in Figure 12, a plot of overpressure versus distance was made. This plot is shown in Figure 19, and is considered by this author to be the best representation of the most significant blast propagation resulting from the Atlas-Centaur abort.

Ever since missiles have been blowing up, comparisons have been made between TNT explosions and propellant explosions. Percentage equivalences have frequently been quoted. To clearly show the shock propagating characteristics of TNT, a plot similar to Figure 12 was made. Figure 20 shows a plot of shock velocity minus sound speed versus distance from the surface burst of 1000 pounds of TNT. Comparing Figure 20 with Figure 12 shows that the propagating characteristics from a propellant detonation (RP-1/Lox) bear no equivalence to TNT at any range.

This analysis may be summarized as follows:

1. The principal blast wave originated from the detonation of the RP-1/Lox propellant,
2. The principal blast wave originated before the fireball had grown to an estimated 50 foot radius,
3. There were no detectable gross asymmetries of the principal blast wave,
4. There probably were blast asymmetries from the detonation that occurred when the fireball had expanded to about 200 feet, and
5. There is no equivalence between the blast propagating characteristics of an RP-1/Lox detonation and a TNT hemispherical charge detonation.

Figure 19. Test No. 205 Atlas Centaur Abort

Thermal (B. E. Bader)

Since it was necessary to disconnect the radiometer and calorimeter channels to eliminate the "noise" in the thermal instrumentation, no direct heat flux data were obtained. Therefore, it was necessary to base all analyses upon data from the four umbilical tower thermocouples and the single launch pad thermocouple which operated satisfactorily.

To check the consistency of the data obtained from the four umbilical tower thermocouples (Figure 21) it was assumed that the data from the fastest response thermocouple (channel 5) represented the effective radiating temperature of the gas. The data from channel 5 were then used as the input to thermal models of the other three thermocouples; an analog computer was used to determine the theoretical responses of these three thermocouples. The computer results are compared with the measured data of Figure 22 which also illustrates the consistency of the data.

Unfortunately, it was not possible to perform this same type of analysis for the launch deck station, because the acquisition of just one temperature channel (Figure 23) eliminated the possibility of obtaining quantitative comparisons. However, a qualitative judgment of this sole launch deck temperature channel indicates these data are reasonable. No direct comparison of the launch deck and umbilical tower temperatures is possible without accompanying heat flux information, because the environments are considerably different at these widely spaced locations. For example, with the dissipation of the fireball, the umbilical tower temperatures rapidly decrease; whereas, the launch deck temperatures remain at relatively high values because of the residual burning of the spilled fuel on the deck.

Finally, it is possible to estimate the peak heat flux from the fireball by once again assuming that temperature channel 5 represents the effective radiating temperature within the fireball. If this is done, a calculation yields a peak heat flux of approximately $425 \text{ BTU/ft}^2 \text{ sec}$.

Conclusions

Test Results

The abort which occurred during this attempted launch can be characterized as producing a relatively low explosive yield in proportion to the total propellant load with a high yield of thermal energy for a short time.

The principal blast wave generated in this accident originated from the RP-1/Lox propellant before the fireball had grown to an estimated 50-foot radius. There were no gross asymmetries of the principal blast wave, but asymmetries were introduced to the explosion pattern when the fireball had expanded to about 200 feet. No true equivalence exists between the propagation of the blast from liquid propellants and a TNT hemispherical charge detonation. The analysis of the data from this accident and reports⁹ from Project Pyro clearly show that the shock propagating characteristics of the liquid propellants are not truly equivalent to TNT.

Because of the lack of radiometric data, the evaluation of the thermal yield of this abort depends on a qualitative analysis of the thermocouple data. Temperatures in excess of 5200°F were generated at the

Figure 20. TNT Surface Burst 1000 lbs Hemispherical Charge

Umbilical Station

Figure 21. Temperature Data from PAMS Record of March 2, 1965

Figure 22. Calculated Temperatures for Launch Abort of March 2, 1965 and Comparison with PAMS Record (umbilical)

Figure 23. Temperature Data from PAMS Record of March 2, 1965

umbilical tower sensor station; and probably throughout the fireball for the 1- to 3-second duration of its maximum intensity. The good correlation among those thermocouples which were operating properly (Figures 21 and 23) gives confidence of a reasonably good description of the time-temperature relationship.

System Performance

The PAMS acquired abort data which were marginal in quantity of thermal measurements but the quality of both pressure and thermal measurements were good. The low sensitivity setting did not significantly interfere with the quality of the readings because of the good resolution of the system. The data were adequate for a reasonably good description of the abort environment.

System Sensitivity

Since the occurrence of this abort, the sensitivity of the pressure measurements has been increased by reducing the full-scale setting on each gauge (see Table I).

Plans have been made to increase the sensitivity of the thermocouple measurements by replacing those thermocouples which have protective sheaths with thermocouples whose sheaths will have a thinner cross-section.

System Operation and Maintenance

Operational shortcomings of PAMS have become apparent during its use at ETR. This is to be expected since it is the first application of these systems to the measurement of pad abort environments. Previous use of these systems, especially the pressure measuring system, was for measuring high-explosive or nuclear tests for which a better prediction of expected ranges of overpressure and thermal energy could be made.

