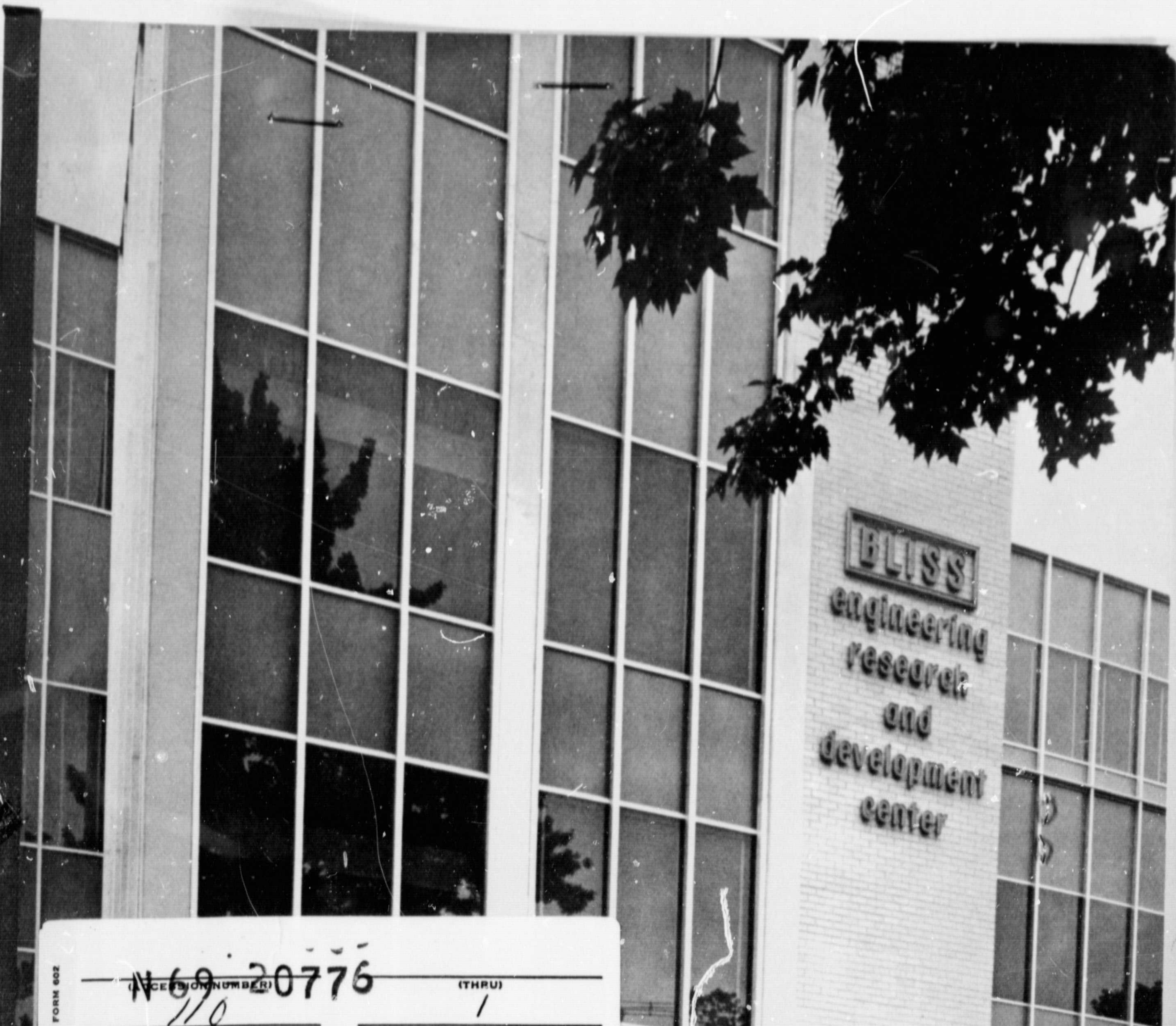

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EVALUATION OF HIGH EXPANSION FOAM FOR SPACECRAFT FIRE EXTINGUISHMENT

CONTRACT NAS 9-7983

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INTRODUCTION

There are many problems associated with fire extinguishment in oxygen-rich environment of manned spacecraft. The feasibility of using high expansion foam was evaluated under National Aeronautics and Space Administration - Manned Spacecraft Center Contract NAS 9-7983. Mr. J. H. Kimzey was the technical monitor of the basic contract with Mr. J. Manheim of Wright-Patterson Air Force Base as the technical monitor of the supplemental work.

Project objective was to demonstrate the feasibility of using high expansion foam to extinguish fires inside an enclosure containing air or oxygen-rich atmospheres at various pressures. Equipment operational characteristics, effective range and time to extinguish a model fire of dry, cellular fuel were observed and recorded.

Project scope was to test the fire extinguishing effect of large volumes of high expansion foam generated within an enclosed region having an atmosphere of both air and oxygen at various pressures from 5 to 16.5 psia.

SUMMARY

The problem was to demonstrate the feasibility of using high expansion foam to extinguish a model fire of dry cellular fuel inside an oxygen rich enclosure at various spacecraft operating pressures.

This problem was solved by assembling a 400 cubic foot hypo/hyperbaric fire test facility in which a 12 inch by 12 inch by 2 inch high opened celled foamed polyurethane fuel specimen, or a cotton twill laboratory smock fuel specimen could be burned in air; 95% Oxygen; 70% Oxygen-30% Helium; and 50% Oxygen-50% Nitrogen environments at 5, 10, 14.7 and 16.5 psia.

The foam was able to extinguish the polyurethane fuel specimens in all cases. Cotton smocks were extinguished in all environments except 16.5 psi and 98% oxygen. These smocks were hung on hangars vertically and had no dummy or animal carcass inside. Thus, it appears that high expansion foam will offer a most effective way of combatting fires in oxygen enriched atmospheres.

CONCLUSIONS

On the basis of tests conducted to date in conjunction with pertinent technical literature the following conclusions are drawn:

1. High expansion foam is an effective extinguishing agent for fires inside enclosures containing oxygen-rich atmospheres at typical spacecraft operating pressures (5 to 16.5 psia).

2. High expansion foam extinguishes without producing toxic pyrolysis products and can be introduced from a relatively few, conviently located dispersing points flowing around structural partitions.

3. Atmospheric clean up was noted by gases such as carbon dioxide and carbon monoxide dissolving in the exposed liquid surface of the foam.

4. Total weight for a foam system to inundate 20% of a space vehicle of 10,000 cubic feet volume, based on projections of collected test data, would run about 50 pounds using on board water supplies.

RECOMMENDATIONS

It is recommended that hardware optimization be initiated as the next logical step for space vehicle foam fire extinguishment work with concentration on:

1. Optimum foam expansion ratio for fire extinguishment in a given environment versus the weight of raw foam material to be carried aloft.

2. Physical size reduction of the foam generator maintaining present efficiency.

3. Special design considerations for weightless foam generation.

Additional areas of future investigation should include:

a. Location of foam generators in a given space vehicle.

b. Incorporating automatic detection/actuation devices, such as ultraviolet solid state detectors and 15 millisecond operation time cartridge actuating valves, in conjunction with manual controls.

c. Determine clean up requirements after use, considering possible electrical hazard and atmosphere contamination.

d. Determine storage considerations.

SCOPE

The original project scope called for twelve (12) total fire extinguishment tests in three environments - air, 95% Oxygen and 50% Oxygen-50% Nitrogen (at four pressures, 16.5, 14.7, 10.0, 5.0 psia) using the same fuel. A Supplement Agreement No. 2 to Contract NAS-9-7983 added four (4) additional tests for Fuels, Lubrications, and Hazards Branch of the Air Force Aero-Propulsion Laboratory. A total of twenty-six fire extinguishment tests were made, however, in order to obtain full and complete data. The initial twenty (20) tests (1 through 12 including reruns 1A through 8A) were conducted from September 25 through October 16, 1968. The last six (6) tests (13 through 18) were conducted during the week of November 4, 1968.

