Naval Research Laboratory

Washington, DC 20375-5320

NRL/MR/6180--00-8517

Assessment of Fire Growth and Mitigation in Submarine Plastic Waste Stowage Compartments

CHUKA C. NDUBIZU
JOHN P. FARLEY

GEO-Centers, Inc.
4640 Forbes Boulevard, Suite 130
Lanham, MD

ROGER A. BROWN
PATRICIA A. TATEM
FREDERICK W. WILLIAMS

Navy Technology Center for Safety and Survivability
Chemistry Division

December 29, 2000

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave Blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 29, 2000	May-September 2000

4. TITLE AND SUBTITLE

Assessment of Fire Growth and Mitigation in Submarine Plastic Waste Stowage Compartments

5. FUNDING NUMBERS

PE - 63721N
Task - S0401000

6. AUTHOR(S)

Chuka C. Ndubizu,* John P. Farley,* Roger A. Brown, Patricia A. Tatem, and Frederick W. Williams

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/MR/6180--00-8517

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Naval Sea Systems Command
2531 Jefferson-Davis Highway
Arlington, VA 22242-5160

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

*GEO-Centers, Inc., 4640 Forbes Boulevard, Suite 130, Lanham, MD 20706

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

This report presents the results of tests to assess the fire growth characteristics and the ease of fire control in the proposed Virginia-class and the Ohio-class submarine plastic waste stowage compartments. Four tests were conducted in the Virginia-class compartment with the door either closed or open and the ventilation either on or off. One test was conducted in the Ohio-class compartment with a partially closed door.

The results show that initially the fire in the proposed Virginia-class submarine plastic waste stowage compartment with the door open grew slowly but developed to about 600 KW fire if the ventilation was off or 400 KW fire if the ventilation was on. In each case the fire produced very thick smoke at the early stage. When the door was closed, the fire was oxygen limited whether the ventilation was on or off. The maximum heat release rate with the door closed was about 160 KW with the ventilation on and about 100 KW with the ventilation off. With the partially closed door in the Ohio-class compartment, the fire was also oxygen limited, and the maximum heat release rate was of the order of 200 KW.

Finally, in each test, the fire was fought after it reached its peak, and all the fires were controllable in less than one min using one unit of bottled Aqueous Film-Forming Foam (AFFF) or water from a 3/4 in. hose line.

14. SUBJECT TERMS

Plastic waste disposal
Burning characteristics
Submarine environment

15. NUMBER OF PAGES

45

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

CONTENTS

ASSESSMENT OF FIRE GROWTH AND MITIGATION IN SUBMARINE PLASTIC WASTE STOWAGE COMPARTMENTS

1.0 INTRODUCTION

In compliance with the Act to Prevent Pollution from Ships (APPS) as amended by the FY99 Defense Authorization Act, the new Navy guidelines for the handling and disposal of wastes in submarines require that all plastic materials be stored onboard for shore disposal. In both surface ships and submarines the plastic waste is processed before storage in order to reduce odor and bulk. In submarines, this involves first cleaning the plastic of residues (e.g. food) and then compacting it inside (polyethylene) cylindrical bags using the trash compaction unit. In the SSN 688 LOS ANGELES class submarine, the compaction pressure is of the order of 100 psi while in the 726 OHIO class and 744 VIRGINIA class submarines the pressures are of the order of 500 psi [1]. A typical compacted bag of plastic waste is approximately 25 cm (10 inches) in diameter, 61 cm (24 inches) long. The compacted plastic waste is contained in two layers of plastic bags, the last of which is heat sealed to reduce odor. These bags are stored in holding compartments for shore disposal. In the VIRGINIA class submarines, it is proposed that the plastic waste bags (PWB) be stored in the 85 ft^3 Environmental space that is connected to the trash room by a doorway opening. This space is ventilated by a 3.54 m^3/min (125 cfm) supply while the trash room is ventilated by a 7.08 m^3/min (250 cfm) exhaust (see Fig. 1). On the SSBN 726 OHIO class submarines, a Food Storage Module is proposed as the holding container which has a volume of about 2.6 m^3 (93 ft^3) and has no ventilation.

In surface ships, plastic waste is processed by first shredding the plastic and then heating it to 149°C (300°F) in a compression chamber to reduce sanitation and odor problems. This significantly reduces the volume of the waste by a factor of about 30. The processed waste on the surface ship is relatively denser than its counterpart in the submarine. A detailed fire hazard assessment of the processed waste onboard surface ships was performed by Leonard et al. in 1994 [2].

The stowage of the plastic waste bags in unprotected spaces in submarines may present significant fire hazard and this hazard needs to be assessed. The initial effort on this problem had theoretically quantified the ignition potential of the bags, the fire growth and ease of fire detection and suppression in the stowage space [1]. Later fire tests were conducted to assess the ignition potential, the fire growth characteristics, ease of detection and control of PWB fires in the OHIO class submarine holding containers [3]. These tests were conducted with simulated PWB.

Manuscript approved October 25, 2000.

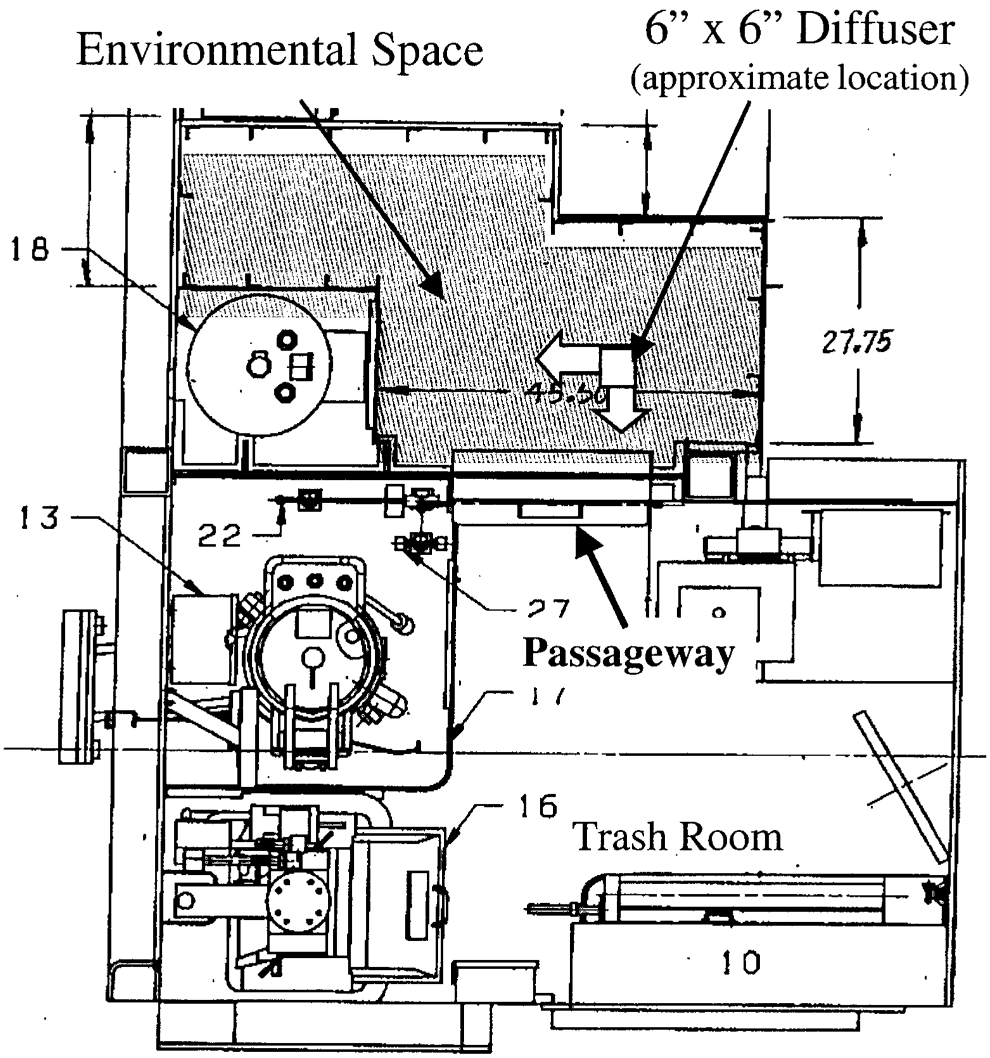

Figure 1: VIRGINIA Class Submarine Potential Plastic Waste Storage Compartment

1.1 Objectives

The current tests were concentrated on the proposed PWB stowage compartment in the VIRGINIA and OHIO Class submarines. The tests were conducted with real PWB from several submarines, for example, the USS MONTEPELIER. Real PWB contain actual submarine generated plastic waste as opposed to laboratory generated (simulated) plastic waste. The objectives of the current tests are:

- To assess the fire growth characteristics of real PWB burning inside the proposed VIRGINIA class plastic waste stowage compartment with and without ventilation;
- To assess the fire growth characteristics of real PWB burning inside the OHIO class stowage compartment with the door closed except for the top one-quarter.
- To assess the effectiveness of and techniques for extinguishing with portable AFFF extinguishers and water hose-line as agents for extinguishing these fires

2.0 APPROACH

The tests were conducted at the Naval Research Laboratory Fire Test Facility at the Chesapeake Bay Detachment. The proposed VIRGINIA class PWB stowage compartment was simulated by modifying an OHIO class submarine Food Storage Module of approximately equal volume, which was used in earlier tests [3]. The compartment was constructed of ~ 2 mm (0.078 inch) thick steel (actual compartment made of aluminum) with dimensions 1.34 m deep, 1.03 m wide and 1.87 m high (53 inches x 41inches x 74 inches). The walls were braced with angle iron for strength. The enclosure has a hinged door 1.03 m x 1.87 m (41 inches x 74 inches) on one of the narrow sides and the enclosure floor has a lip 9cm (3.5 inches) high to prevent molten plastic from flowing outside the container. The compartment was modified by the provision of a 3.54 m^3/min (125 cfm) supply ventilation through a diffuser at the center of the ceiling and the construction (on the existing door) of a door similar in size and shape to the passageway opening in the VIRGINIA class submarine compartment. In the VIRGINIA class tests, the larger door was always closed while the smaller door was open or closed depending on the test requirement. A picture of the modified compartment is shown in Figure 2.

2.1 Fire growth and extinction

Fire growth was assessed in terms of increase or decrease (with time) of temperatures, oxygen (O_2), carbon dioxide (CO_2) and carbon monoxide (CO) concentrations and heat release rate inside the fire compartment. Each test was conducted with 20 PWB packed in three layers within the lower 1/3 of the compartment as shown in Figure 3. This lower 1/3 of the compartment was lined with aluminum foil to make clean up easier. The compartment was instrumented with 6 thermocouples (thermocouples 1-6) in the space above the bags and 2 thermocouples (7 and 8) placed in between the bags. The gas-sampling probe for a continuous sampling of the hot gases is at the center of the compartment (Fig. 3). Figure 4 shows the front and plan views of the compartment showing the positions of these sensors.