Required functional improvements, which have become apparent from PAMS operation, are thermal sensor mount redesign, DC amplifier improvement, and incorporation of more pressure transducer stations. Present design of the thermal sensor mounts was made at the time when so little was known about the propellant explosions or fires that an over-design resulted. Now that experience and knowledge have been gained, these mounts can be redesigned for maximum ease of operation and minimum installation time. The performance of the DC amplifiers has been poor, but PAA and Sandia electronic engineers are modifying these units to improve amplifier performance. Two pressure transducers should be added to the system for measurements at or near the payload level on the umbilical tower, or, if this is not practical, the present pressure station layout should be modified to accomplish these measurements.

Data Reduction

Reading the quantities of interest from the oscillograph records presents no difficulties. These quantities are: significant pressure variations, peak overpressures, pressure rise time and duration, impulse (area under the pressure pulse), negative pressure phase amplitude and duration, temperature, and thermal flux variation versus time.

Time correlation between the pressure pulses registered by the different gauges and derivation of actual centers of explosion require knowledge of shock wave propagation and decay characteristics. The iterative processes needed to refine the computations may take appreciable time. Correlation of events becomes involved if there is a series of explosions. A considerable amount of time is needed to carry out proper data reduction and interpretation. However, it is felt, at this time, that manual reduction is more practical than a computerized routine.

APPENDIX A
PAD ABORT MEASURING SYSTEM DESCRIPTION

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APPENDIX A. PAD ABORT MEASURING SYSTEM DESCRIPTION

Pad Abort Measuring System, Description

The pad-abort measuring system consists of contact-type sensors and a recording ground station. The sensors are located so that they will be in contact with or in the immediate vicinity of the abort environment if the abort occurs on or near the launch pad. The connection between sensors and the ground station is by hard-wire. The ground station is located in the corresponding blockhouse.

Pressure Sensors

The pressure phenomena (Figure A-1) are monitored by an array of pressure sensors.

Figure A-1. Variation of Overpressure and Dynamic Pressure with Time at Fixed Location

The layout of the array is based on a spacing scheme designed to provide independent readings and on considerations of expected lack of symmetry in the pressure distribution, both in range and in azimuth. The result is a spiral centered about the launch pad, with sensors located at the intersection of the spiral and two perpendicular axes drawn through the launch pad (Figure A-2).

Figure A-2. Pressure Sensor Layout

The high-pressure sensors are close to the expected location of the source, and the most sensitive sensor is near the perimeter of the complex. There are 11 sensors with a maximum range varying between 20,000 and 1 psi and an additional 1-psi sensor on the launch stand to measure normal launch overpressures. The pressure sensors are bridge-type variable reluctance transducers, driven by a 3-kc carrier. The output is an AM signal, with a zero amplitude when the bridge is balanced and an amplitude proportional to pressure when the arm of the bridge coupled to the sensing diaphragm is unbalanced by an overpressure.

Thermal Sensors

Temperatures are sensed by four thermocouples of different characteristics. Thermal energy (the total heat power) is sensed by a radiometer and a calorimeter. There are two assemblies, each made up of four thermocouples, a radiometer, and a calorimeter (Figure A-3). One assembly is at the base of the umbilical tower; the other one is mounted on the umbilical to extend data acquisition time as the fireball rises. Depending on the exact location of the source and on the particular point in time, the thermal assemblies may or may not be enveloped in the fireball. To ensure survival of the instrumentation and cabling, the base of the sensors and the cable are water cooled. The four thermocouples have different characteristics (Figure A-4). The most sensitive of the thermocouples, a tungsten-tungsten-rhenium thermocouple in a thin tantalum case, can follow the steep rise of the expected thermal pulse (its time constant is 10 milliseconds) but is expected to disintegrate short of its maximum temperature range of 5400°F. A tungsten-tungsten-rhenium thermocouple encased in siliconized molybdenum for greater protection will have a slower response but will survive longer; this thermocouple is expected to follow the peak and some of the decay of the pulse. Slow-response but high-survivability platinum-platinum-rhodium and chromel-alumel thermocouples, housed in a stainless-steel case, measure the end of the decay and the steady state temperature. The temperature ranges of these thermocouples are 3300°F and 2650°F, respectively.

Figure A-3. Thermal Sensor Layout

Figure A-4. Thermal Pulse and Thermocouple Response

A Naval Radiological Laboratory radiometer senses thermal radiant energy up to $800 \text{ BTU/ft}^2/\text{sec}$, while a calorimeter picks up both radiant and convective energy of the order of $500 \text{ BTU/ft}^2/\text{sec}$. The partially redundant characteristics of the sensors are a result of their different degrees of survivability and their overlapping ranges for continuous coverage. The signals from the sensors are low-level DC; they are amplified by DC amplifiers located immediately below the launch stand before being fed to the ground station tape recorder.

Calibration

Predetermined simulated pressure and temperature signals can be remotely applied to the system at the location of each sensor so that the whole system can be calibrated at once from sensor to recording tape.

Running Time

Because the nature of the phenomena is unpredictable, the requirement of recording the event from its very significant beginning has been solved by starting recording before the inception of any hazardous sequence and continuing recording for up to 3 hours. After 3 hours, a quick change of tape reels gives an additional 3 hours. The process can be repeated as many times as required. Thus the lengthiest operations, including any likely holds, can be monitored.

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