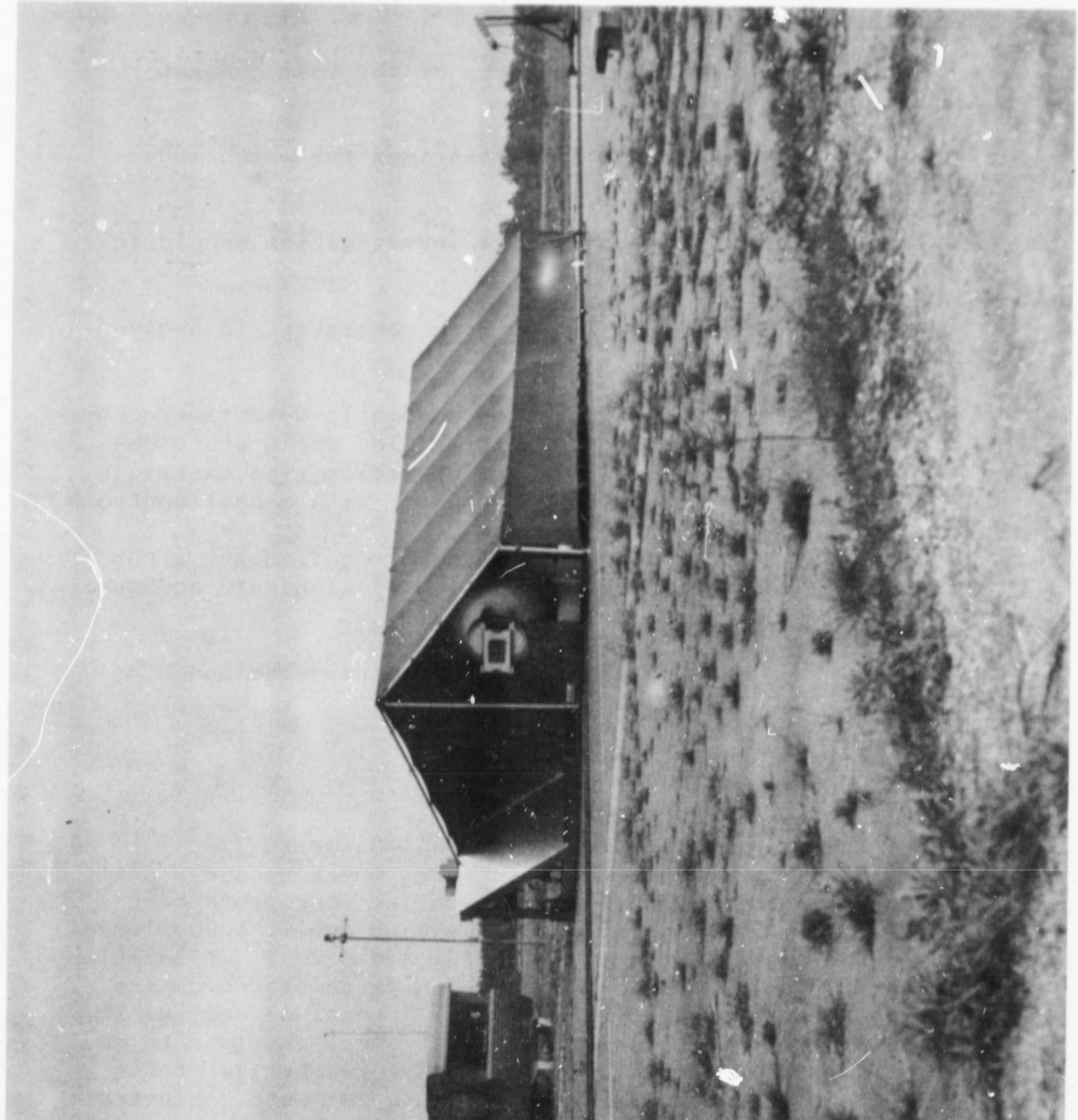

FIGURE 1 - OVERALL VIEW OF HYPO-HYPERBARIC TEST CHAMBER FACILITY

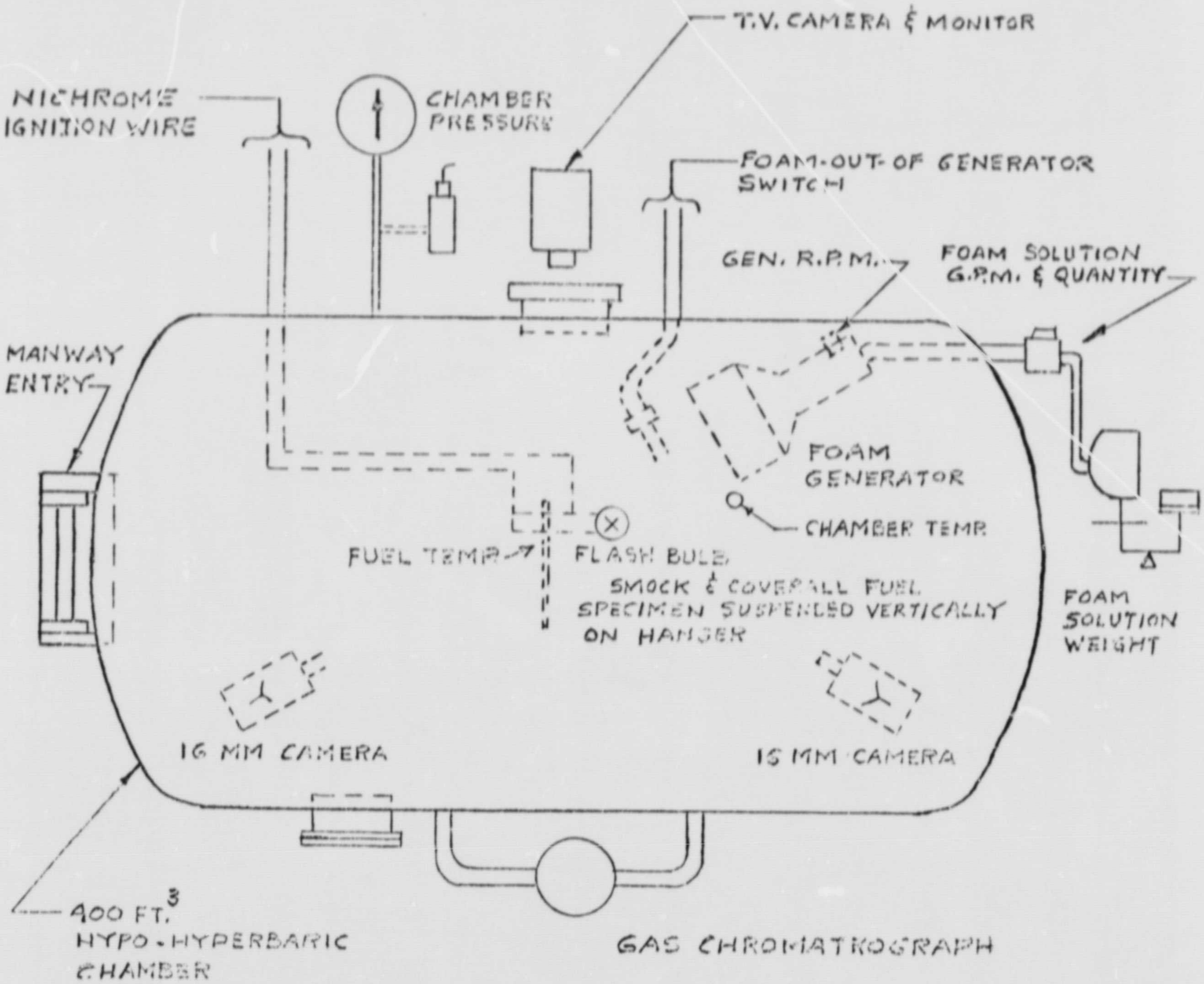

FIGURE 2 - SCHEMATIC OF TEST CHAMBER

FIGURE 3 - INSTRUMENTATION AND CONTROL CENTER INSIDE TRAILER

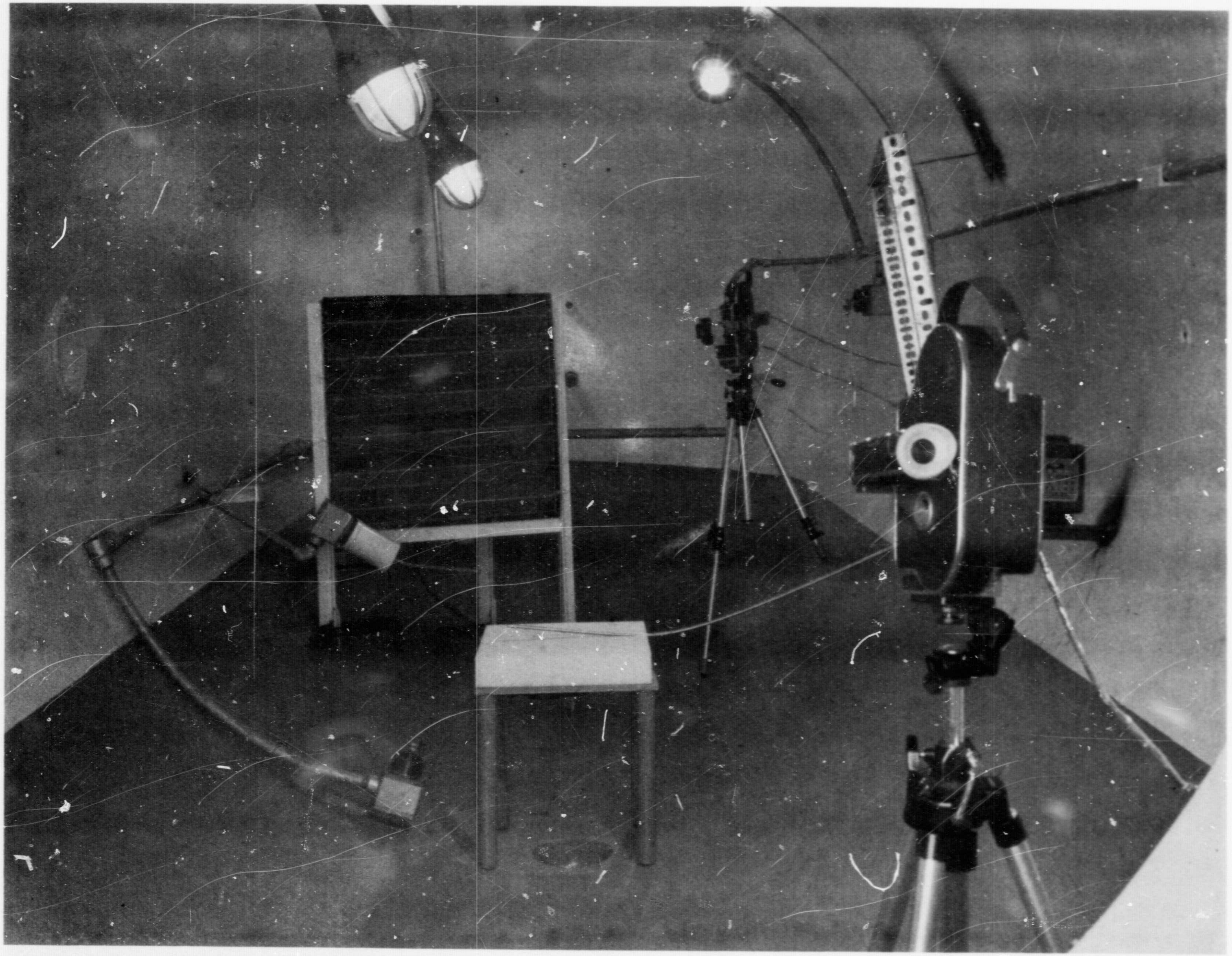

FIGURE 4 - INSIDE OF TEST CHAMBER BEFORE TYPICAL TEST WITH POLYURETHANE FUEL

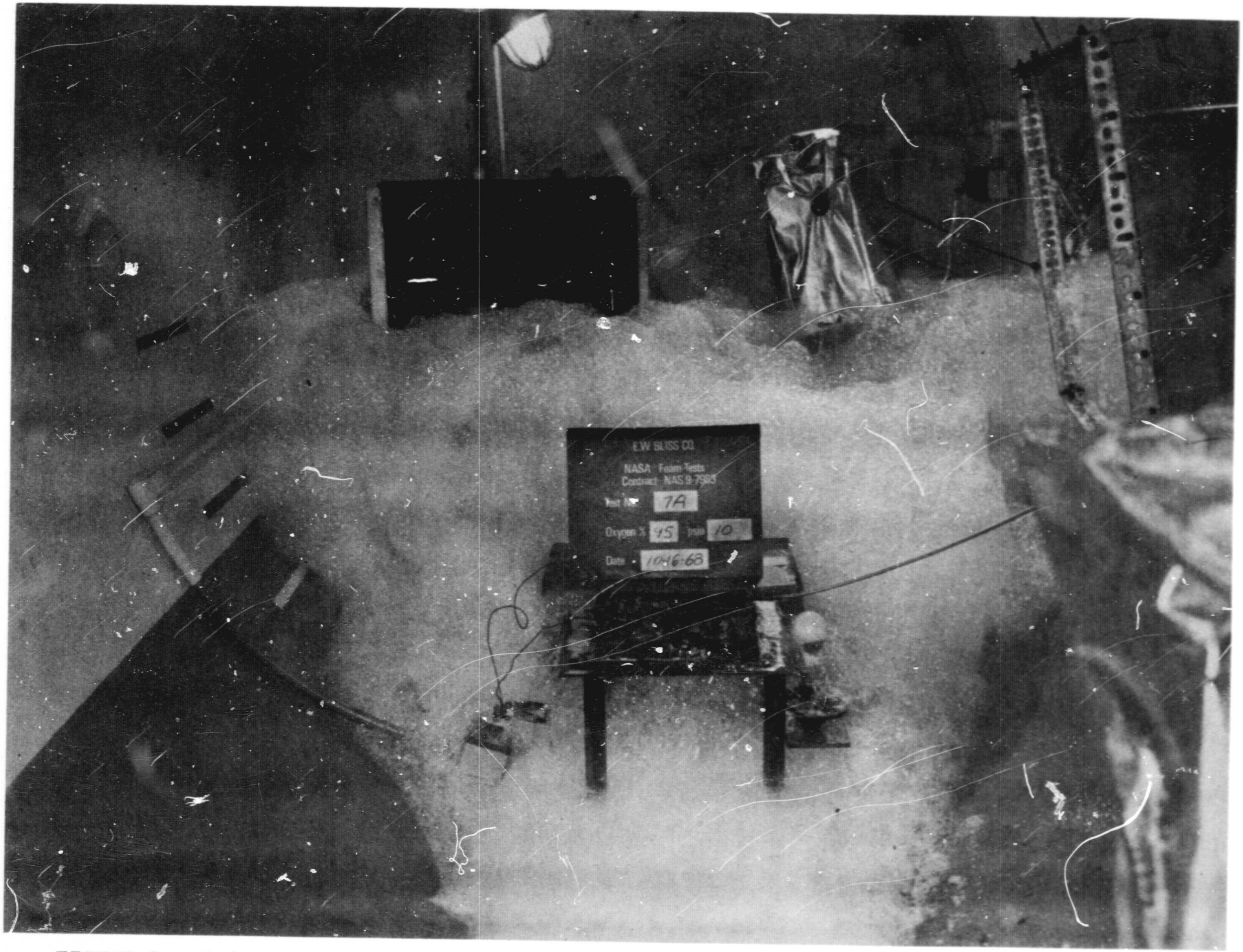

FIGURE 5 - INSIDE OF TEST CHAMBER AFTER TYPICAL TEST WITH POLYURETHANE FUEL - TEST 7A

EQUIPMENT

Test Site equipment included:

1. Test Chamber - 400 cubic feet, 6 feet inside diameter X 16 feet long with 30 inch diameter entry manway.

2. Vacuum Pump - 50 cfm @ 0 inches Hg, 20 inches Hg continuous duty.

3. Air Compressor - 50 cfm unit.

4. Oxygen feed system.

5. Oxygen - Nitrogen (also Helium) feed system.

6. Instrumentation Sensors.

   a. Pressure Transducer 0-30 psia (Chamber Pressure)

   b. Inconel sheathed chromel-alumel thermocouple (for fuel specimen temperature thermocouple location refer to Table 6)

   c. Inconel sheathed iron-constantan thermocouple (for chamber temperature thermocouple location see Table 6)

   d. Turbine Flow Meter - 0-50 gpm (foam solution flow and quantity

   e. Proximity Sensor (generator rpm)

   f. Ultra low current sensor (foam-out-of generator switch)

   g. Pressure Gage (Chamber Pressure)

7. Instrumentation Recorders - Brush Mark 260 Oscillograph six analog channel, 4 event channel recorder.

8. Control Panel - To control automatic/manual burn-foam sequence, vacuum, oxygen, oxygen-nitrogen, air systems, chamber lights, photographic flood lights and chamber drain/purge system.

9. Foam Cart - Contains foam solution tank, nitrogen regulator and connecting quick disconnects.

10. Foam Generator - Bliss Rockwood JET-X-2 unit, same as commercial model used by municipal fire departments (2,000 cfm capacity).

11. Safety Wall and Tent - Separates instrumentation control equipment from chamber and provides sun-rain shelter for chamber.

12. TV Camera and Monitor - Provides remote visual observation of inside of chamber.

13. Gas Chromatograph - (with gas sampling system) consisted of two 13 foot X 1/4 inch metal columns - 3 feet BPL activated charcoal, 6 feet Poropak R, 4 feet Mol Sieve 5A. Columns in series as listed, detector between Poropak and Mol Sieve, and after Mol Sieve, CO_2 analyzed from charcoal-Poropak combination; O_2 and CO analyzed after elutriation from Mol Sieve. This equipment was provided, calibrated, and operated by Greenwood Laborotories Incorporated, Analytical Chemists and Consultants, Chadds Ford, Pennsylvania - 19317.

14. Movie Cameras

a. Two 16mm remote operating cameras. These were installed inside the chamber to monitor the activity at 16 frames per second.

b. One 16mm camera. To record before and after chamber conditions as well as after close-ups of fuel specimen as required.

c. One 4 inch X 5 inch still camera. To record before and after chamber conditions as well as after close-ups of fuel specimen as required.