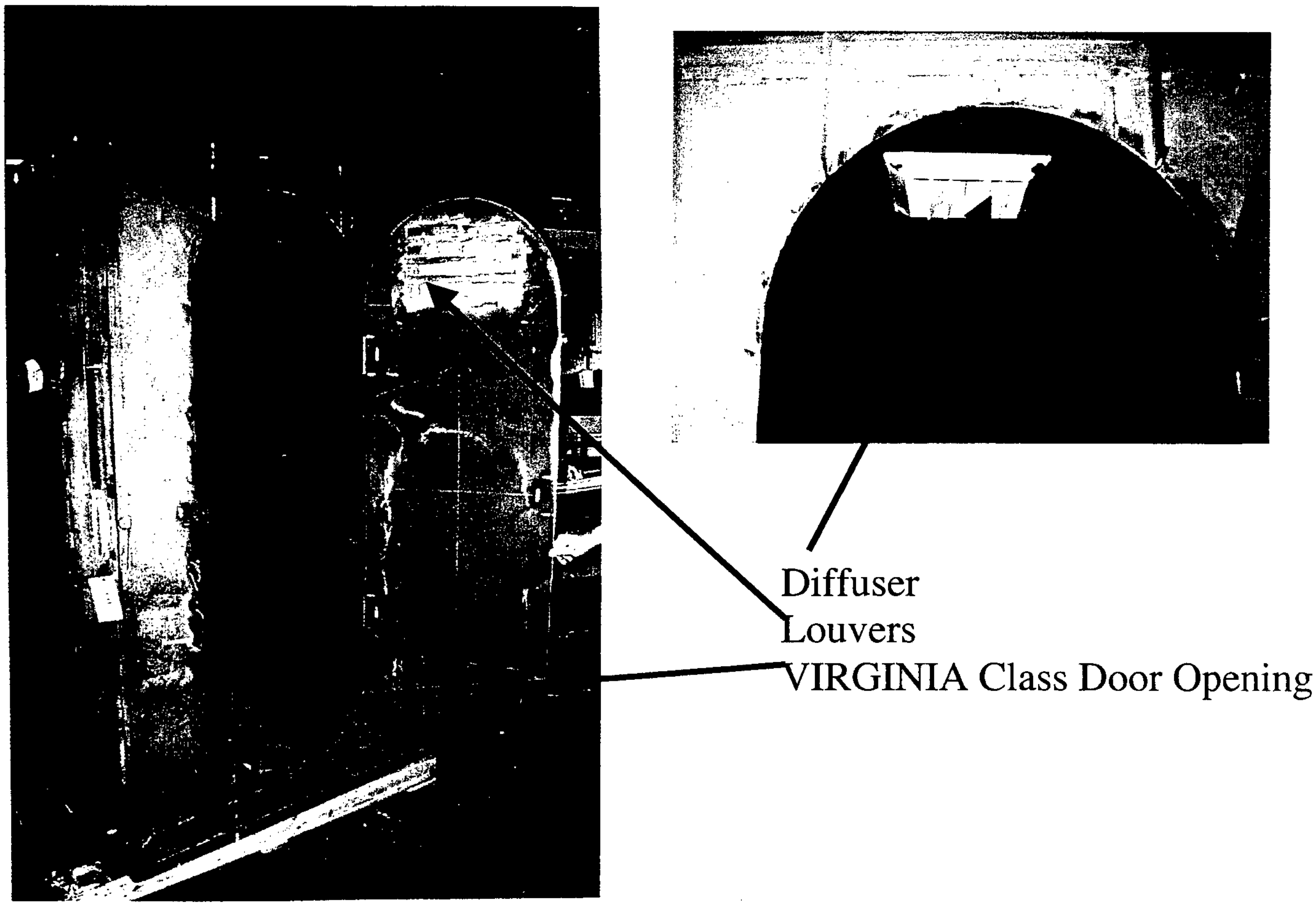

Figure 2: A picture of the modified OHIO class Submarine Plastic waste stowage compartment for the VIRGINIA Submarine Plastic waste stowage compartment fire test.

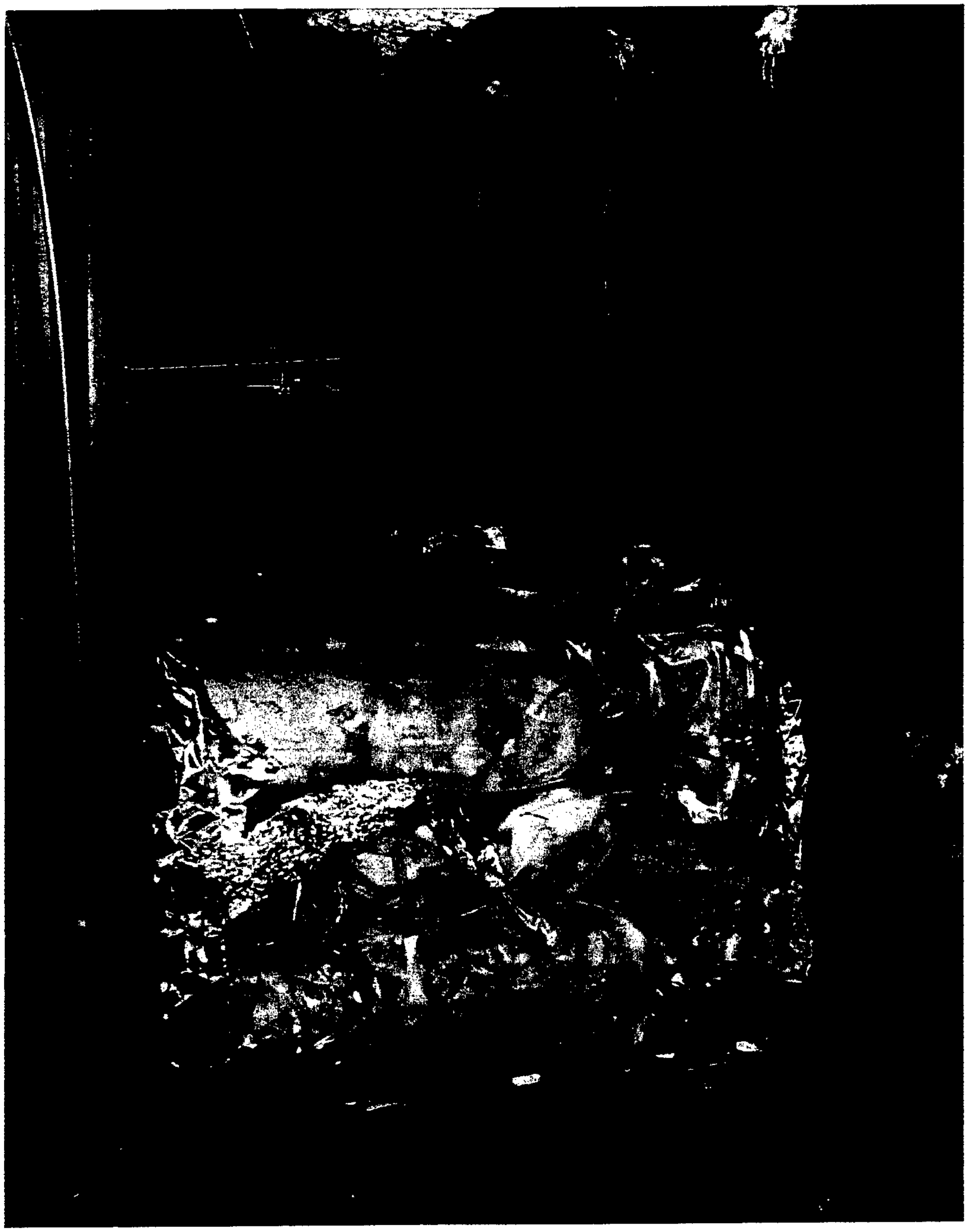

Figure 3 : Arrangement of the bags in the compartment before ignition

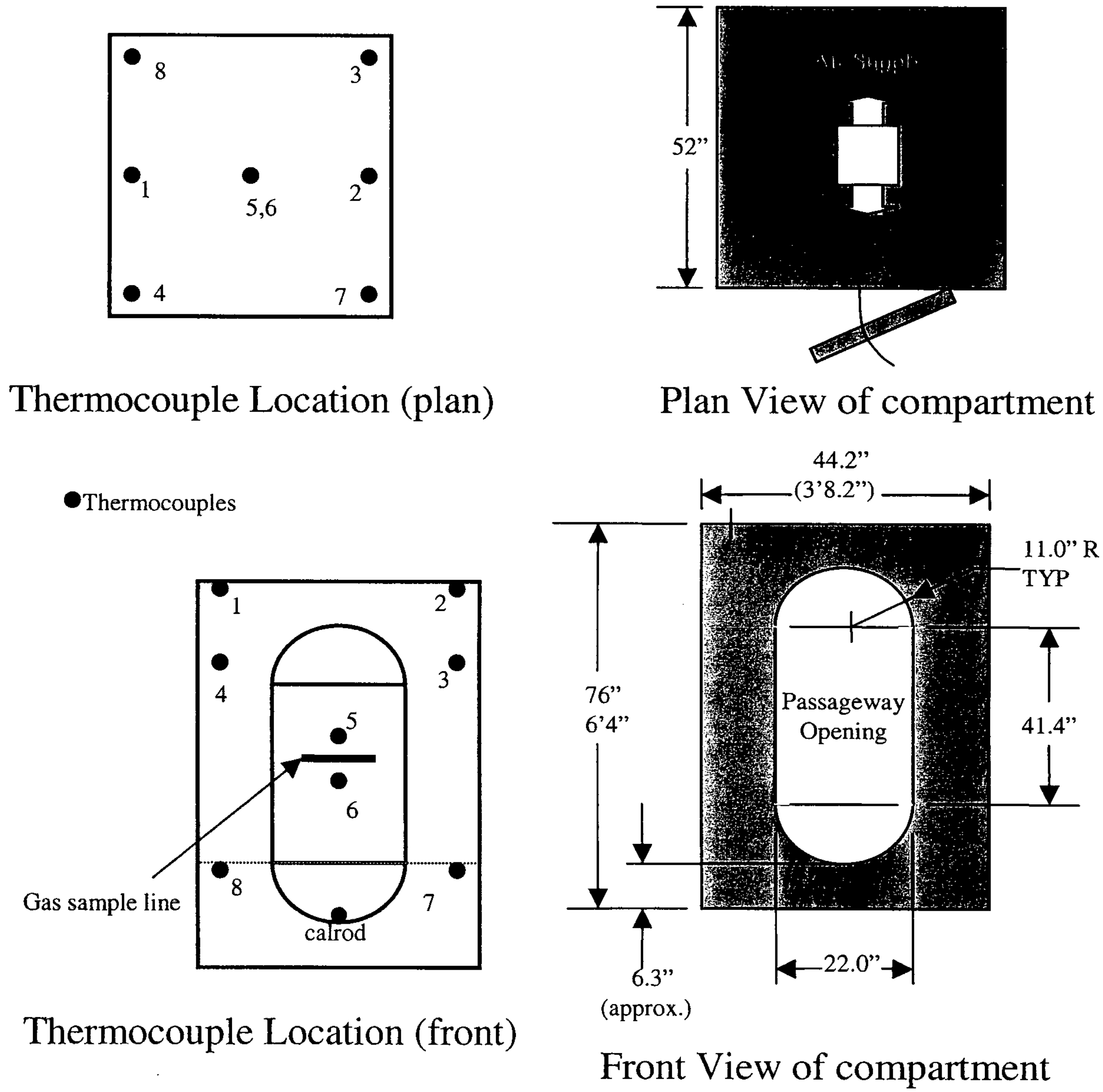

Figure 4: Location of the sensors inside the Compartment

A calrod was used as the ignition source since it was easier to work with when the door was closed. The rod was located in the center of the compartment and placed between the top and middle layer of bags. In tests where the passageway door was open, two thermocouples (9 and 10) were positioned about two feet in front of the door to monitor the temperatures around the space where the fire fighter would stand. Thermocouple number 11 was in the 15-cm (6 inches) ventilation duct, about 1 meter behind the diffuser. It was used to sense the flow of hot gases through the ventilation system.

Heat release rate was determined using the oxygen consumption method [4]. The test compartment was centered under the huge calorimeter hood that was mounted beneath the roof of the burn building. A large plastic "skirt" was hung from the hood to about 1 meter from the floor to completely surround the test compartment. This ensures that all combustion products are sucked through the measurement location in the calorimeter duct where the temperature, pressure drop (ΔP) in the flow and species concentrations are measured. Heat release rate measurement with the oxygen consumption calorimeter is based on the assumption that all combustion products are collected and passed through the measurement section of the duct. A schematic of the calorimeter is shown in Figure 5.
With the cross sectional area of the duct (A) and the temperature of the combustion products (T_e), the mass flow rate (m_e) of the combustion products (assuming the flow to be turbulent [5]) is:

$$m_e = 24.574A(\Delta P/ T_e)^{1/2} \qquad (1)$$

The heat release rate (Q) is obtained by:

$$Q = \{ E\varphi -(E_{CO}-E)((1-\varphi)/2)X^e_{CO}/X^e_{O2}\}\{m_e M_{O2}\, X^a_{O2}(1-X^a_w)/[(1+\varphi(\alpha-1))M_a]\} \quad (2);$$

where,

E = Heat release per unit mass of O_2 consumed,

E_{CO} = Heat release per unit mass of O_2 consumed for combustion of CO to CO_2 (17.6 KJ/g),

m_e = mass flow rate of combustion products,

M_{O2} = molecular weight of oxygen (32g/mol),

M_a = molecular weight of the ambient air (29 g/mol),

X = mole fraction,

α = volumetric expansion factor (= 1.105),

and φ = Oxygen depletion factor,

$$= \{X^a_{O2}(1-X^e_{CO2} - X^e_{CO}) - X^e_{O2}(1- X^a_{CO2})\}/\{(1- X^e_{O2} - X^e_{CO2} - X^e_{CO})X^a_{O2}\} \quad (3).$$

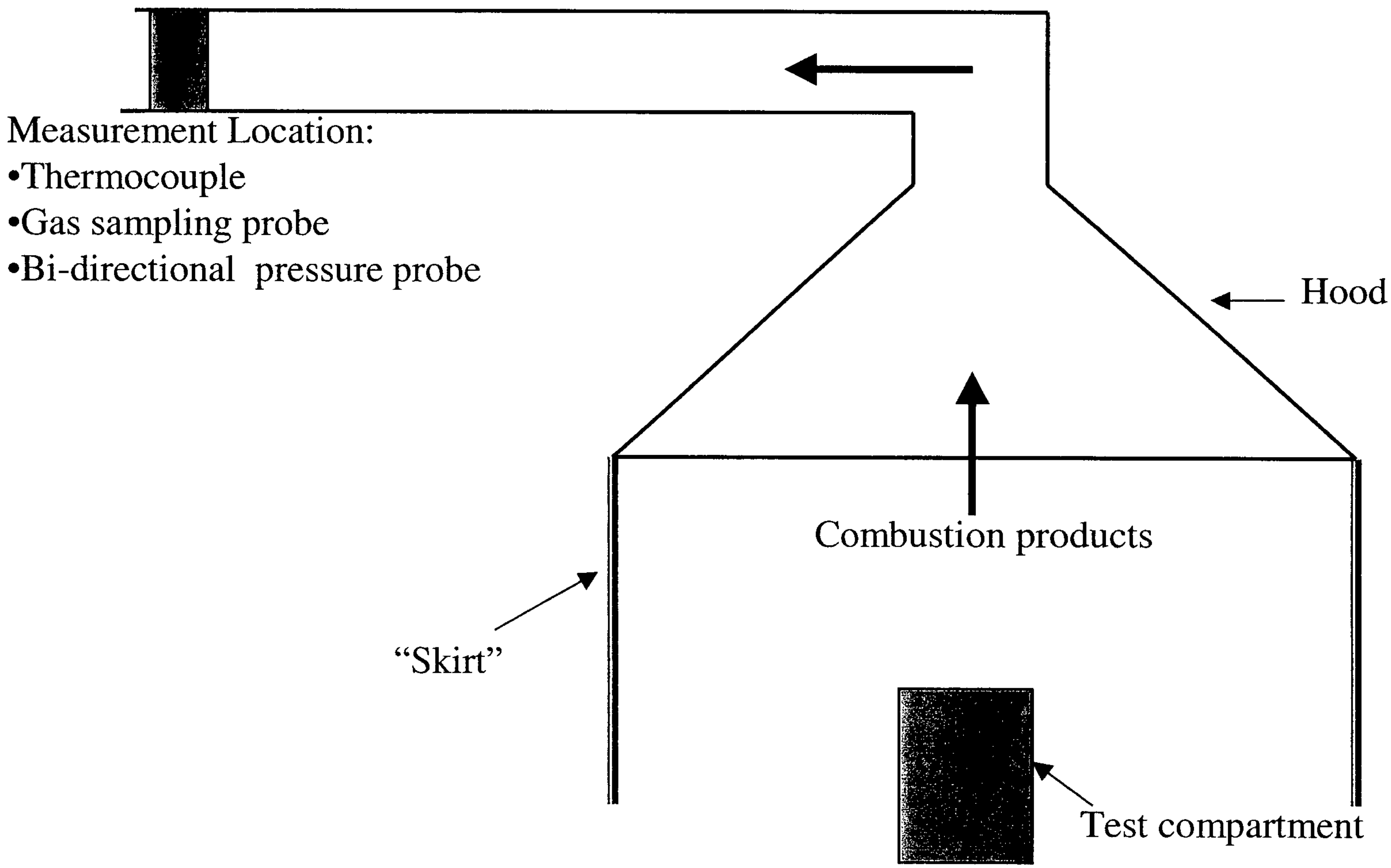

Figure 5: A Schematic of the Calorimeter.

Subscripts:

O_2 = Oxygen,

CO = Carbon monoxide,

CO_2 = Carbon dioxide,

w = water vapor;

Superscripts; **e** for combustion products and **a** for ambient air.

The calorimeter was calibrated before the tests using certified pure grade propane. Details of the calibrations are discussed in the Appendix A.

A preliminary test was run with simulated bags to test the instrumentation. Five additional tests were run with the real PWB, four in the simulated VIRGINIA class submarine compartment and one in the OHIO class submarine compartment. The tests in the VIRGINIA class compartments were conducted with the door open or closed and the ventilation turned on or off. The test matrix is summarized in Table 1.

The fires were fought according to the recommended doctrine for plastic waste fires (see Appendix B). In the VIRGINIA class tests the fires were fought with either Aqueous Film Forming Foam (AFFF) portable fire extinguishers or water. The portable AFFF fire extinguisher is a stainless steel cylinder that stores 2.5 gallons of a premixed solution of 6% AFFF concentrate in fresh water. A ¾ inch non-collapsible fresh water hose with a ¾ inch vari-nozzle and a pressure of 40 psi at the hydrant was used as the firefighting water source. These are the fire fighting agents readily available to the crew in the submarine compartment. In tests I and III, the plan was to apply up to two portable units of AFFF, if necessary. If the fire was not extinguished, then water would be applied using a ¾ inch hose reel. If the AFFF units were effective in extinguishing the fires in tests I and III, then only water would be used to fight the fires in tests II and IV. AFFF was used to fight the fire in test V (OHIO class).

2.2 Test Procedure

First the bags were packed in the compartment and all the instruments were checked. Then the calorimeter fan was turned on. The gas-sampling pump was turned on and the gas analyzer calibrations were re-checked to assure that the analyzer calibrations were correct. Then the calrod was inserted between the bags and the door was closed if necessary. Background data were collected for 60 seconds before the ignition source was turned on. The heater was turned off after a self-sustaining flame was established in the compartment.

Table 1: The Test Matrix

Tests	Compartment	Door open/closed	Louver open/closed	Forced ventilation On/off	Fire fighting agent
I	Simulated Virginia-class Submarine Environmental space	Open	-	On	AFFF (water)*
II		Open	-	Off	Water (AFFF)**
III		Closed	Open	On	AFFF (Water)*
IV		Closed	Closed	Off	Water (AFFF)**
V	Ohio-Class Submarine Module	Closed except for top 1/4	-	Off	AFFF

* Water is used only after 2 units of AFFF could not extinguish the fire.
** Start fire fighting with AFFF only if 2 units of AFFF could not extinguish the fires in tests I and III.

Fire fighting was commenced only after the fire had reached its peak and this is determined as follows. In the closed-door tests, the continuous rise in temperatures would stop and fire growth would go up and down as a result of unsteady oxygen supply. This quasi-steady burning was allowed to continue until it was determined that the fire would no longer intensify. At this point the door was opened and the fire fighting commenced immediately with the appropriate agent. In the open door tests the fire was allowed to grow until the flame had spread to all the bags and fire growth was seen to have leveled off. Then the fire was fought with either AFFF or water. After the flames were extinguished the compartment was thoroughly overhauled. Data collection was allowed to go on for additional 60 seconds after the fire was extinguished.

The outputs of the thermocouples in the burn building and in the duct were very noisy. This was caused by induced voltage from the big calorimeter fan motor and also by induced voltages from power lines and any other electromagnetic activities in the surrounding area. Wrapping an electrical insulator around the thermocouple sheath wherever it came in contact with a conducting material minimized the noise.

3.0 RESULTS AND DISCUSSIONS

3.1 Test I – In the Simulated VIRGINIA class compartment with door open, ventilation on:

The test started with the bags smoldering. Soon ignition was obtained. Fire spread very slowly within the pile of bags, although dripping of molten plastics enhanced fire spread amongst the bags. However, fire spread into the bags was difficult because of the effects of compaction as was demonstrated in our earlier tests with simulated bags [3]. Smoke in the compartment grew intense and thick smoke rose from the top 1/3 of the door. After about 15 minutes, flaming intensified and the temperatures in the space above the bags rose as shown in Figure 6. Simultaneously, the oxygen concentration decreased and the CO_2 concentration increased (Fig. 7). Figure 8 shows that after about 15 minutes the heat release rate rose rapidly above 100 KW as the fire spread throughout the compartment. As the fire spread to the bags next to the door, the bags broke open and their contents spilled outside the compartment spreading fire outside the compartment. After about 20 minutes the fire peaked at about 400 KW (Fig. 8), with the temperature near the ceiling of about 950 K (1250°F) (Fig. 6). At this time the O_2 concentration in the compartment dropped below 15% and the CO_2 concentration rose to above 5% (Fig. 7). Meanwhile, flames had covered all the plastic surfaces in the container and it seemed as if the fire would not grow any further. The fire was allowed to burn at this quasi-steady state for another five minutes before extinguishing (Fig. 9). The fire was extinguished easily within 30 seconds using less than one unit of AFFF. AFFF was applied to the surface of the burning PWB with a sweeping motion. Following knockdown of the flames, the extinguisher nozzle was inserted between bags and discharged to extinguish smoldering pockets observed in the PWB. As PWB were removed from the compartment, AFFF was applied to any smoldering plastic waste.