PROCEDURE

Equipment was prepared for test fires in controlled environments to demonstrate the performance of high expansion foam at the E. W. BLISS Test Facility in Woodbine, New Jersey.

The test equipment was assembled and calibrated. A functional check of equipment was performed in three environments: 20 psia air with a 1 minute preburn, 72% oxygen 14.7 psia with an 8 second preburn, and 7 psia air with a 1 minute preburn.

A typical test procedure follows: (Refer to Appendix B for Check Off List used).

1. Install two motion picture cameras inside the flammability test chamber at a distance of less than five feet.

2. Install a weighed fuel specimen and igniter.

3. Position extinguishing equipment and prepare for remote operation.

4. Photograph interior with still and motion picture camera.

5. Charge chamber with appropriate gaseous atmosphere. Record temperature and pressure.

6. Withdraw gas sample for chemical analysis. Verify oxygen content as specified.

7. Start camera.

8. Ignite fuel. Wait ten seconds.

9. Actuate foam generator. Record performance with stop clock and instrumentation recorders.

10. Stop foam as soon as fuel is enveloped.

11. Stop other equipment after thermocouples establish that the fire is out.

12. Withdraw gas sample for chemical analysis.

13. Return to atmospheric pressure. Open chamber and record results photographically, using a placard to identify all photographs.

14. Remove foam and record condition of fuel to demonstrate degree of fire damage.

15. Remove fuel, dry and weigh.

Data for each test was monitored continuously and included: (Refer to Appendices C, D and E for typical raw data, oscillograph, and gas analysis data)

1. Weight of dry fuel specimen before and after test.

2. Oxygen percent and total pressure of atmosphere prior to test.

3. Time of actuating foam generator relative to ignition.

4. Time of first foam appearance.

5. Time for foam generator to reach maximum output.

6. Flow rate of generator.

7. Time to envelope burning material.

8. Time to extinguish fire.

9. Temperature of atmosphere in chamber and the top surface of the fuel during tests.

10. Pressures during tests.

11. Gas Analysis of atmosphere after fire is out: oxygen, carbon dioxide and carbon monoxide.

12. Volume of foam generated, depth, area covered, slope angles and effects of structural partitions.

13. Weight and volume of foam raw material.

14. Color still and motion picture documentation.

Figure 1 is an overall view of hypo-hyperbaric test chamber facility and Figure 3 shows the instrumentation and control center inside the trailer. Figure 2 is a schematic of test chamber. Figures 4 and 5 show the interior of the chamber, before and after a typical test.

The pressure during testing was virtually constant. The heating, gaseous products of combustion, and added liquid had a very slight effect. Gas used in generating the fire extinguishing foam was in all cases, the ambient gas in the test chamber. No gas was added or removed during tests.

TEST FIRES

Fuel for tests 1 through 12 consisted of a 2 inch thick open cell foamed polyurethane 12 inches square. Fuel for tests 13 through 18 was a size 42, white cotton twill, laboratory smock. Ignition source was a 48 inch long piece of Nichrome wire coiled into a helix one inch in diameter and 17 inches long, placed across the diagonal of the polyurethane foam. The same Nichrome length igniter wire was threaded through the bottom of the lab smock. Figures 4 and 5 illustrate typical arrangements of igniter wire and fuel specimens, etcetera. Ignition was accomplished by applying an AC voltage across the Nichrome igniter wire for a preset period of time. The voltage was applied through the sequence timer for about 10 seconds. Flames would appear in about 2 to 3 seconds after timer circuit was closed. This technique ignited the weighed fuel specimen directly eliminating contamination of the chamber environment by burning interface materials. The fuel specimens were located in the center of the chamber, the polyurethane on an 18 inch high stand and the lab smock was vertically suspended on a coat hangar so its bottom was about 1 foot above the chamber floor. Both specimens were 3 feet from the foam generator, measured horizontally.

A flash bulb was paralleled across the igniter wire to provide a time link between the oscillograph data and the movie coverage. Bulb ignition was considered zero time, and oscillograph data could be correlated to this point since an event channel recorded when electrical voltage was impressed and removed from the Nichrome igniter wire.

RESULTS

Table 1 tabulates "Chamber Environment and Total Burn Time" for each test. Chamber environment data includes chamber gas, oxygen percent of this gas and total chamber pressure. Actual flame burn times ran about 12 seconds (polyurethane fuel) and were obtained from movie data. Estimated burn times were extracted from oscillograph data for Nichrome wire actuation. In general the actual flame burn times will slightly exceed the estimated values because the foam took additional time (beyond de-energizing of Nichrome wire) to envelope burning fuel specimen.

Table 2 presents "Time Information from Movie and Oscillograph Data for Key 95% Oxygen Tests". It includes elapsed times from initiation of flame to start of foam discharge, to loss of vision (i.e. camera lens in inundated by foam), and to apparent extinguishment.

Table 3 presents the "Loss of Weight of Fuel Specimens". Included are type of fuel material, original weight, final weight and loss of weight in grams. Weight loss is also presented in percent. A circuit breaker failure resulted in a 90% fuel specimen weight loss for test no. 2. Test no. 1 through 6 and 1A show erratic fuel specimen weight losses due to widely varying burn time. For air tests no. 3 and 4 a 45 second burn which seemed to be optimum was excessive when used for Oxygen test no. 5. Test no. 6 was, therefore, conducted with burn reduced to 20 seconds. Based on weight consumed (40%), this burn was subsequently reduced to 10 seconds for all other polyurethane fuel specimen tests.

Table 4 tabulates, "Time Histories from Oscillograph Data" for each test. It includes time of foam generator actuation relative to ignition, time of first foam appearance, time for foam generator to reach maximum output, time for foam to envelope burning fuel specimen, and time to extinguish fire. All elapsed times for the above events are relative to ignition (start of Nichrome wire energizing) except time for foam generator to reach maximum output. Time to extinguish fire was measured from ignition to a point when the fuel temperature dropped to 140°F. (This was an arbitrarily selected temperature). In a few of the tests the temperature stayed below 140°F.

Table 5 presents the "Gas Analysis Data" and it includes oxygen percent by volume before and after each test fire, parts per million by volume of carbon monoxide (CO) and carbon dioxide (CO_2). The decrease in CO_2 level between the two measurements is attributed to the solubility of CO_2 in the aqueous foam material. The first measurement was taken immediately after the test fire and foaming extinguishment, while the second was taken approximately 12 minutes after the first commenced.

Table 6 presents "Chamber Pressure and Temperature, Fuel Specimen Temperature and Foam Solution Flow Rate". Pressure and temperature data include start, i.e. prior to start of test fire and maximum values.

Table 7 summarizes the color photographic coverage (still and 16mm movie) not enclosed in this report. It consisted of still and movie "before" and "after" chamber pictures from the chamber manway door, and "before", "during" and "after" movie coverage from the two cameras located inside the chamber.

Table 8 tabulates "Volume of Foam Generated and Foam Solution Used". Included are the following data for each test: volume of foam generated in cubic feet, depth of foam generated in test chamber in inches, weight of raw foam solution used (includes 95% water by volume), volume of foam solution used (again includes 95% water by volume - the other 5% is Jet-X liquid) and expansion ratio of foam. The term "expansion ratio" is defined as the volume of foam generated relative to volume of foam solution (the mixture of 5% Jet-X and 95% water) consumed.

Observations of key 95% oxygen fire extinguishment tests are presented. Additional material can be found in Experimental Procedure and Observations section of Appendix A.

TEST NO. 5A

The chamber was charged with 93% oxygen, 14.7 psia. The actual burn was 13.25 seconds resulting in a 3% by weight loss of fuel. Counting elapsed time from beginning of Nichrome wire energizing, the following occurred:

Elapsed Time in Seconds	Event
0	energize Nichrome igniter wire
4	igniter wire gets cherry red
4.25	flame starts
5.5	flame completely envelopes fuel specimen
9.95 *	igniter wire de-energized
12.05 *	foam solution solenoid valve energized
12.3 *	foam generator fan starts to move
12.23	foam appears (film)
13.05 *	foam hits foam-out-of-generator switch
16.5	foam envelopes burning fuel specimen
17.5	apparent extinguishment

Elapsed Time in Seconds	Event
20.8	foam obscures vision (reaches lens of inside camera)
24.3 *	foam solution solenoid valve closes-foam on for 12.25 seconds

* Data from Oscillograph

TEST NO. 6A

90.6% oxygen, 16.5 psia chamber environment and 12.52 second actual burn. Percent loss of fuel specimen by weight was 4. Time-Event history for this test is as follows:

Elapsed Time in Seconds	Event
0	energize igniter wire
4.06	Nichrome ignition wire gets cherry red
4.18	flame starts
5.37	flame completely envelopes fuel specimen
9.75 *	de-energize igniter wire
12.05 *	foam solution solenoid valve open
12.06	foam appears in movies
12.3 *	foam generator fan starts to turn
13.45 *	foam hits foam-out-of-generator switch
15.70	foam envelopes burning fuel specimen
16.7	apparent extinguishment
18.37	foam obscures vision (reaches lens of inside camera)
19.75 *	foam solution solenoid valve closes-foam on 7.7 seconds

TEST NO. 7A

99.9% oxygen, 9.8 psia chamber environment and 12.3 second actual burn. The loss of fuel specimen was 2% by weight. Time Event History for this test is as follows:

Elapsed Time in Seconds	Event
0	energize igniter wire
4.12	ignition wire gets cherry red
4.7	flame starts
6.12	flame completely envelopes fuel specimen
9.9 *	de-energize igniter wire
12.4 *	foam solution solenoid valve opens
12.39	foam appears (movie)
13.2 *	foam hits foam-out-of-generator switch
15.4	foam generator reaches maximum output (This data not evident on all tests - refer to Appendix D)
16.0	foam envelopes burning fuel specimen
17.0	apparent extinguishment
18.7	foam obscures vision
24.6	foam solution solenoid valve closed-foam on 12.2 seconds

TEST NO. 8A

90.6% oxygen, 4.3 psia chamber environment and 13.69 actual burn. Percent loss of fuel was 0.5. Time Event History for this test is as follows:

Elapsed Time in Seconds	Event
0	energize igniter wire
3.56	ignition wire reaches cherry red
4.56	flame starts
7.2	flame completely envelopes fuel specimen
9.8 *	de-energize Nichrome wire
12.0 *	foam solution solenoid valve opens
12.3 *	foam generator fan starts to turn
12.39	foam appears (movie)
13.0 *	foam hits foam-out-of-generator switch

Elapsed Time in Seconds	Event
17.25	foam envelopes burning fuel specimens
18.25	apparent extinguishment
19.82	foam obscures vision
20.4 *	foam solution solenoid valve closes-foam on 8.4 seconds

* Data from Oscillograph

TABLE 1

CHAMBER ENVIRONMENT AND TOTAL BURN TIME

TEST NO.	CHAMBER GAS, NOMINAL	CHAMBER OXYGEN PERCENTAGE	CHAMBER PRESSURE PSIA *	TOTAL BURN TIME-SECONDS **
1	Air	20.1	14.7	20.6 ***
1A	"	20.2	14.7	19.3 ***
2	"	19.0	16.6	148.5 ****
2A	"	20.2	16.5	10 ***
3	"	20	10.1	44.7 ***
3A	"	23.1	10	10.1 ***
4	"	21.5	5	45 ***
4A	"	21.1	5	10 ***
5	95% O_2	91.4	14.7	44.6 ***
5A	"	93	14.7	13.25
6	"	86.3	16.5	19.7 ***
6A	"	90.6	16.5	12.52
7	"	96.75	10	9.85***
7A	"	99.9	9.8	12.3
8	"	93.2	5	9.9 ***
8A	"	90.6	4.3	13.69
9	50%O_2-50%N_2	53.8	16.5	10 ***
10	"	53.8	14.9	9.9 ***
11	"	50.5	10.2	9.9 ***
12	"	49.6	5.3	9.7 ***
13	100% O_2	98.8	16.2	Misfire
13A	"	98	15.8	20.92
14	"	98.3	16.4	20
15	"	97.9	4.9	7.43
16	"	98.4	5	16.0
17	"	98.5	9.8	15.93
18	70%O_2-30%He	70	4.9	28.03

* Pressure was measured prior to ignition. See Table 6 for maximum pressures during tests.