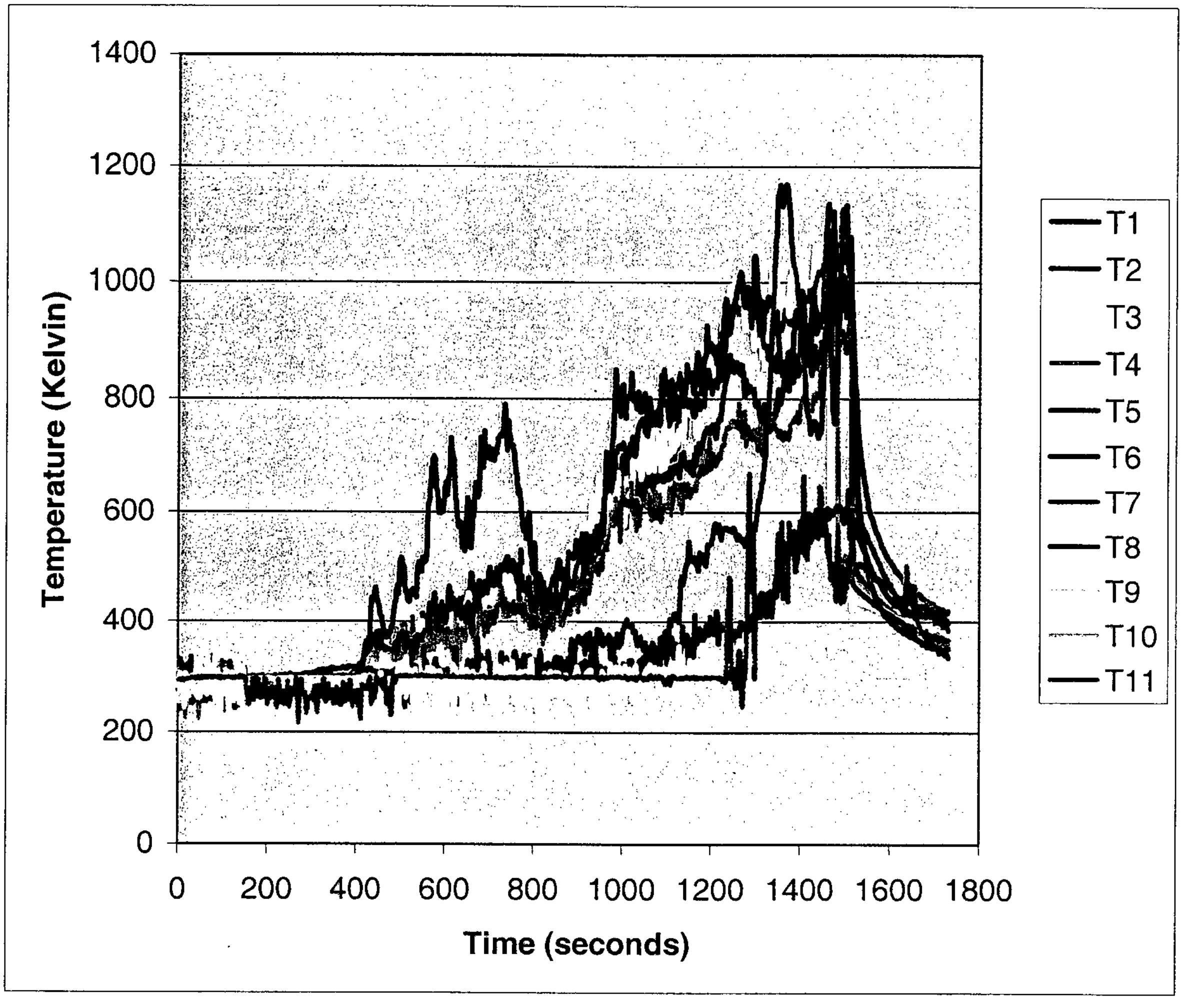

Figure 6: Temperatures in the Simulated VIRGINIA class submarine stowage compartment on fire with the door open and the ventilation on.

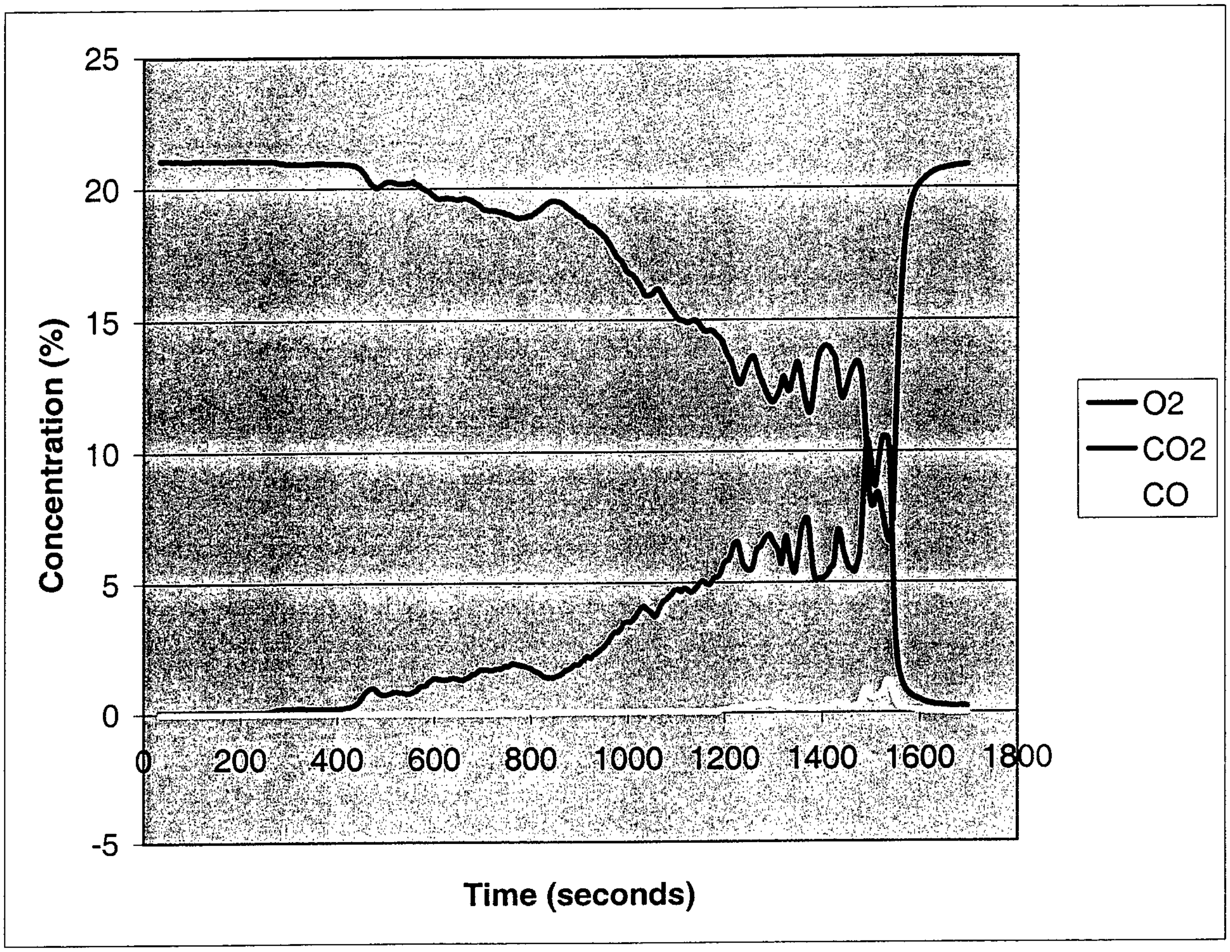

Figure 7: Concentration of gases in a Simulated VIRGINIA class Submarine stowage compartment fire with the door open and the ventilation on.

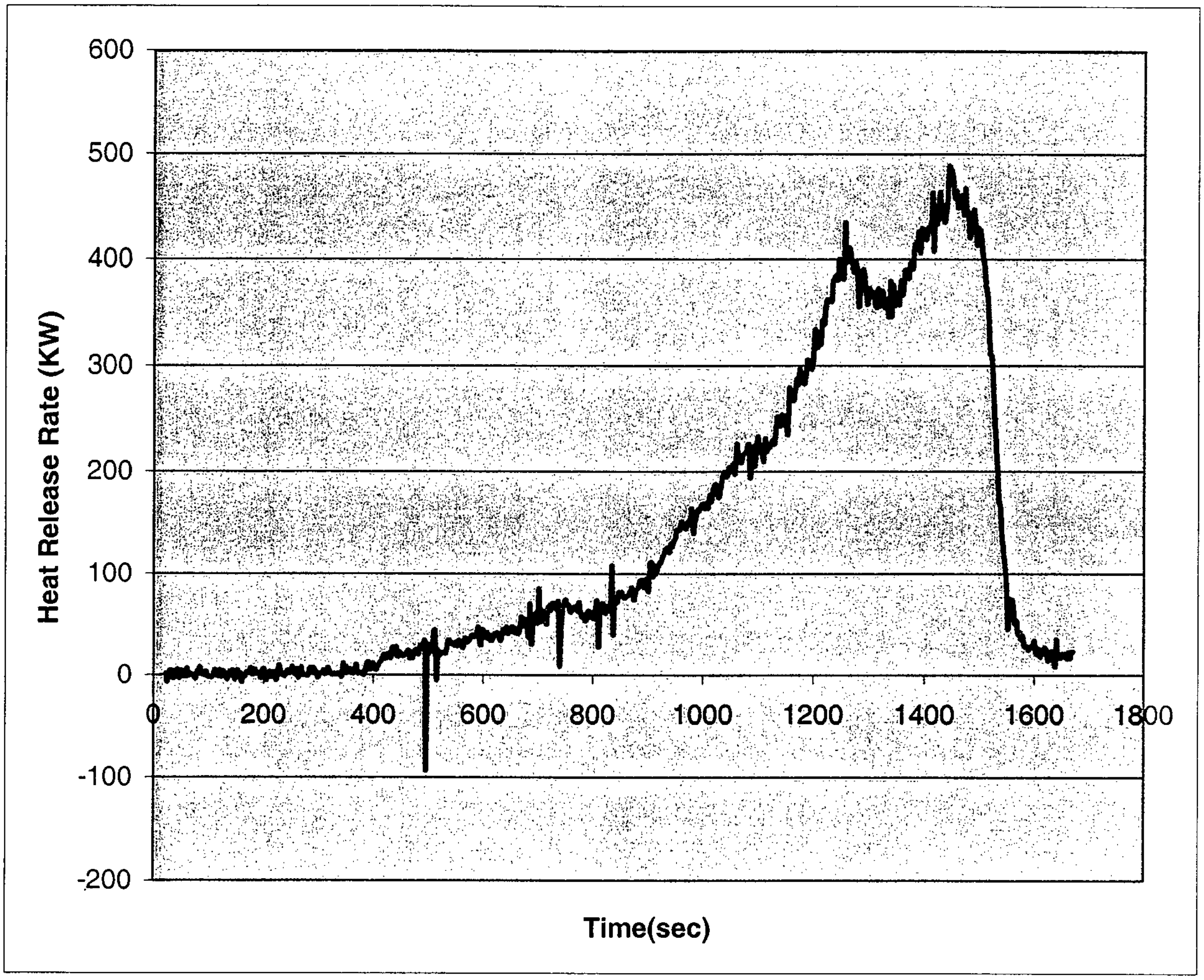

Figure 8: Heat Release Rate in a simulated VIRGINIA class submarine stowage compartment fire with the door open and the ventilation on.

Figure 9: Picture of the fully developed fire in a simulated VIRGINIA class submarine stowage compartment with the door open and the ventilation on.

3.2 Test II - Simulated VIRGINIA class compartment with door open, ventilation off:

In this test, the fire started off like in the previous test with heavy smoking. With the ventilation turned off the smoke was a little heavier than in the previous test and it took about 20 minutes (compared to 15 minutes) for flaming to intensify. Figure 10 is a picture of the heavy smoking fire. Smoke poured out through the door and spread through the ventilation duct to the blower location about 10 m from the compartment. In the current tests, the calorimeter fan was exhausting the combustion products at about 284.8 m^3/min (10,056 cfm) and at this high flow rate the smoke did not spread around the compartment to obscure the vision of the camera or the observers. In the real VIRGINIA class submarine space, this thick smoke will be pouring into the trash room (see Fig. 1), which has an exhaust ventilation of only 7.08 m^3/min (250 cfm). Therefore, it is very likely that smoke would fill the trash room, severely obscuring vision and would make fire fighting difficult.

Fire spread to all the bags in the compartment after approximately 27 minutes. The bags next to the door broke open and spilled their contents outside the compartment, spreading fire outside the compartment. Flames shot up to the compartment ceiling and the flame temperature in the compartment rose above 1100 K (1520 °F) (Fig. 11). Oxygen concentration at the middle of the compartment fell below 5% while CO_2 concentration rose above 10% as shown in Figure 12. The fire at this time was burning at a quasi- steady state with a maximum heat output of nearly 600 KW as shown in Figure 13. This is higher than the maximum heat output when the ventilation was running.

Since the fire had spread to every part of the compartment it was unlikely that the fire would grow any bigger at this stage. The gas phase temperatures at this stage were observed not to be increasing significantly (Fig 11). This was taken as the worst stage of the fire so the fire was then fought with water spray from ¾" hose line. Water was applied to the surface of the burning PWB with a narrow angle fog and sweeping motion. Due to the larger volume of water used, most deep-seated pockets were extinguished. Following knockdown of the flames, the PWB were removed from the compartment and water applied to any remaining smoldering plastic waste. The fire was under control within 30 seconds.