** Elapsed time from initiation of flame until apparent extinguishment.

*** Estimated burn time based on energized period for Nichrome wire.

**** Circuit breaker failure occurred.

TABLE 2

Time Information from Movie and Oscillograph Data for Key 95% Oxygen Tests

TEST NO.	FROM INITIATION OF FLAME TO START OF FOAM DISCHARGE	FROM INITIATION OF FLAME TO APPARENT EXTINGUISHMENT*	FROM INITIATION OF FLAME TO LOSS OF VISION (CAMERA LENS INUNDATED)
5A	8.8	13.25	16.55
6A	9.27	12.52	14.19
7A	8.5	12.3	14.0
8A	8.44	15.26	13.69

* Apparent extinguishment established from movie data as elapsed time until foam envelopes burning fuel specimen plus one second. Using elapsed time/event data from test 5A as example:

16.5-4.25=12.25 seconds - Time from initiation of flame to foam envelopes burning fuel specimen

12.25+1.0=13.25 seconds - Time from initiation of flame to apparent extinguishment

TABLE 3

LOSS OF WEIGHT OF FUEL SPECIMEN

TEST NO.	FUEL SPECIMEN MATERIAL	ORIGINAL WEIGHT GRAMS	FINAL WEIGHT GRAMS	LOSS GRAMS	LOSS PERCENT	
1	polyurethane foam	149.0	143.2	5.8	3.9	
1A	"	144.5	140.7	3.8	2.6	
2	"	141.0	136.0	127.4	90.5	*
2A	"	146.3	145.1	1.2	0.8	
3	"	145.6	134.0	11.0	7.7	
3A	"	144.9	144.5	0.4	0.3	
4	"	144.0	142.5	1.5	1.0	
4A	"	146.5	145.7	.8	0.5	
5	"	141.6	0	141.6	100.0	**
5A	"	146.0	117.8	29.0	19.7	
6	"	145.5	87.0	58.5	40.0	**
6A	"	147.3	113.5	33.8	22.9	
7	"	146.3	137.6	8.7	6.0	
7A	"	142.1	116.3	25.8	18.2	
8	"	143.5	133.0	10.5	7.3	
8A	"	148.5	144.1	4.4	3.0	
9	"	143.5	129.4	14.1	9.8	
10	"	143.0	137.8	5.2	3.6	
11	"	133.5	132.1	1.4	1.1	
12	"	144.5	139.5	5.0	3.5	
13	lab smock	722.4		MISFIRE		
13A	"	720.5	81.3	639.2	87.3	
14	"	733.5	80.5	633.0	89.3	
15	"	707.9	698.1	9.8	1.4	
16	"	710.5	467.5	243.0	34.2	
17	"	714.0	203.8	510.2	71.5	
18	coveralls	1151.4	736.0	415.4	36.1	

* Circuit breaker failed-causing ignition but no extinguishing agent delivery

** Burn time too long

TABLE 4

TIME HISTORIES FROM OSCILLOGRAPH DATA

TEST NO.	TIME OF ACTUATING FOAM GENERATOR RELATIVE TO IGNITION SECONDS	TIME OF FIRST FOAM APPEARANCE SECONDS	TIME OF FOAM GENERATOR TO REACH MAX.OUTPUT SECONDS	TIME FOR FOAM TO ENVELOPE BURNING FUEL SECONDS	TIME TO EXTINGUISH FIRE* SECONDS
1	21.8	22.8	1.2***	33.8	N/A
1A	20.5	21.3	0.3	21.3	N/A
2	148.5	149.5	N/A	----	N/A
2A	12.0	13.0	0.3	13	**
3	46.6	47.6	3.2	47.6	N/A
3A	12.2	13.2	0.3	13.2	**
4	46.7	47.7	N/A	47.7	N/A
4A	12.1	13.95	0.4	13.95	**
5	46.5	47.3	N/A	47.3	93.0
5A	12.05	13.05	0.2	13.05	104.3
6	20.58	21.78	0.3	21.78	145.0
6A	12.05	13.45	0.3	13.45	156.9
7	12.0	13.3	1.8	13.3	80.0
7A	12.4	13.2	4.0	13.2	64.6
8	12.6	12.9	0.4	12.9	18.0
8A	12.0	13.0	0.4	13.0	60.4
9	12.2	13.5	0.3	13.5	88.5
10	12.0	12.8	0.3	12.8	95.0
11	12.0	13.3	0.6	13.3	38.0
12	11.7	12.8	0.4	12.8	25.0
13	2.5	3.5	0.5	3.5	MISFIRE
13A	5.0	7.9	0.4	7.9	140.0
14	4.3	5.4	0.5	5.4	35.0
15	5.0	6.2	6.0	6.2	**
16	15.0	16.2	1.1	16.2	45.0
17	6.9	7.7	N/A	7.7	19.0
18	14.5	25.5	N/A	25.5	100.0

* Fuel temperature drops to 140°F
** Fuel temperature never reached 140°F
*** Note comments on page 37

TABLE 5

GAS ANALYSIS

TEST NO.	BEFORE TEST PERCENT OXYGEN BY VOLUME	AFTER TEST [1] PERCENT OXYGEN BY VOLUME	PPM CO	PPM CO_2
1	19.4	17.7	50	686
1A	20.2	20.3	50	807-898
2	18.8	16.7	50	2880
2A	21.0	20.8-20.5	50	593-583
3	19.9	19.3	50	2750-1548
3A	21.2	20.7-21.0	50	714-110
4	20.4	20.7	50	2210-1150
4A	21.1	21.1-20.55	50	760-702
5	89.0	87	63	17100
5A	93.0	91.3-91.4	133.8	4790-4430
6	89.0	88.8-89.8	50	8250-6820
6A	94.2	90.0-90.3	50	5790-3985
7	96.75	93.6	50	5670-4670
7A	99.3-99.9	97.8-97.9	50	5410-4640
8	93.2	89.2	257	9250
8A	90.6	86.4	50	4325
9	53.8	53.0	50	2720-1950
10	53.8	53.3	50	3290-2420
11	50.5	49.2-48.8	50	2745-1970
12	49.6	47.8-47.8	50	2020-1925
13	98.8	MISFIRE		
13A	98	89.2-88.8	70	65,000-52,500
14	98.3	91.2-92	69	67,200-54,500
15	97.9	92-91.5	50	2225-2225
16	98.4	89.7-80.4**	2185-337	52,400-36,550
17	98.5	78.4-82.3	***183-151.5	48,100-53,200
18	70	57.5-59.2	1740-740	13,400-9570

1 Samples of gas were taken from atmosphere 4-1/2 feet above burning fuel specimen

* Decrease in CO level attributed to solubility of CO in aqueous foam material. The first measurement was taken immediately after test while second was taken approximately 12 minutes after the first.

** Nitrogen accidently injected from foam cart after fire for second sample only

*** Nitrogen accidently injected from foam cart after fire for both samples

TABLE 6

CHAMBER PRESSURE AND TEMPERATURE, FUEL TEMPERATURE AND FOAM SOLUTION FLOW RATE

TEST NO.	CHAMBER PRESSURE START/MAX. PSIA	CHAMBER TEMPERATURE* START/MAX. °F	FUEL SPECIMEN TEMPERATURE** START/MAX. °F	FLOW RATE FOAM SOLUTION GALLONS/MINUTE
1	14.7/NA	NA/NA	NA/NA	NA
1A	14.7/15	NA/83	NA/NA	27.5
2	16.5/17.1	NA/NA	NA/NA	NA
2A	16.5/16.8	66/71	66/123	25.6
3	10/10.5	NA/NA	NA/NA	NA
3A	10/NA	74/NA	77/138	26.8
4	5/5.4	NA/NA	NA/NA	NA
4A	4.6/4.8	75/79	75/102	28.7
5	14.7/18.8	NA/NA	87/905	NA
5A	14.7/15.6	68/85	68/458	26.0
6	16.5/21.3	NA/NA	77/1002	26.0
6A	16.5/18.8	75/99	77/541	26.0
7	10/10.6	NA/NA	77/287	26.0
7A	9.8/10.6	88/101	77/386	24.5
8	5/5.4	NA/NA	70/160	29.0
8A	4.3/4.8	68/75	77/186	28.2
9	16.5/17	74/91	77/319	25.4
10	14.9/15.4	74/88	77/274	27.5
11	10.2/10.4	81/92	87/191	27.5
12	5.3/5.4	75/88	95/165	28.2
13	16.2/16.2	46/49	55/55	21.0
13A	15.8/26.5	82/367	77/447	20.2
14	16.4/27.3	67/399	77/643	21.2
15	4.9/5.1	67/67	77/117	23.5
16	5/6.5	53/169	75/314	20.2
17	9.8/14.6	67/357	75/186	20.2
18	4.9/6.6	68/383	77/251	18.5

* Thermocouple was located 5 inches below chamber ceiling (above foam generator) and 30-1/2 inches away from fuel specimen

** Thermocouple was laid directly on polyurethane fuel specimen and affixed to front of lab smock at thigh level

TABLE 7

PHOTOGRAPHIC LOG*

TEST NO.	STILL		16mm MOVIE**		
	BEFORE	AFTER	BEFORE	DURING	AFTER
1	X	X	X	X	X
1A	NO COVERAGE				
2	X	X	X	(1)	(1)
2A	X	X	X	X	X
3	X	X	X	X	X
3A	X	X	X	X	X
4	X	X	X	X	X
4A	X	X	X	X	X
5	X	X	X	X	X
5A	X	X	X	X	X
6	-	X	X	X	X
6A	X	X	X	X	X
7	-	X	X	X	X
7A	-	X	X	X	X
8	X	X	X	X	X
8A	X	X	X	X	X
9	X	X	X	X	X
10	X	X	X	X	X
11	X	X	X	X	X
12	X	X	X	X	X
13	MISFIRE				
13A	X	X	X	X	X
14	X	X	X	X	X
15	X	X	X	X	(2)
16	X	X	X	(3)	X
17	X	X	X	X	X
18	X	X	X	X	X

* Color photographic (still and 16mm movie) coverage not enclosed in this report

** Consisted of using 3 cameras: Outside camera in chamber manway for before and after coverage; inside front camera for before, during and after coverage; inside rear camera for before, during and after coverage

(1) Partial coverage on during and after inside cameras due to short circuit

(2) No coverage from inside front camera after test

(3) No coverage from inside front camera during test

TABLE 8

VOLUME OF FOAM GENERATED AND FOAM SOLUTION USED

TEST NO.	VOLUME OF FOAM GENERATED-CUBIC FEET	DEPTH OF FOAM GENERATED INCHES	WEIGHT OF FOAM SOLUTION USED-POUNDS	VOLUME OF FOAM SOLUTION USED CUBIC FEET	EXPANSION RATIO OF FOAM (FOAM GENERATED RELATIVE TO FOAM SOLUTION USED)
1	299	48	77	1.23	242:1
1A	256	42	49.5	.79	322:1
2			CIRCUIT BREAKER FAILURE		
2A	370	60	62	.99	372:1
3	256	42	46	.73	347:1
3A	299	48	54	.86	345:1
4	256	42	42	.67	383:1
4A	208	36	43.5	.69	298:1
5	256	42	42	.67	381:1
5A	299	48	62.5	1.00	295:1
6	256	42	65.7	1.05	243:1
6A	164	30	42.5	.68	241:1
7	256	42	73	1.17	227:1
7A	299	48	55.5	.89	336:1
8	256	42	--	--	-----
8A	256	42	52	.83	308:1
9	256	42	52	.83	308:1
10	299	48	51	.82	364:1
11	299	48	53	.85	352:1
12	256	42	44	.70	332:1
13			MISFIRE		
13A	370	60	103.5	1.66	223:1
14	416	72	105.5	1.69	246:1
15	339.5	66	111.5	1.79	190:1
16	416	72	112	1.8	232:1
17	416	72	116	1.86	224:1
18	416	72	--	--	-----

DISCUSSION

Loss of weight of fuel specimens varied from 0.5 to 7.7 percent for the air environment tests 1 through 4A. Suitable burn times were determined in tests 1, 1A, 3 and 4 all of which exceeded the 10 second period. A circuit breaker failure during Test Number 2 caused an apparent burn of 148.5 seconds and 90.5% of the fuel specimen was consumed. Tests 2A, 3A and 4A illustrated an increased fuel loss tendency with increasing chamber pressure. Oxygen environments with consistent burn times averaging 12 seconds illustrated the same tendency as air but with more fuel specimen being consumed, except at the 5 psia pressure level.

Data for 50% oxygen-50% nitrogen falls between air and 95% oxygen environments for tests 9 through 12 respectively. A plot of this data is presented in Figure 6. Table 3 presents a tabulation of all weight loss data.

Chamber Pressure	Percentage Fuel Loss Air	50% O_2	95% O_2
16.5	0.8	9.8	22.9
14.7	NA	3.6	19.7
10	0.3	1.1	18.2
5	0.5	3.5	3.0

Weight losses of fuel specimens used during tests 13 through 18 are discussed in Appendix A.

Oxygen percent and total pressure of chamber environment prior to each test is tabulated in Table 1. Tests 1 to 4A were air, 5 to 8A were 95% oxygen, 9 to 12 were 50% oxygen-50% nitrogen, 13 to 17 were 100% oxygen, and 18 was 70% oxygen-30% helium.

Time of actuating foam generator relative to ignition was determined from oscillograph data and consisted of the elapsed time from initiation of Nichrome wire energizing until foam solution valve is actuated. This time averaged 12 seconds for the 95%, 50% oxygen and some air test (5A through 8A and 9 through 12 and 2A, 3A and 4A). Air and some preliminary 95% oxygen tests varied due to changing burn times (tests 1, 1A, 2, 3, 4, 5 and 6). Tests 13 through 18 are covered in Appendix A.

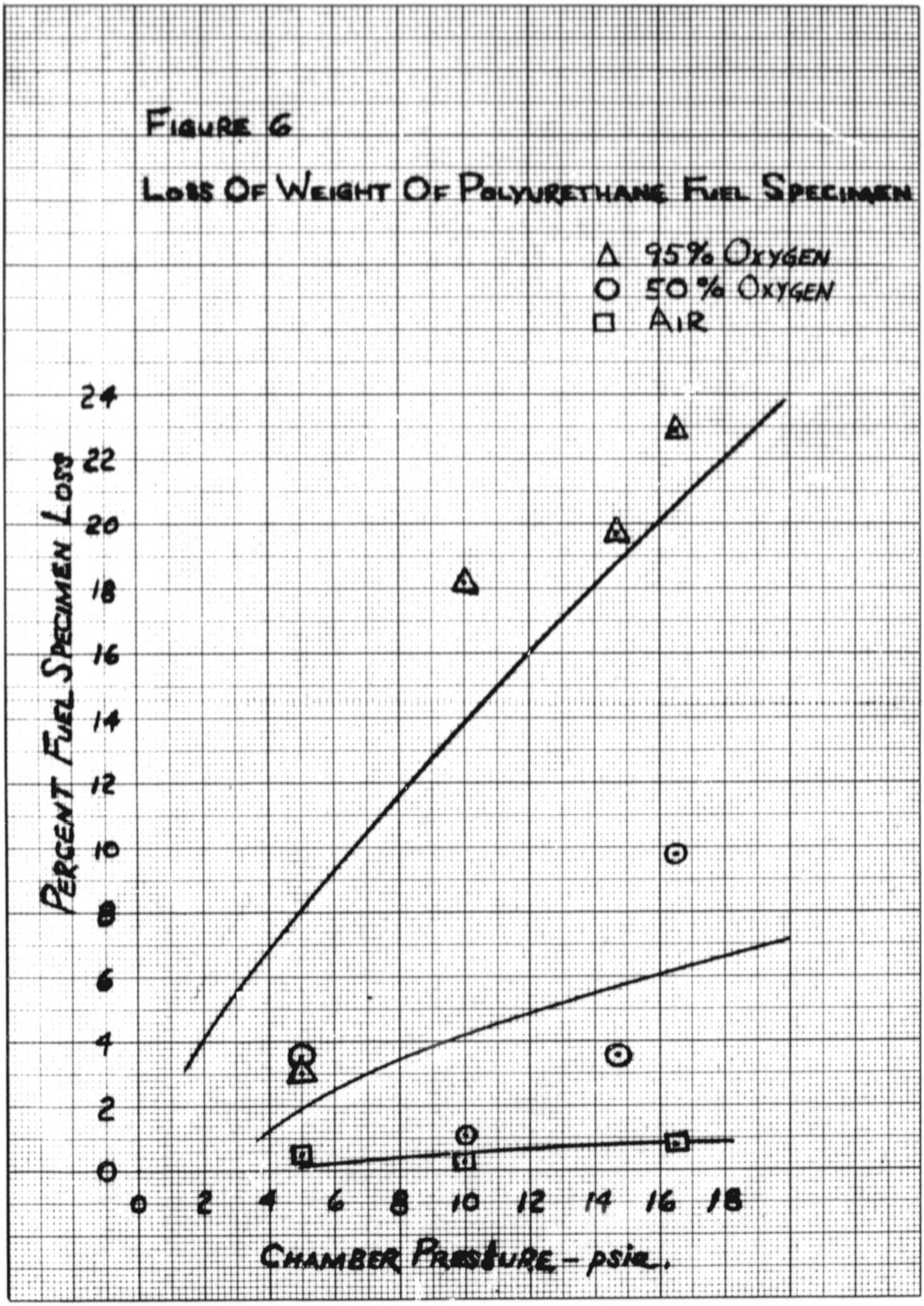
FIGURE 6
LOSS OF WEIGHT OF POLYURETHANE FUEL SPECIMEN
△ 95% OXYGEN
○ 50% OXYGEN
□ AIR
PERCENT FUEL SPECIMEN LOSS
0
2
4
6
8
10
12
14
16
18
20
22
24
CHAMBER PRESSURE - psia.

Appendix D illustrates typical oscillograph data and shows the four event channels used to record main switch, Nichrome wire switch (designated "Preburn"), foam solution solenoid valve switch, and foam-out-of-generator switch. The second and third channels respectively are used to provide time of actuating foam generator relative to ignition data. Table 4 presents this data.

Time of first foam appearance relative to ignition (see Table 4) was determined from oscillograph data and consisted of the elapsed time from initiation of Nichrome wire energizing until foam actuated foam-out-of-generator switch. This time averaged 13 seconds for the 95%, 50% oxygen and some of the air tests (5A through 8A and 9 through 12 and 2A, 3A and 4A); or, in other words, it took an average of one (1) second to flow down and fill the 10 feet of pipe and tubing that separated the foam solution solenoid valve and foam generator reaction motor, accelerate the reaction motor, and produce foam from the generator. A solenoid or cartridge-actuated valve mounted directly adjacent to the generator with a more rapid response time would easily reduce this time into the millisecond range. The valve used during the test program was a pilot-operated solenoid valve (slow actuating type) and was mounted outside the chamber wall - 10 feet removed from the generator. The second and fourth event channels were used to obtain this data. The foam out-of-generator switch consisted of two stainless rods separated by a 1/2 inch air gap, mounted directly in front of the foam generator. Foam flowing out of the generator would complete the switch circuit.

Time for foam generator to reach maximum output was determined from oscillograph data - the fifth analog channel monitoring generator rpm. This was the time from the start of energizing the solenoid, which released the pressurized liquid, until generator rpm reached a level output. Typical times ran 4 seconds, however, most data from analog channel Number 5 with exception of Test 3, 7A and 15 showed erratic performance in that the foam generator appeared to reach maximum output in a greatly reduced time interval.

Foam solution flow rate in gallons per minute varied from 18.5 to 29.0. This data is tabulated in Table 6. Flow rate output of foam from the generator would be a function of expansion ratio of foam, i.e. cubic feet per minute foam solution times expansion ratio yields foam rate out of generator. A typical example is Test 7A, where the foam solution flow was 24.5 gpm or 3.28 cfm. Expansion ratio from Table 8 was 336:1, therefore, flow rate out of generator is 1100 cfm.

Time to envelope burning polyurethane fuel specimen relative to ignition (start of Nichrome wire energizing) took an average of 16 seconds according to data from movie coverage. Oscillograph data indicated an average of 13 seconds, however, this data should more properly be called "Time for Foam to Contact Burning Fuel Specimen" or "Time to Energize Foam-Out-of-Generator Switch". This is because the foam-out-of-generator switch consisted of an ultra low current sensor located at a point 1/3 of the distance separating the foam generator and fuel specimen. This sensor is visible just in front of the foam generator in Figure 4 and is located 1 foot away from the generator outlet and 2 feet away from the fuel specimen. Time to envelope burning lab smock fuel specimen relative to ignition depends on whether this is referred to the top or bottom of the vertically suspended, 4 foot long smock. This data is tabulated in Table 4.

Time to extinguish polyurethane fuel specimen fire in a 95% oxygen environment took an average of 4.5* seconds after activating extinguisher. This is approximate, but fairly accurate, since it was established by adding one (1) second to the time it took the foam to envelope the burning fuel specimen (see Table 2), and the fire had been visually observed to burn under the foam for less than one second. Time to extinguish polyurethane fuel specimen fire relative to ignition (start of energizing igniter) was determined from oscillograph data by measuring the time for the fuel temperature to drop to 140°F. This did not always provide definitive data. Some tests illustrated response time lag of the thermocouple, while other tests never reached 140°F, due to the large metal shroud around the temperature sensors. This data appears in the last column of Table 4.

The temperature of the atmosphere inside the test chamber was monitored by an Inconel sheathed thermocouple located 5 inches below the chamber ceiling (in the vicinity, above the foam generator) and 30-1/2 inches away from the fuel specimen. Temperature increases above ambient of 7° to 24°F were observed for the 95% oxygen tests (5A-8A), 11° to 17°F for the 50% oxygen tests (9-12) and 116° to 332°F for the 98% oxygen-lab smock fuel tests (13-18). This data is tabulated in Table 6.

* From elapsed time-event histories of key 95% oxygen tests

The temperature of the top surface of the fuel specimen ranged from 186° to 541°F for 95% oxygen tests (5A-8A), and 165° to 319°F for 50% oxygen tests (9-12) and 117° to 643°F for 98% oxygen-lab smock fuel tests. Column 4 of Table 6 presents this data. An Inconel jacketed thermocouple was laid directly on the polyurethane fuel specimen prior to each test, and affixed to the front of the lab smock at thigh level. The front of the smock was the side furtherest away from the foam generator.

The maximum chamber pressures during the tests reached levels ranging from 0.4 to 4.8 psia above initial chamber pressures for the 95% oxygen tests (5-8A), 0.1 to 0.5 psia for the 50% oxygen tests (9-12) and 0.2 to 10.9 psia for the 98% oxygen-lab smock fuel tests, (13-18). The maximum change (16.4 initial to 27.3 psia) took place during test number 14 where the greatest amount of fuel was consumed (89.3% or 653 gms) and highest chamber temperature reached (399 F). Chamber pressures are tabulated in Table 6.

Gas analysis of chamber environment after fire was out, made with gas chromatograph, showed a decrease in oxygen content ranging from 1.5 to 4.2 percent for 95% oxygen tests (5A-8A), from .5 to 1.8 percent for 50% oxygen tests (9-12), and from 5.9 to 8.8 percent lab smock fuel tests (13-17). After fire carbon dioxide levels inside the chamber ranged from 4790 to 5790 ppm (parts per million) for the 95% oxygen tests, from 2020 to 3290 ppm for the 50% oxygen tests (9-12), and from 2225 to 6720 ppm for the lab smock fuel tests (13-18). The second (lower value) presented in Table 5 was an analysis of a gas sample taken approximately 12 minutes after the first, which was taken immediately after foaming was complete. The decrease in the CO_2 level from first to second measurement is attributed to solubility of CO_2 in the aqueous foam material. After fire, carbon monoxide levels did not exceed 50 ppm in any test (1 to 12 including A test) except 5, 5A and 8 and these levels respectively were 63, 133.8, and 257 ppm. Lab smock fuel tests (13-15) ran from 50 to 70 ppm. Tests 16, 17 and 18 had first CO measurements (in ppm) of 2185, 183 and 1740 respectively and second measurements of 337, 151, and 740 respectively. A comparison of weight of lab smock consumed versus CO_2 generated indicated a linear relationship, i.e. increasing weight consumed yielded increasing CO_2 generated. A comparison of the ratio of CO to CO illustrated the following trends: A decrease of the ratio of CO to CO_2 with increasing oxygen content, decrease of the ratio with increasing pressure and an increase in the ratio with an increase rate of consumption.

Test No.	% CO / CO_2	Weight Consumed in Grams	Time Consumed in Seconds	Rate of Consumption gm/ Seconds
13	.108	640	11.9	54
14	.102	633	12 Approx.	52.8
15	2.25	9.8	7.43	1.3
16	4.17	243	16	15
17	.38	510	16	32
18	13.0	415.4	28	14.8

It is not clear why the CO level in tests numbers 16 and 18 are so high. According to our gas analysis subcontractors, Greenwood Laboratories, the industrial tolerance level for carbon monoxide has been set a maximum of 100 ppm for an 8 hour exposure or 400 ppm for a 1 hour exposure.

Volume of foam generated ranged from 164 to 400 cubic feet and this represents a depth of 30 to 72 inches measured at the chambers centerline. This data is tabulated in Table 8. The foam filled the chamber from the bottom up just as a liquid would and the area covered at any given time was simply the segment of the cylinder below its depth. Effect of foams ability to flow around structural partitions was shown dramatically during 16mm movie films of test 13A (the misfire). Here the foam is shown to flow around the vertically suspended smock fuel. A small wave formed behind the smock, making the foam higher by 12 to 15 inches in the back of the smock as opposed to the front. The back of the smock was facing the foam generator.

The weight of foam raw material consumed ranged from 42 to 77 pounds for the air test (1-4A), from 42 to 73 pounds for the 95% oxygen tests (5-8A), from 44 to 53 for the 50% oxygen tests (9-12) and from 103.5 to 116. for lab smock fuel tests (13-18). Similarly the volume of foam raw material (foam solution includes water and foam concentrate - BLISS Jet-X^R) used is .67 to 1.23 cubic feet for air tests, .67 to 1.05 cubic feet for 95% oxygen tests, .70 to .85 cubic feet for 50% oxygen tests, and 1.66 to 1.86 cubic feet for lab smock fuel tests. This data is tabulated in Table 8. These weight and volume values could be reduced by increasing the expansion ratio of foam, i.e. volume of foam generated relative to volume of foam raw material consumed. This can be accomplished by varying the pressure level of the raw material. It was a control here and not optimized for every chamber environment. The expansion ratio in one standard atmosphere (air) varies as an approximate parabolic function with inlet pressure into the generator; its maximum expansion ratio occurs at 100 psia, the pressure used for all tests. Obviously, this approach in conjunction with such hardware optimization techniques such as reducing system inertia and repackaging would reduce the amount of foam raw material required.