To compare the results of the closed-door tests with the ventilation on and off, one assumes that the composition of the plastic waste in both tests is about the same. Obviously, if the composition in both tests were vastly different, then the difference in material properties and condition would affect the measured fire growth. One notes from comparing Figs. 8 and 13 that the fire grew faster when the ventilation was on than when the ventilation was off. For example, 20 minutes into the test we had approximately 200 KW fire with the ventilation running, while within the same period we had below 50 KW fire when the ventilation was off. At this early stage of the fire the upward fire flow and entrainment were not very strong. Therefore, the ventilation air provided additional oxygen for enhanced combustion. Consequently, the gas temperatures at this stage were higher in the test with the ventilation running than in the test with the ventilation off (Figs. 6 and 11). On the other hand, after the fire was fully developed (quasi-steady burning period), the

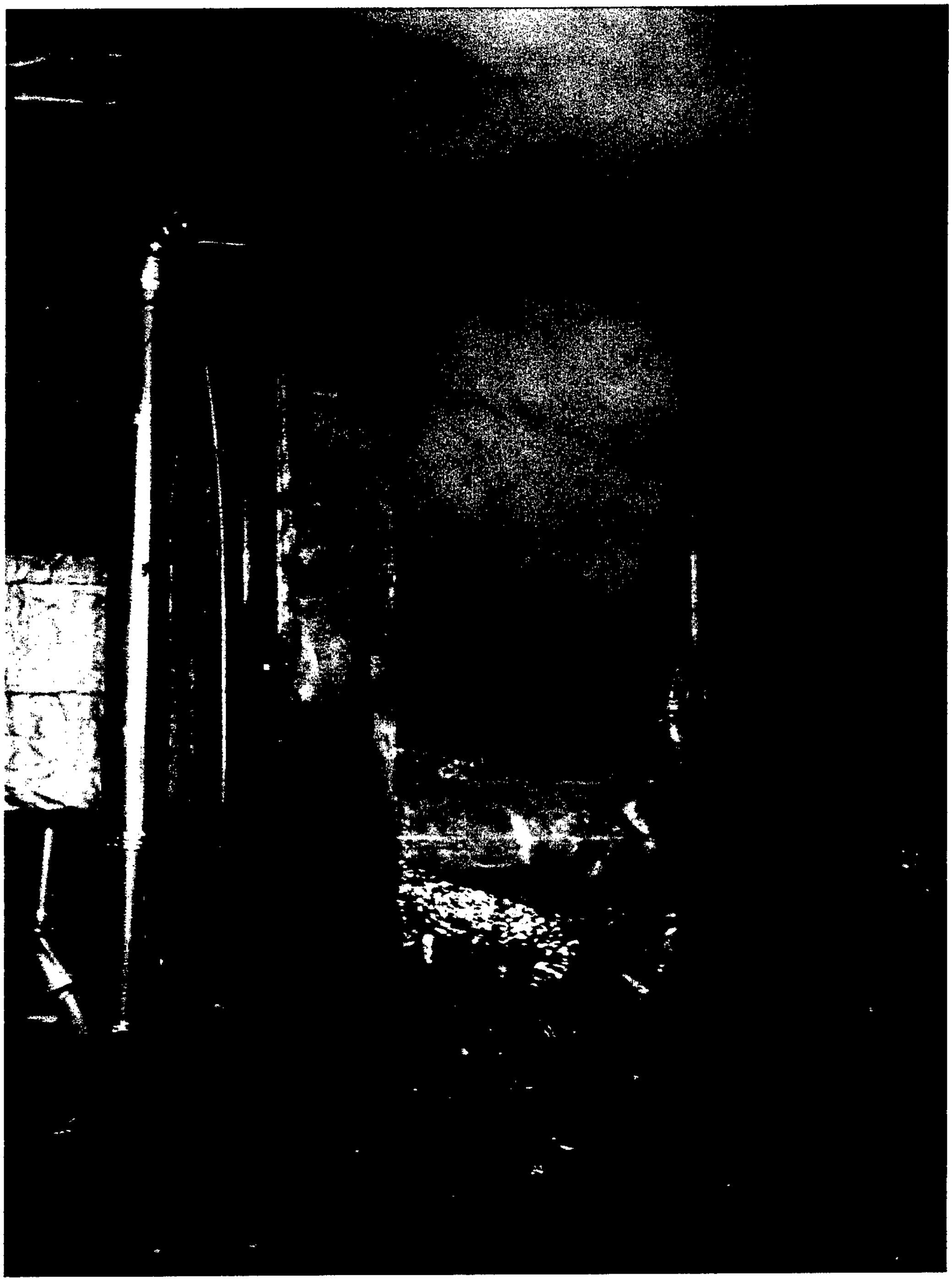

Figure 10: Picture of a developing fire in a simulated VIRGINIA class submarine stowage compartment with the door open and the ventilation turned off.

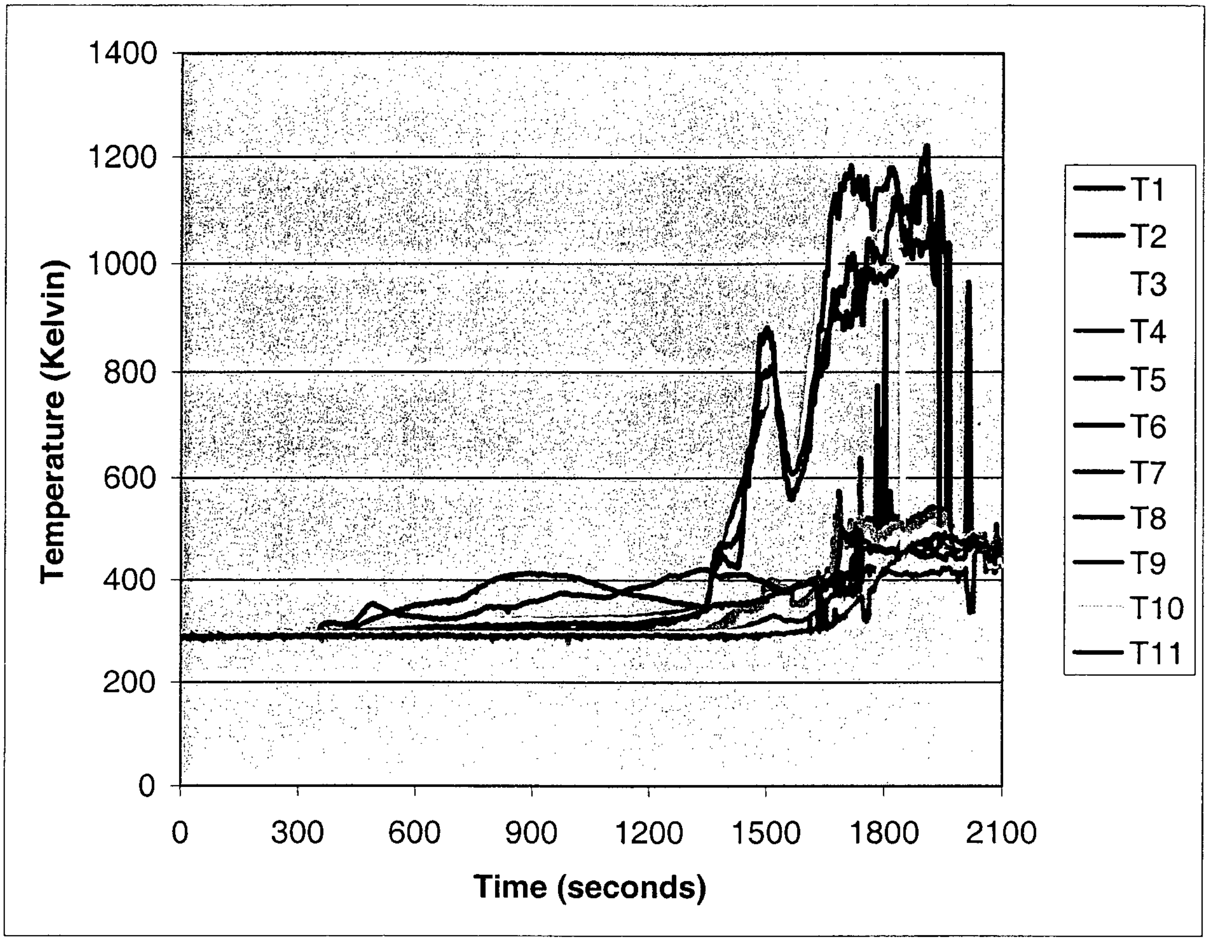

Figure 11: Temperatures in a simulated VIRGINIA class submarine stowage compartment fire with the door open and the ventilation turned off.

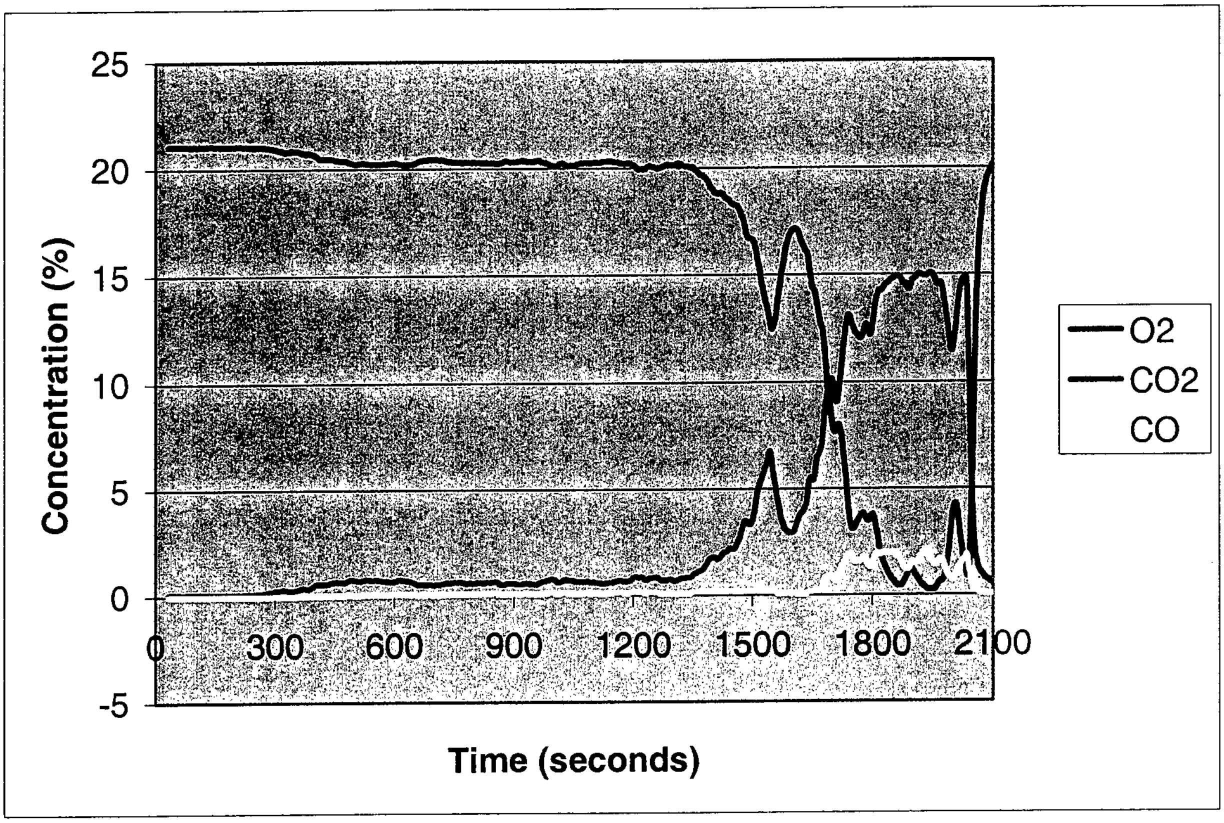

Figure 12: Gas Concentrations in a simulated VIRGINIA class submarine stowage compartment fire with the door open and ventilation turned off.