Formulation date and batch numbers of the E. W. BLISS COMPANY Jet-X^R foam concentrate, which is a proprietary formulation consisting of primarily an aqueous blend of anionic alkyl sulfates and amphoteric protein hydrolysate, are listed below:

Test No.	Description and (Formulation No.)	Formulation Date	Batch No.
	E. W. BLISS CO.'s	May 1968	C-135
1 through 8 including 1A through 7A inclusive	Rockwood Jet-X^R Foam Liquid (UX-3180)		
8A through 15 inclusive	(UX-3180)	July 1968	C-137
16 and 17	(UX-3180)	Sept 1968	C-141
18	(UX-3180)	Apr 1968	C-130

A projection of assembled test data to show performance expected in a space vehicle of 10,000 cubic feet folume at both 5 and 10 psia would be somewhat difficult to accomplish at this point. However, directly extrapolated requirements can be predicted. Assuming that a fully optimized foam generator system could produce 2000 cfm of foam, it would take a generator one minute to inundate 20 percent of the space vehicle including whatever might be burning. Further, assuming the expansion ratio for these optimized generators would reach 500:1 then the generator would require 4 cubic feet of raw foam material. Total weight of raw material would be 250 pounds.

If water from the life support system could be utilized (assuming 237.5 pounds are available) then only 12.5 pounds would be required for Jet-X[R] foam liquid concentrate. Total weight of a flight generator is conservatively estimated at 15 pounds. Therefore, total weight for a flight system could be as low as 27.5 pounds plus another 25 pounds for tank, lines and a flexible hose.

It is recommended that hardware development optimization be initiated as the next step for the space vehicle fire protection with concentration on:

1. Optimization of foam expansion ratio.

2. Size and weight reduction of the foam generator unit.

3. Special design considerations for weightless foam generation.

4. Location of generators in space vehicle.

5. Incorporating automatic detection (actuation) devices.

APPENDIX A

SPECIAL USAF TEST REPORT

on Test 13 to 18

E.W. Bliss Company
Research and Development Division
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A GULF + WESTERN COMPANY

PREPARED BY R. J. Charno
R. J. CHARNO

DATE 10 January 1969

CHECKED BY F. Schw

APPROVED BY M. Q. Mezi

EVALUATION OF HIGH EXPANSION FOAM FOR SPACECRAFT FIRE EXTINGUISHMENT

CONTRACT NAS 9-7983
MIPR NUMBER APO-69-003
PROJECT NUMBER 3048
TASK 304807

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INTRODUCTION

Fire extinguishing tests using high expansion foam in 100% oxygen and 70% oxygen-30% helium were conducted by the E. W. BLISS COMPANY under Contract NAS 9-7983, Supplement Agreement Number 2, MIPR Number APO-69-003, Project 3048, Task 304807. Four tests were added to a group of twelve foam evaluation tests conducted for NASA. This report presents the results of the added tests only. These tests were conducted during the week of 4 November 1968.

SUMMARY

High expansion foam has proven itself an excellent fire-fighting tool in normal environments such as one atmosphere and 20 percent oxygen. In other environments, such as oxygen enriched atmosphere (OEA), the only data collected to date has been from approximately twenty feasibility type tests. These tests firmly indicate that fully optimized foam fire extinguishing systems will prove to be an excellent fire-fighting tool for environments encountered in hypobaric and hyperbaric conditions.

Six tests were conducted in oxygen enriched atmospheres to determine the effectiveness of high expansion foam in extinguishing the fires. The foam extinguished the vertically suspended white cotton laboratory smocks which had burned from 6 to 28 seconds in all cases, except in the 16.5 psia 100% oxygen environment, and saved 64% to 99% of these smocks. The smocks consumed could have been saved by introducing the foam into the chamber at faster rates. Foam generator used in this series of tests was a standard municipal fire department type unit, whose heavy duty, high inertia, rotating components precluded rapid acceleration and short reaction time. With more optimized hardware, it is anticipated that most of the smock could have been saved under the same test conditions.

A wild field mouse was placed three feet from the fire area for the 100% oxygen 10 psia test (17). After approximately 16 seconds of burn of the smock, apparent extinguishment took place. Maximum chamber temperature (at ceiling six feet away from mouse) reached 357°F. The mouse apparently suffered no ill effects as a result of foam or his one hour stay in the

chamber after being exposed to the fire and then being fully submerged in the foam.

The first two fire tests (13 and 14) in 16.5 psia 100% oxygen environments illustrated that the foam must be introduced at a faster rate than was capable with the test hardware. The flame engulfed the coat faster than the foam propagated up the vertically suspended coat, therby precluding extinguishment from occurring. The nap fire took 2.69 seconds to propagate from bottom of the coat (where Nichrome igniter wire was embedded in material) to top. Bulk material fire initiated all over the smock, in holes the size of quarters. This occurred 1.18 seconds after nap fire had reached the top of the smock. The bulk material fire consumed 87% of the smock in 8 additional seconds, or a total of 11.87 seconds after nap flames appeared. Foam reached the coat hanger 20.92 seconds after the nap fire started at the bottom of the smock. In a similar group of tests, but with an aluminum mannequin inside the lab smock, the mannequin seated, and the smock ignited by a Nichrome wire around the mannequin's hips, approximately one-half of the smock was saved after 11 seconds of burn.

The second two fire tests (15 and 16) in 5 psia 100% oxygen environments illustrated that foam can extinguish lab smocks that burned for 7.5 and 16 seconds and save 99 and 66% of the garment respectively.

The last test (18) in 5 psia 70% oxygen-30% helium environment illustrated high expansion foams ability to extinguish cotton coveralls that burned 28 seconds while saving 64% of the garment.

In conclusion, it appears that high expansion foam provides an excellent method for extinguishing fire in a hypobaric spacecraft type environment. It is recommended that the development of prototype hardware for hypobaric and hyperbaric environments be initiated.

EXPERIMENTAL PROCEDURES AND OBSERVATIONS

A 400 cubic foot hypo/hyperbaric fire test chamber facility was assembled and foam generator system arranged as shown in Figure A-1, schematic of test chamber, and Figure A-2, photograph of inside of chamber showing smock in place after Test 15. The foam generator was placed inside the chamber while the foam solution and gas pressurizing system was placed outside. Pressurized foam solution passed through the tank wall into the generator while the chamber environment was used to expand the foam solution. (Some of this foam is still in evidence under and behind the coat in Figure A-2)

The following fire tests were accomplished:

Test Number 13A

Foamed in chamber with 98.8% oxygen and 16.2 psia. No ignition occurred, due to energizing the igniter wire for too short a time, however, review of movie coverage illustrated the foam's ability to flow around the vertically suspended smock. A small wave formed behind the smock making the foam higher by 12 to 15 inches in the back of the smock as opposed to the front. The back of the smock was facing the foam generator.

Test Number 13B

Installed new lab smock and increased length of time igniter wire was energized to 5 seconds. Counting elapsed time from beginning of Nichrome wire energizing, the following occurred:

Elapsed Time in Seconds	Event
0	energize Nichrome wire
2.88	nap fire starts
4.8 *	de-energize Nichrome wire
5.0 *	open foam solution solenoid valve
5.57	nap fire propagates to top of lab smock (5.57 - 2.88=2.69 second propagation time)

Elapsed Time in Seconds	Event
6.75	bulk fuel ignites <u>all over</u> smock in holes the size of quarters due to nap flash fire
7.9 *	foam comes out of generator (bulk fuel burn time so far = 7.90 - 6.75 = 1.15 seconds)
14.75	87% of smock consumed by flames and flame intensity subsides (14.75 - 6.75 = 8 seconds bulk fuel fire)
23.80	foam reaches coat hanger - total depth 70-inches

* Data from oscillograph record, other from movie photos.

The flame engulfed the smock before the foam had a change to begin extinguishing it. 87% of the garment was consumed.

<u>Test Number 14</u>

Same as Test Number 13B except modified automatic control system to permit remote (at the chamber window instead of control panel) operation of foam solution solenoid valve. Results were similar with an 8 second bulk fuel fire and foam enveloping the burn 7 additional seconds later. 89% of the garment was consumed.

<u>Test Number 15</u>

Foamed in chamber with 97.9% oxygen and 4.9 psia. Saved 99% of the smock with a burn of 6.43 seconds, apparent extinguishment took place 7.5 seconds after flame initiation or 6.88 seconds after activating extinguisher. Time-Event History for this test is as follows:

Elapsed Time in Seconds	Events
0	energize igniter wire
4.45	bulk fuel (no nap fire) fire ignites at Nichrome wire
4.9 *	de-energize igniter wire

Elapsed Time in Seconds	Event
5.0 *	open foam solution solenoid valve
6.2 *	foam comes out of generator and hits switch
8.32	foam starts to cover floor of chamber beneath bottom of smock
10.88	bulk fuel fire enveloped by foam
11.88	apparent extinguishment occurs. Elapsed time from flame start 11.88 - 4.45 = 7.43 seconds
17.52	foam obscures vision, i.e. reaches camera lens level

Test Number 16

Similar parameters to Test Number 15 except burned longer, 16 seconds, while saving 66% of smock. Time-Event History for this test is as follows:

Elapsed Time in Seconds	Event
0	energize igniter wire
4.5	bulk fuel (no nap) fire ignites at Nichrome wire
4.9 *	de-energize igniter wire
15 *	open foam solution solenoid valve
16.2 *	foam comes out of generator and hits switch
18.9	foam starts to cover floor of chamber beneath bottom of smock
19.5	bulk fuel fire enveloped by foam
20.5	apparent extinguishment occurs. Elapsed time from flame start 20.5 - 4.5 = 16 seconds
26.7	foam obscures vision, i.e. reaches camera lens level

Test Number 17

Foamed in chamber with 98.5% oxygen and 9.8 psia

A wild field mouse was placed in chamber three (3) feet from smock fuel. Mouse survived test and one (1) hour post-foaming stay in chamber and apparently suffered no ill effects. Chamber temperature reached 357°F. 71% of the smock fuel was consumed after a burn of 15.93 seconds. Time-Event History is as follows:

Elapsed Time in Seconds	Event
0	energize the igniter wire
3.19	nap fire starts
3.56	bulk fuel fire starts
4.50	ignition wire becomes visibily red
4.90 *	de-energize ignition wire
4.94	nap fire propagates to top of coat (4.94 - 3.19 = 1.75 seconds)
6.9	foam solution solenoid valve actuated
7.32	foam starts
7.7 *	foam hits foam-out-of-generator switch
10.58	foam envelopes bottom of coat
19.12	foam envelopes top of coat
19.12+	apparent extinguishment and 29.0% of smock saved

Test Number 18

Foamed in chamber with 70% oxygen-30% helium using white coverall with left arm missing. Burned for 28 seconds and saved 64% of coveralls. Time-Event History is as follows:

Elapsed Time in Seconds	Event
0	energize igniter wire
4.06	smoke appears from igniter wire area
4.56	Nichrome igniter wire becomes visibly red in color
4.9 *	de-energized igniter wire
7.88	bulk fuel fire starts - no nap fire

Elapsed Time in Seconds	Event
14.5	foam solution solenoid valve triggered but back-up ball valves were closed causing no-flow condition
23.55 **	foam starts up (movie)
24.7 *	back-up ball valves opened - foam solution starts to flow
25.5 *	foam comes out of generator and actuates foam-out-of-generator switch
26.56	foam envelopes top of coveralls fuel specimen
31.55	foam obscures vision to bottom of coat
35.91	foam obscures vision to top of coat
35.91+	apparent extinguishment takes place and 63.9% of coveralls were saved

* Data from oscillograph record, other from movie coverage
** This point approximately determined from movie data

TEST DATA SUMMARIES

TABLE 1	Chamber Environment
TABLE 2	Time Information from Movie Coverage and Oscillograph Data
TABLE 3	Loss of Weight of Fuel Specimen
TABLE 4	Time Histories from Oscillograph Data
TABLE 5	Gas Analysis Data
TABLE 6	Chamber Pressure and Temperature, Fuel Temperature and Foam Solution Flow Rate
TABLE 7	Photographic Log
TABLE 8	Volume of Foam Generated and Foam Solution Used

TABLE 1

Chamber Environment

Test Number	Chamber Oxygen Percentage	Chamber Pressure Psia
13	98	15.8
14	98.3	16.4
15	97.9	4.9
16	98.4	5
17	98.5	9.8
18	70 *	4.9

* 30% Helium Diluent

TABLE 2

Time Information from Movie Coverage and Oscillograph Data

	TIME IN SECONDS		
Test No.	From Initiation of Flame to Start of Foam Discharge	From Start of Foam Discharge to Loss of Vision (Camera Lens Inundated)	From Initiation of Flame to Apparent Extinguishment
13	5.02	15.9	N/A
14	N/A	N/A	N/A
15	1.75	11.32	7.43
16	11.7	10.5	16
17	4.51	11.42	15.93+
18	17.62	10.41	28.03+

TABLE 3

Loss of Weight of Fuel Specimen

Test No.	Original Weight, Grams	Final Weight, Grams	Loss, Grams	Loss, Percent
13	720.5	81.3	639.2	87.3
14	733.5	80.5	653.0	89.3
15	707.9	698.1	9.8	1.38
16	710.5	467.5	243.0	34.2
17	714	203.8	510.2	71.5
18	1151.4 *	736.0	415.4	36.1

* Coveralls, all others are white cotton lab smocks

TABLE 4

Time Histories from Oscillograph Data

Test No.	Time of Actuating Foam Generator Relative to Ignition, Seconds	Time of First Foam Appearance, Seconds	Time for Foam Generator to Reach Maximum Output, Seconds	Time for Foam to Envelope Burning Fuel Specimen, Seconds	Time to Extinguish Fire,* Seconds
13	5	7.9	5.4	7.9	140
14	4.3	5.4	4.8	5.4	35
15	5	6.2	5.7	6.2	***
16	15	16.2	15.5	16.2	45
17	6.9	7.7	7.2	7.7	19
18	14.5	25.5	24.7	25.5	100

* Fuel temperature drops to approximately 140°F

** Fuel specimen temperature stayed below 140°F

TABLE 5

Test Chamber Gas Analysis Data

	Before Test	After Test		
Test No.	Percent Oxygen by Volume	Percent Oxygen by Volume	PPM CO	PPM CO_2
13	98	89.2-88.8	70	65,000-52,500*
14	98.3	91.2-92.0	69	67,200-54,500*
15	97.9	92.0-91.5	50	2,225- 2,225
16	98.4	89.7-80.4**	2185-337	52,400-36,550*
17	98.5	78.4-82.3***	183-151.5	48,100-53,200
18	70	57.5-59.2	1740-740	13,400- 9,570*

* Decrease in CO level attributed to solubility of CO_2 in aqueous foam material. The first measurement was taken immediately after the test while the second was taken approximately 12 minutes after the test.