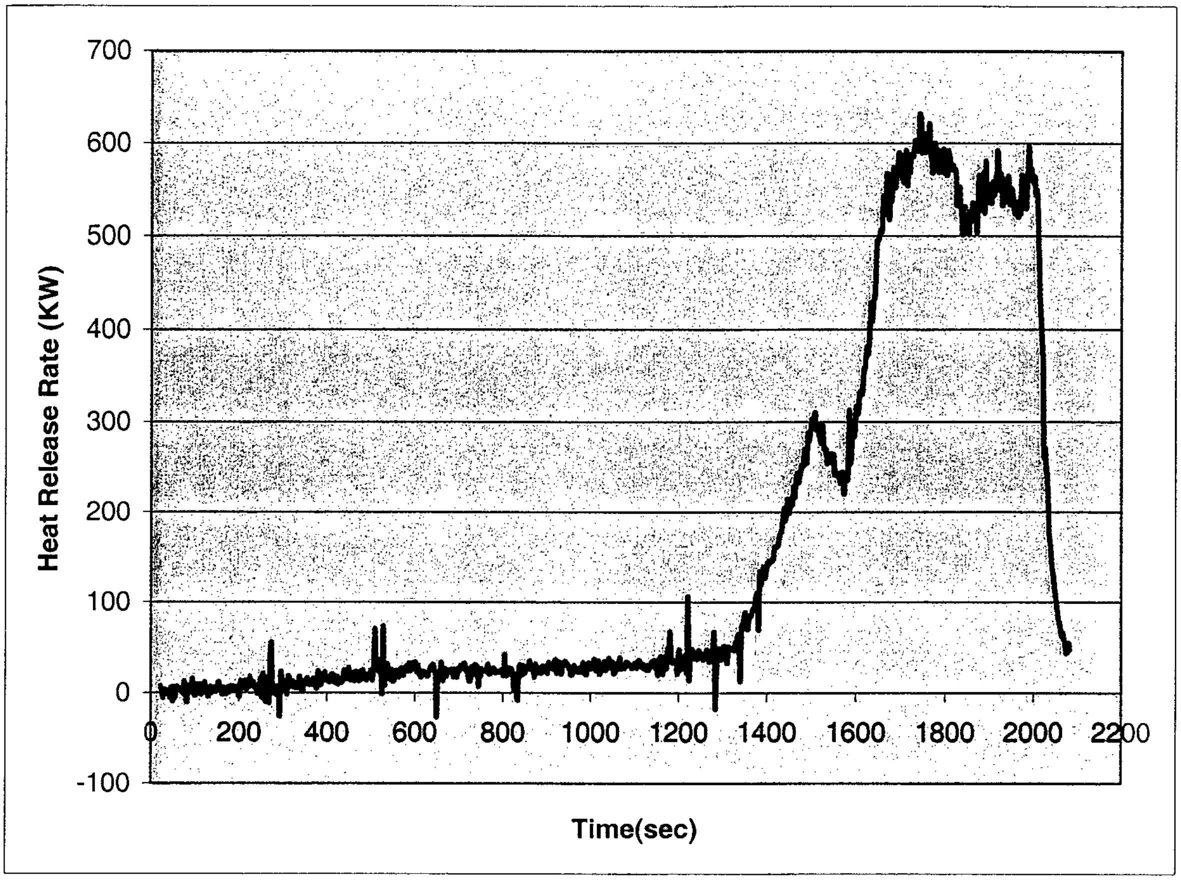

Figure 13: Heat Release Rate in a simulated VIRGINIA class submarine stowage compartment fire with the door open and the ventilation off.

entrainment flow became very strong and the oxygen from the ventilation flow became less effective. It seems at this time that the fire with the ventilation running had "excess air" compared to the fire with the ventilation turned off. Hence, at this stage its temperature was lower, the oxygen concentration was higher, the CO_2 concentration was lower and the heat release rate was lower.

In both tests with the door open, the maximum temperatures measured by thermocouples #9 and #10 which were located about 2 feet in front of the door were low (about 400 K (260°F)). This was as a result of the cooling effects of the entrainment flow into the compartment. Thus, the fire fighter had no problem fighting the fire from this location.

3.3 Test III - Simulated VIRGINIA class Submarine compartment with the door closed, ventilation on and louver open:

The set ventilation flow into the compartment of 3.54 m^3/min (125 cfm) decreased slightly when the door was closed and was not adjusted. About 10 minutes into the test the fire started to grow rapidly. The fire spread more toward the side where thermocouple number 2 was located, hence T_2 rose to about 800 K early in the test as shown in Figure 14. After approximately 20 minutes the oxygen concentration in the compartment fell below 15% while the CO_2 concentration rose above 5%. This is shown in Figure 15. From this point onward the fire growth seemed to have a few plateaus. Figure 16 shows the heat release rate plateaus at about 80 KW and 160 KW. The fire burned intensely especially close to the door where additional air was available through the various openings around the door. Flames shot out of some of those openings as shown in Figure 17. The maximum temperature inside the compartment was about 900 K (1160°F). The test lasted for over 42 minutes after which the door was opened and the fire was fought with AFFF. AFFF was applied to the surface of the burning PWB with a sweeping motion. Following knockdown of the flames, the extinguisher nozzle was inserted between bags and discharged to extinguish smoldering pockets observed in the PWB. As PWB were removed from the compartment, AFFF was applied to any smoldering plastic waste. Fire fighting was complete in less than one minute, using up less than one unit of AFFF. There was no flash back when the door was opened.

3.4 Test IV - Simulated VIRGINIA class compartment with the door closed, ventilation off and louver closed:

The results of this test are summarized in Figures 18 to 20. The highest temperatures were measured by thermocouple number 7, which was placed between the bags close to the door (Fig. 18). Between 6 minutes and 36 minutes into the test fire growth was going up and down. This can be seen more clearly in Figure 19, which shows the concentration of oxygen and that of CO_2. Within this time the fire was being starved of oxygen. It depended on oxygen coming in from the openings around the door. That was why the fire seemed to be gasping for oxygen and burning was intense only near the door. After about 20 minutes the oxygen concentration inside the compartment fell below 5% and the CO_2 concentration rose above 10%. The CO concentration showed significant rise (up to 2.5%) at this time

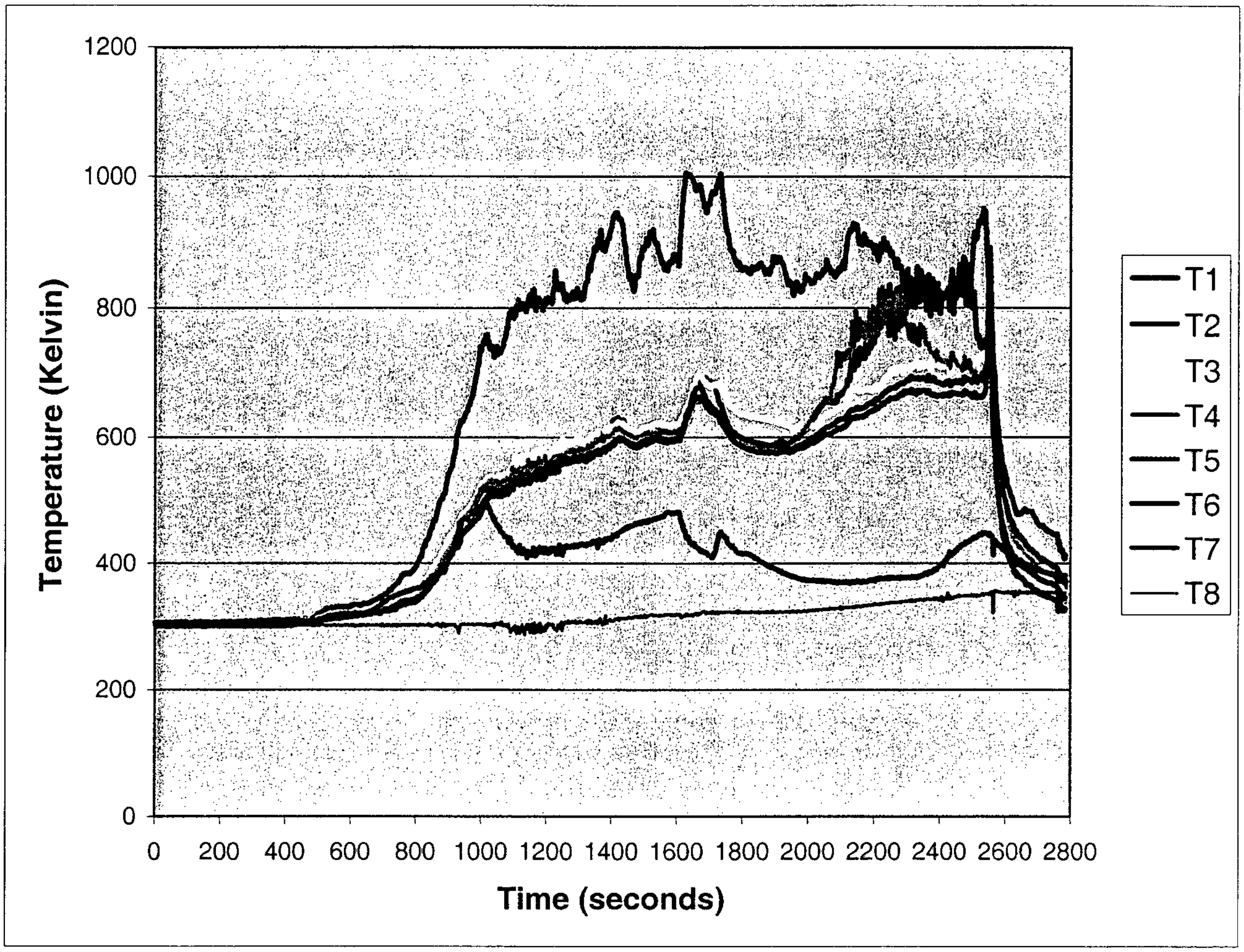

Figure 14: Temperatures in a simulated VIRGINIA class submarine waste storage compartment fire with the door closed, Louvers open and the ventilation on.

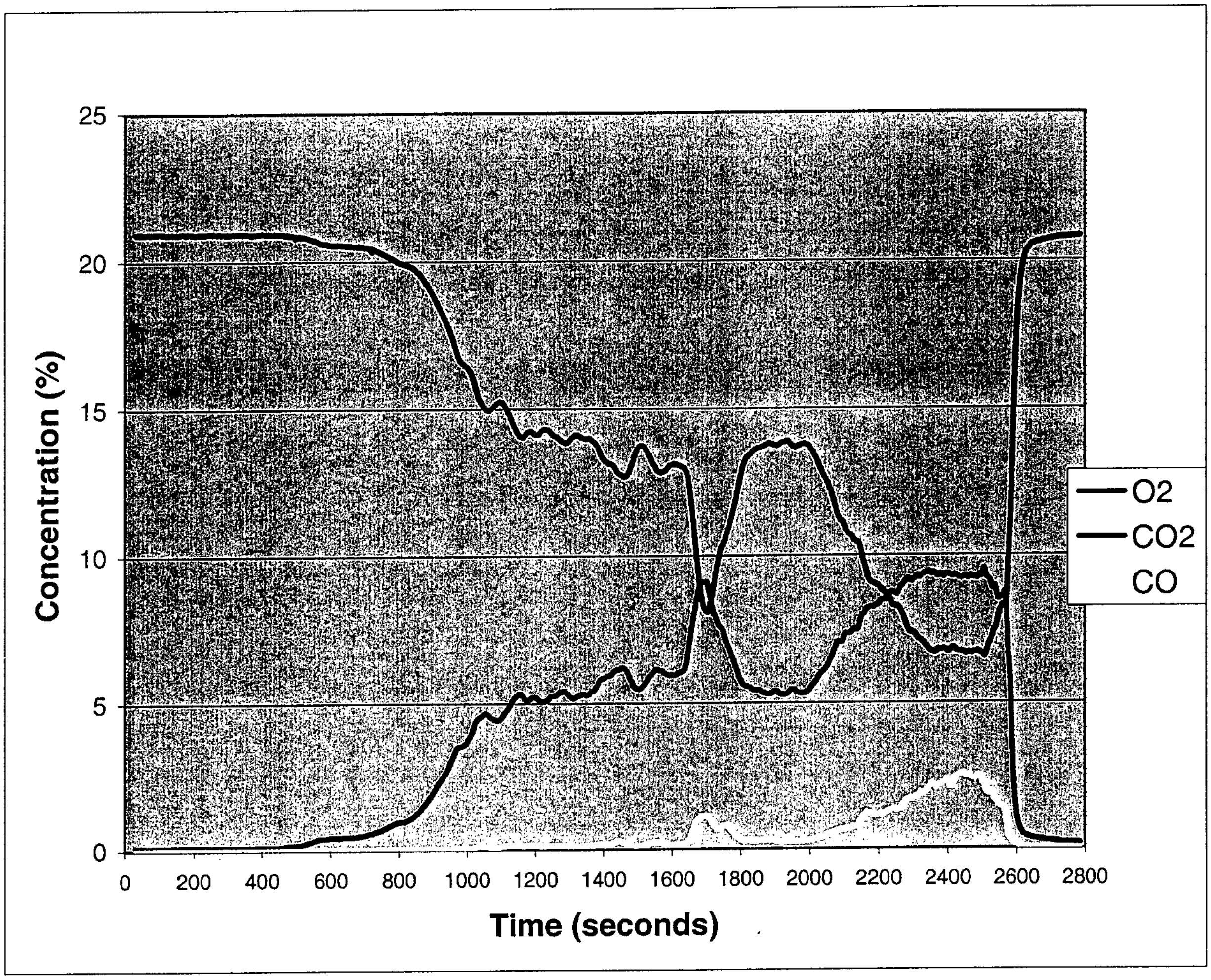

Figure 15: Gas Concentrations in a simulated VIRGINIA class submarine waste stowage compartment with the door closed, Louvers open and the ventilation turned on.

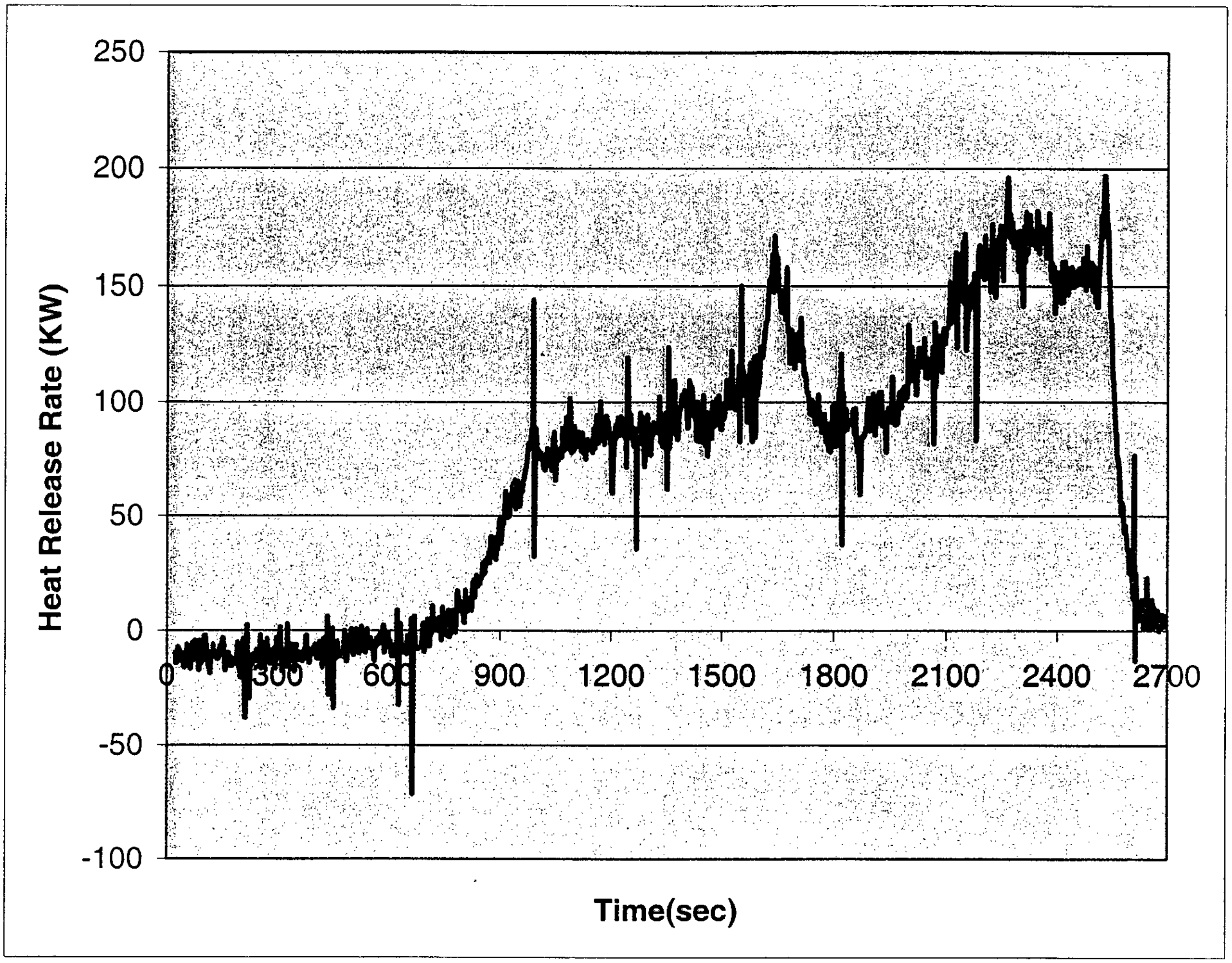

Figure 16: Heat Release Rate in a simulated VIRGINIA class submarine waste stowage compartment fire with the door closed, Louvers open and ventilation turned on.

Figure 17: Fire inside a simulated VIRGINIA class submarine waste stowage compartment with the door closed, louvers open and the ventilation on.

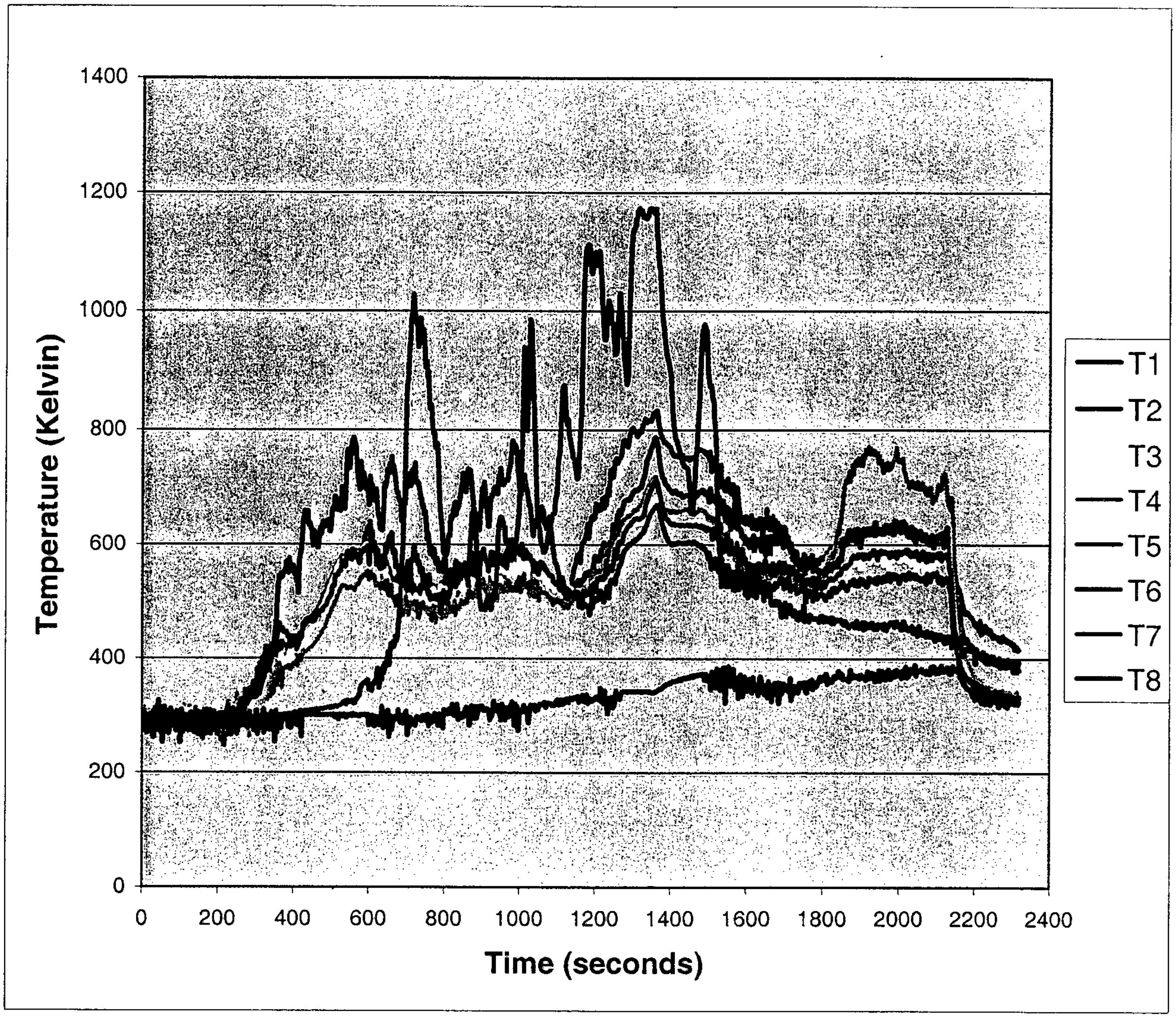

Figure 18: Temperatures in a simulated VIRGINIA class submarine waste stowage compartment fire with the door close, the louver closed and the ventilation off.

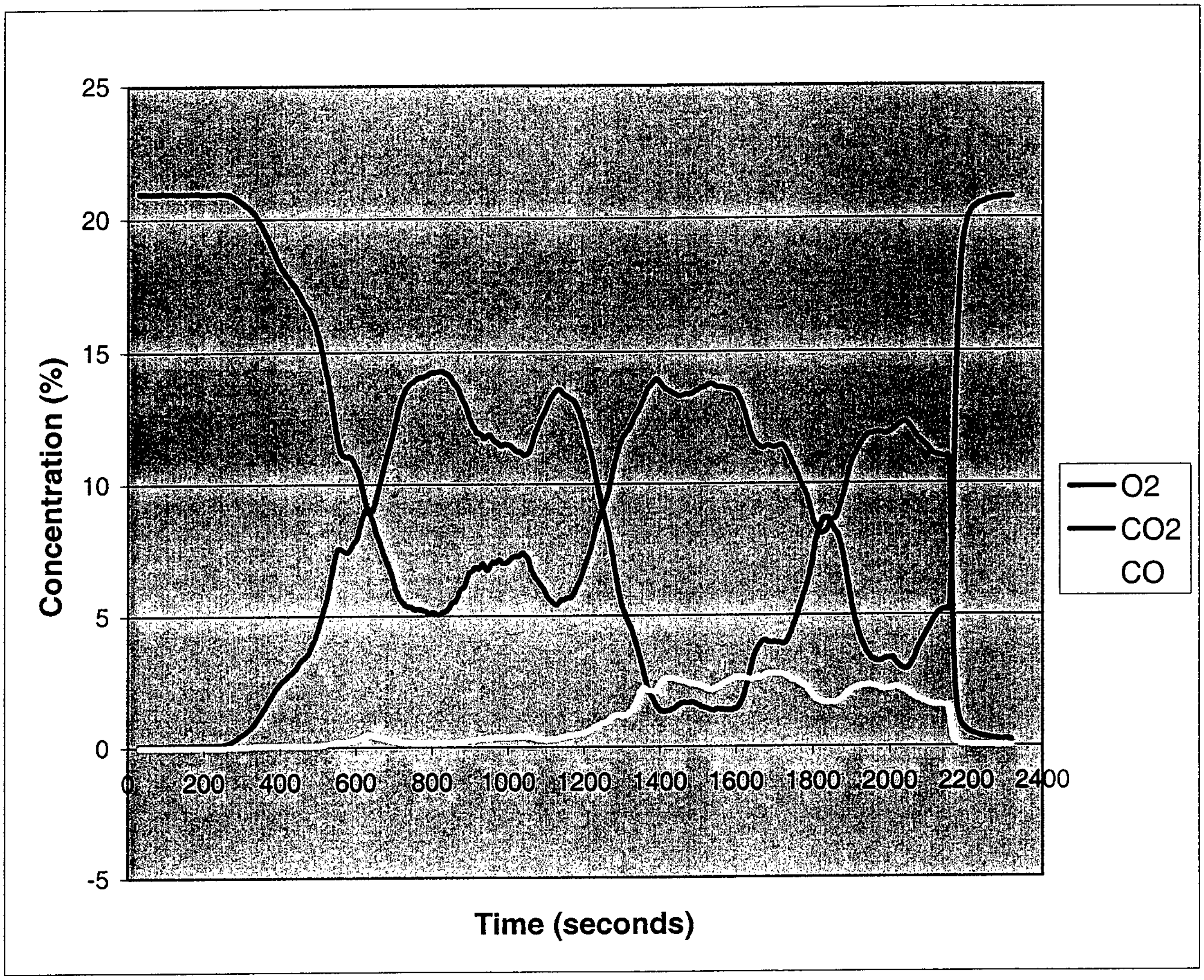

Figure 19: Gas Concentrations in a simulated VIRGINIA class submarine waste stowage compartment fire with the door closed, louvers closed and ventilation turned off.