** Nitrogen accidentally injected from foam cart after fire for second sample only.

*** Nitrogen accidentally injected from foam cart after fire for both samples.

TABLE 6

Chamber Pressure and Temperature, Fuel Temperature and Foam Solution Flow Rate

Test No.	Chamber Pressure Start/Max, Psia	Chamber Temp. Start/Max, °F	Fuel Specimen Temperature Start/Max, °F	Flow Rate Foam Solution Gallons/Minute
13	15.8/26.5	82/367	77/447	20.2
14	16.4/27.3	67/399	77/643	21.2
15	4.9/ 5.1	67/67	77/117	23.5
16	5 / 6.5	53/169	75/314	20.2
17	9.8/14.6	67/357	75/186	20.2
18	4.9/ 6.6	68/383	77/251	18.5

TABLE 7

Photographic Log *

	Still		16mm Movie **		
Test No.	Before	After	Before	During	After
13A	X	Misfire	X	Misfire	
13B	-	X	-	X	X
14	X	X	X	X	X
15	X	X	X	X	(1)
16	X	X	X	(2)	X
17	X	X	X	X	X
18	X	X	X	X	X

* Photographic (color still and 16mm movie) coverage not enclosed in this report.

** Consisted of using 3 cameras: Outside camera in chamber manway for before and after coverage; inside front camera for before, during and after coverage; inside rear camera for before, during and after coverage.

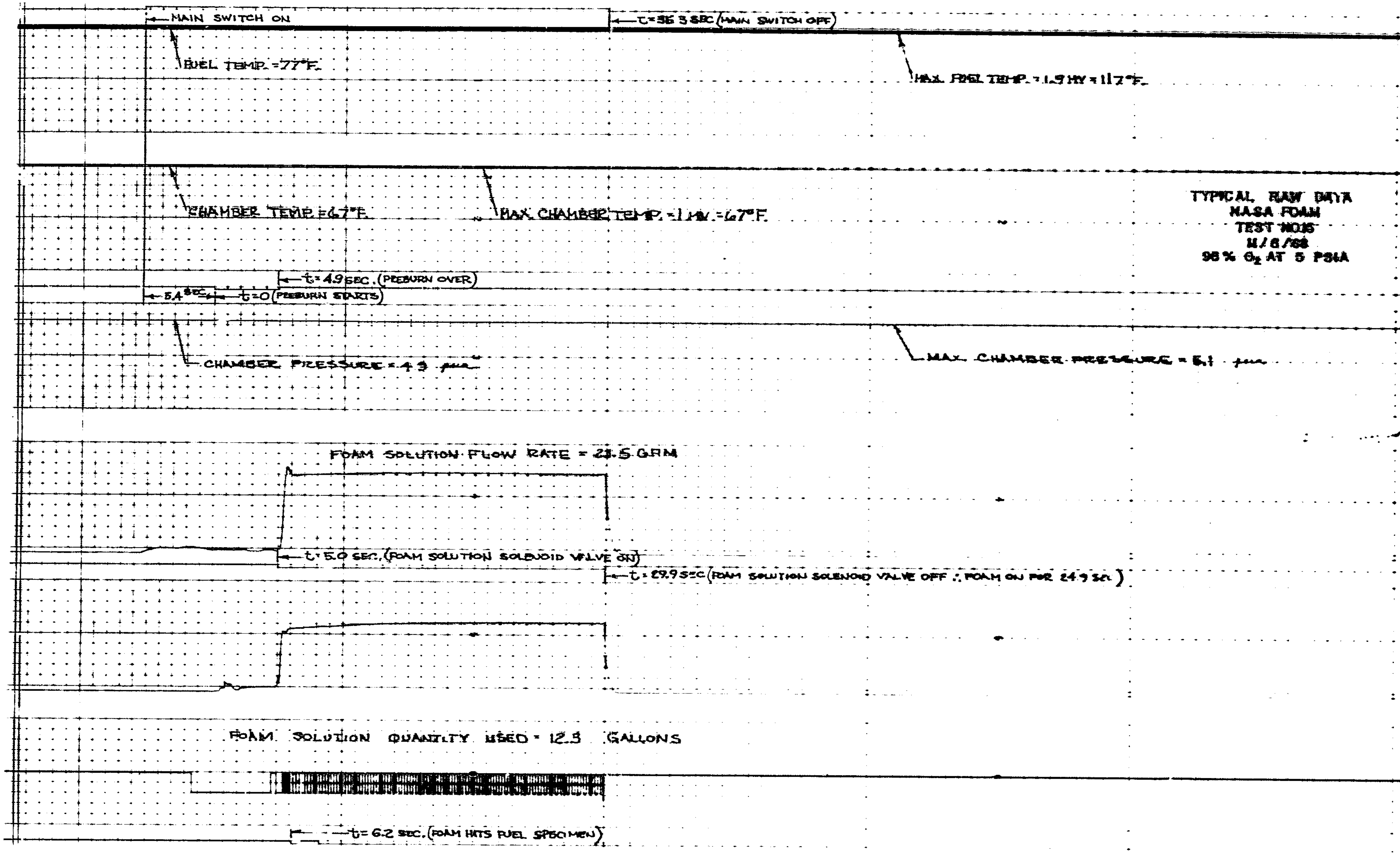
(1) No coverage from inside front camera after test.

(2) No coverage from inside front camera during test.

TABLE 8

Volume of Foam Generated and Foam Solution Used

Test No.	Volume of Foam Generated, Cubic Feet	Depth of Foam Generated, Inches	Weight of Foam Solution Used, Pounds	Volume of Foam Solution Used, Cubic Feet	Expansion Ratio of Foam (Foam Generated Relative to Foam Solution Used)
13	370	60	103.5	1.66	223:1
14	416	72	105.5	1.69	246:1
15	339.5	66	111.5	1.79	190:1
16	416	72	112	1.8	232:1
17	416	72	116	1.86	224:1
18	416	72	N/A	N/A	N/A


MAIN SWITCH ON
t = 56.3 SEC (MAIN SWITCH OFF)
FUEL TEMP. = 77°F.
MAX. FUEL TEMP. = 1.5 MV = 117°F.
CHAMBER TEMP. = 67°F.
MAX. CHAMBER TEMP. = 1 MV. = 67°F.
TYPICAL RAW DATA
NASA FOAM
TEST NO36
11/6/68
98% O_2 AT 5 PSIA
t = 4.9 SEC. (PREBURN OVER)
5.4 SEC.
t = 0 (PREBURN STARTS)
CHAMBER PRESSURE = 4.9 psia
MAX. CHAMBER PRESSURE = 5.1 psia
FOAM SOLUTION FLOW RATE = 23.5 GPM
t = 5.0 SEC. (FOAM SOLUTION SOLENOID VALVE ON)
t = 29.9 SEC (FOAM SOLUTION SOLENOID VALVE OFF ∴ FOAM ON FOR 24.9 SEC.)
FOAM SOLUTION QUANTITY USED = 12.3 GALLONS
t = 6.2 SEC. (FOAM HITS FUEL SPECIMEN)

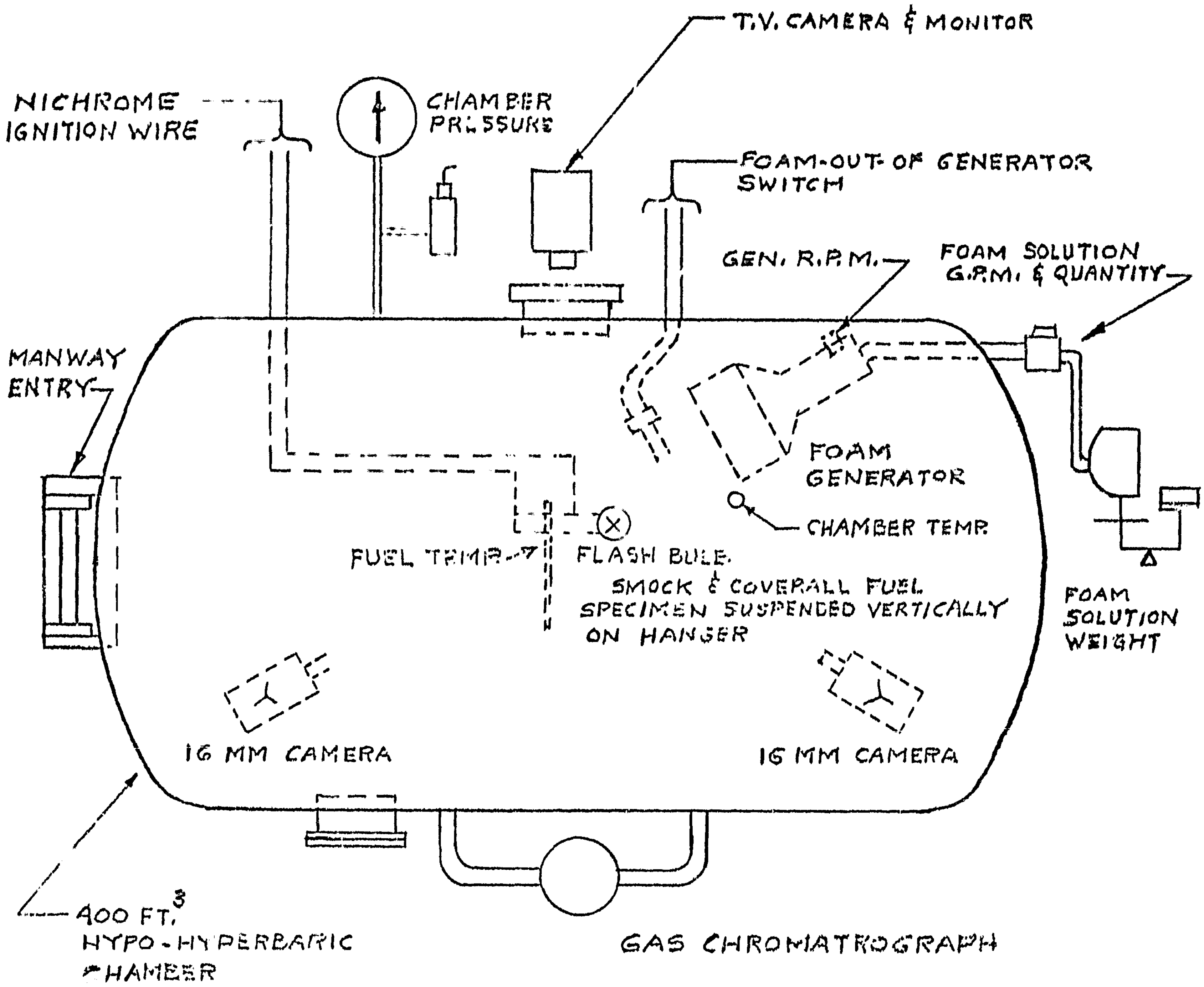


FIGURE A-1 - SCHEMATIC OF TEST CHAMBER

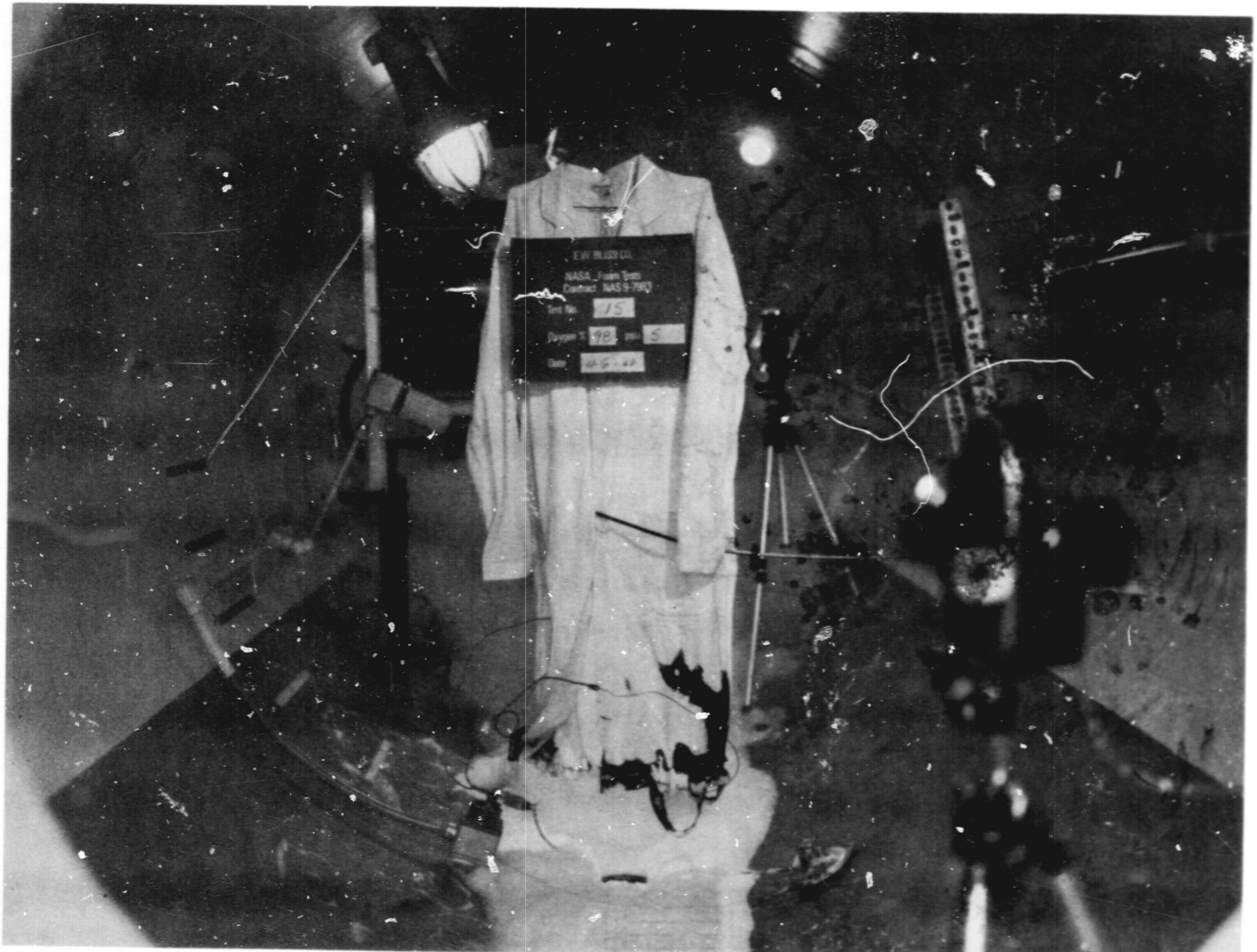


FIGURE A-2 - PHOTOGRAPH OF INSIDE OF TEST CHAMBER SHOWING SMOCK FUEL IN PLACE AFTER TEST NO. 15

APPENDIX B

NASA FOAM TESTS - CHECK OFF LIST

TEST NUMBER 7A

(X) Check Off
(*) Get Data

1. Load all cameras and install 2 remotely operated cameras ___X___ (X)
2. Weight of fuel specimen __142.1__ grams (*)
   Take one 4X5 "before" picture of fuel specimen ___X___ (X)
3. Install fuel specimen, igniter and flash bulb ___X___ (X)
4. Check foam generator - turns free ___X___ (X)
5. Charge foam carts ___X___ (X)
6. Weight foam carts __470__ (*)
7. Pressure setting on foam cart __100 psi__(*)
8. Install marked placard and take movies ___X___ (X)
9. Run remote cameras 30 seconds on placard ___X___ (X)
10. Remove placard and set cameras for remote operation ___X___ (X)
11. Close chamber door ___X___ (X)
12. Charge chamber with gas
    __95% O_2__ (air, O_2, etc) (*)
    __9.8__ psia (*)
    __65__ °F (*)
13. Withdraw and analyze two gas samples
    __99.9__ % O_2 before (*)
14. Open solenoid protecting "Ball Valves" ___X___ (X)
15. Burn ___X___ (X)
16. Stop foam ___X___ (X)
17. Amount of foam generated - height in inches __48__ (*)
18. Time foam generator on __12.2__ seconds (*)
19. Shut off instrumentation when fuel temperature hits 140° __64.6__ (*)
20. Maximum fuel specimen temperature __386°F__ (*)
21. Maximum chamber temperature __101°F__ (*)
22. Withdraw and analyze two gas samples ___X___ (X)
23. Percent of O_2 __97.8__ (*) 97.9
24. PPM of CO __50__ (*)
25. PPM of CO_2 __5410__ (*) 4640
26. Vent to atmosphere ___X___ (X)
27. Open door ___X___ (X)
28. Get foam away from fuel specimen for pictures ___X___ (X)
29. Reinstall placard ___X___ (X)
30. Take 1 still of inside of chamber ___X___ (X)
31. Take movies of inside of chamber ___X___ (X)
32. Run rest of film on remote cameras off on placard ___X___ (X)
33. Remove remote cameras, unload and mark film containers ___X___ (X)

34. Take one (1) still of burned fuel specimen outside of chamber __X__ (X)
35. Put films together for shipment to office Attn: Ed Cheslack __X__ (X)
36. Remove placard and erase markings __X__ (X)
37. Sketch with dimensions amount of fuel consumed __X__ (X) Mark with date and test number
38. Mark fuel specimen with test number, put away to dry out overnite __X__ (X)
39. Weight of dried fuel specimen __116.3__ grams (*)
40. Weight of foam cart after test __414.5__ lbs (*)
41. Pressure N_2 cylinder in foam cart after test __2000__ psi (*)
42. Gallons of foam solution consumed __6.6__ (*)
43. Cubic feet of foam solution consumed __.89__ (*)
44. Expansion ratio of foam __336:1__ (*)
45. Observations -

After Temperature = 80°F
Evacuated 2 psia +
Filled 14.7 psia O_2
Evacuated 2 psia
Filled 10 psia = 99.9% O_2

APPENDIX C

NASA FOAM TESTS - RAW DATA

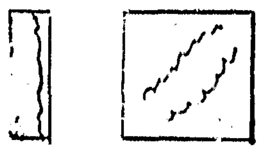
TEST NUMBER 7A

A. Gas: 95% oxygen
B. Pressure: 10
C. Burn Time: 9.9 Seconds

1. Weight of dry fuel specimen

Before 1666.6 grams
After 1640.8 grams
Burned 25.8 grams

Sketch showing amount burned



40% of specimen surface consumed

2. Before test oxygen % 99.9
Before test pressure psia 9.8

3. Time of actuating foam generator relative to start of ignition 12.4 seconds

4. Time of first foam appearance relative to start of ignition 13.2 seconds

5. Time for foam generator to reach maximum output relative to start of ignition 12.6 seconds

6. Flow rate of foam solution to generator 24.5 GPM

7. Time to envelope burning material relative to start of ignition 13.2 seconds

8. Time to extinguish fire relative to start of ignition NA seconds
(Time for fuel specimen temperature to reach 140°F, <u>however</u>, observe and compare what happens when foam hits fuel specimen - there may be thermocouple lag)

9. Maximum fuel temperature 386°F
Maximum chamber temperature 101°F

10. Maximum chamber pressure 10.6 psia

11. After test

    % O_2 97.8-97.9

    PPM CO_2 5410-4640

    PPM CO 50

12. Volume of foam generated 299 cubic feet
    Depth of foam generated 48 inches
    Comments about how foam filled chamber:

13. Weight of foam solution used 55.5 pounds
    Volume of foam solution used 6.66 gallons

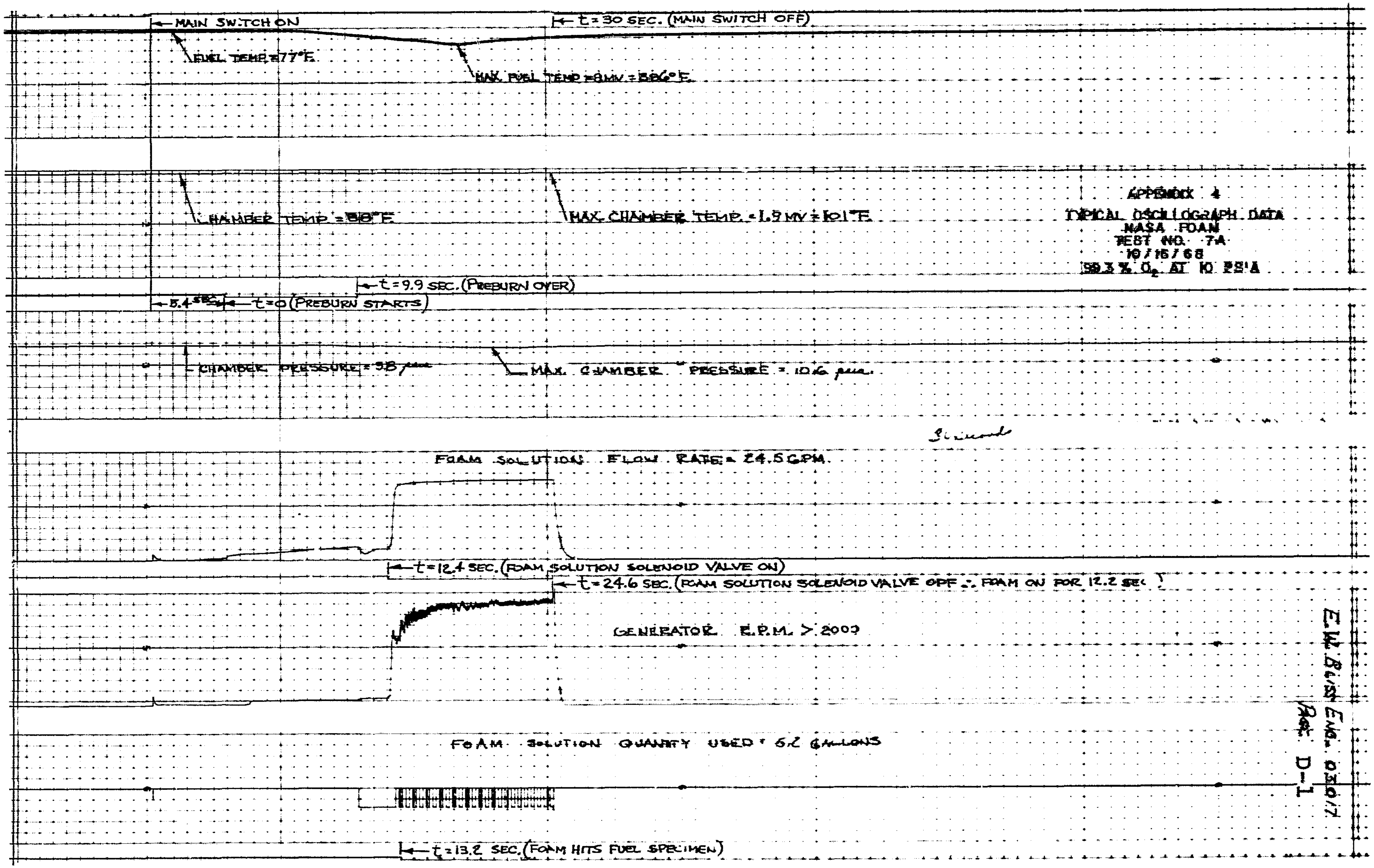
14. Formulation and batch numbers of foam used

    Batch No. C-135   Formulation No. UX-3180

15. Expansion ratio of foam 336:1

16. Observations

APPENDIX D



MAIN SWITCH ON
t = 30 SEC. (MAIN SWITCH OFF)
FUEL TEMP = 77°F.
MAX. FUEL TEMP = 8MV = 886°F.
CHAMBER TEMP = 88°F
MAX. CHAMBER TEMP. = 1.9 MV = 101°F.
APPENDIX 4
TYPICAL OSCILLOGRAPH DATA
NASA FOAM
TEST NO. 7A
10/16/68
59.3 % O_2 AT 10 PSIA
t = 9.9 SEC. (PREBURN OVER)
5.4 SEC.
t = 0 (PREBURN STARTS)
CHAMBER PRESSURE = 5.8 psia
MAX. CHAMBER PRESSURE = 10.6 psia
FOAM SOLUTION FLOW RATE = 24.5 GPM.
t = 12.4 SEC. (FOAM SOLUTION SOLENOID VALVE ON)
t = 24.6 SEC. (FOAM SOLUTION SOLENOID VALVE OFF ∴ FOAM ON FOR 12.2 SEC)
GENERATOR R.P.M. > 2000
FOAM SOLUTION QUANTITY USED = 5.2 GALLONS
t = 13.2 SEC. (FOAM HITS FUEL SPECIMEN)
E.W. Bliss Eng. 03017
Page: D-1

APPENDIX E

TYPICAL GAS ANALYSIS DATA - TEST 7-A