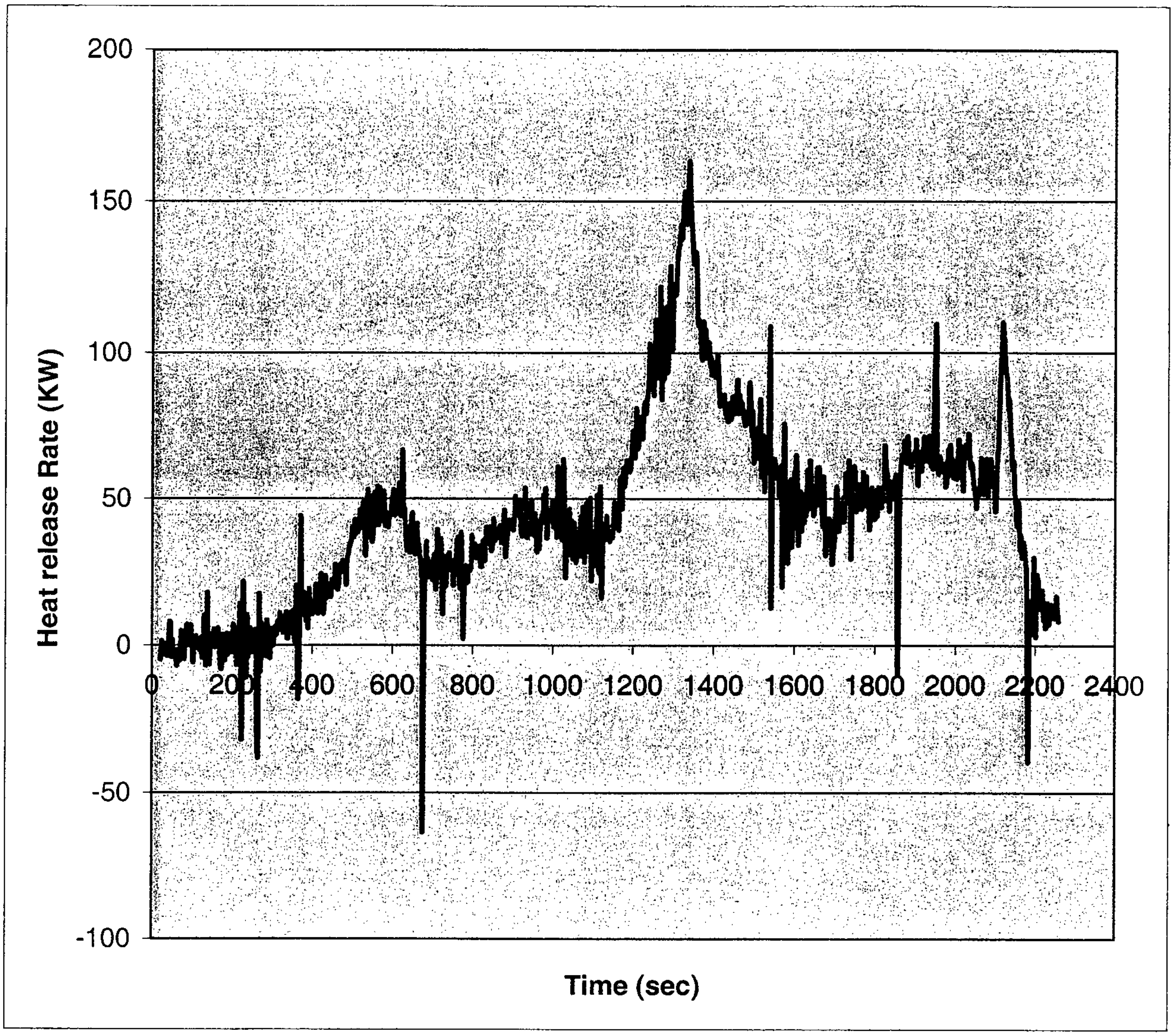

Figure 20: Heat Release Rate in a simulated VIRIGINA class submarine waste stowage compartment fire with the door closed, louvers closed and ventilation turned off.

(Fig. 19). The highest temperature in the hot gases was of the order of 700 K (800°F). Heat release rate remained under 100 KW (except for one spike) because of limited oxygen supply. This fire was fought with water and was under control within 30 seconds. Water was applied to the surface of the burning PWB with a narrow angle fog and sweeping motion. Due to the larger volume of water used, most deep-seated pockets were extinguished. Following knockdown of the flames, the PWB were removed from the compartment and water applied to any remaining smoldering plastic waste.

The temperatures and heat release rates were lower in test IV where the ventilation was off than in test III where the ventilation was on. With the door closed, the ventilation air provided the much-needed oxygen in the test where the ventilation was running. Hence, the temperatures and heat release rate in this test were higher. That notwithstanding, both fires were oxygen limiting.

3.5 Test V – OHIO class compartment fire, door closed except for the top ¼ of the doorway:

Figure 21 shows the picture of the OHIO class submarine plastic waste stowage compartment with the door open only in the top one quarter. The results of the test in this compartment are presented in Figures 22 and 23. Initially, the fire grew slowly but finally flames reached the ceiling. The flames near the ceiling were bluish. This suggests that the flue gases were fuel-rich and that the excess fuel reacted with oxygen near the ceiling where air was entrained from outside. After about 40 minutes into the test, the fire was oxygen limited and began "puffing" and gasping for oxygen. Figure 21 shows that the oxygen concentration fell to about 5% and the CO_2 concentration rose to about 10% during his time. The CO concentration also increased to 2.5%. After burning in the oxygen-limiting situation for about 10 minutes, the fire was fought with AFFF through the opening near the ceiling. Due to the obstruction from the locker panel, it was difficult to aim the extinguishing agent at the source of the fire. When the flame was noticeable knocked down, and the first AFFF extinguisher was completely discharged, the panel was removed and the fire began to re-flash. The second AFFF unit was used to control the re-flash and to extinguish the remaining smoldering plastic waste as the bags were removed from the locker. The maximum heat release rate in this test was about 200 KW. Since the fire was oxygen limited, burning took place mainly close to the door where more oxygen was available. Figure 24 is a picture of the compartment after the fire was extinguished. It shows that more of the bags close to the door were burned compared to the bags inside.

There were no temperature measurements presented for this test. This is because in the earlier tests, the multi-pair thermocouple cable that carried the temperature signals was severely damaged by heat as it lay against the hot compartment wall. The mishap was noticed when this test was already underway and we noticed that the temperatures were not increasing as expected. No corrective action could be taken at this stage. However, this mishap gives an indication of the level of heat damage that could be expected from the outside surface of the stowage compartment on fire if the heat resistance across the walls is comparable to that across a 2 mm thick steel.

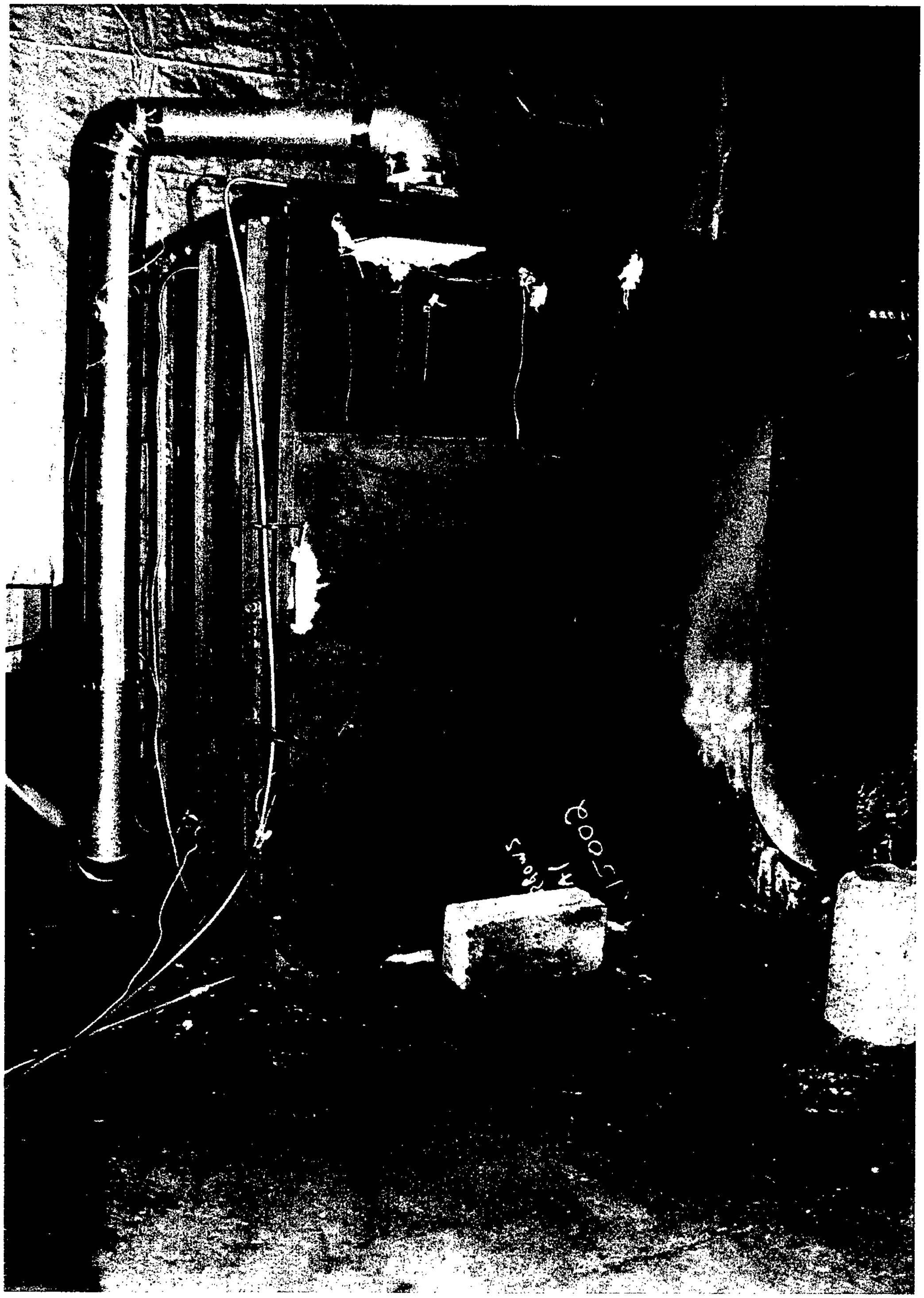

Figure 21: Picture of the OHIO class submarine plastic waste stowage compartment with the door partially closed.

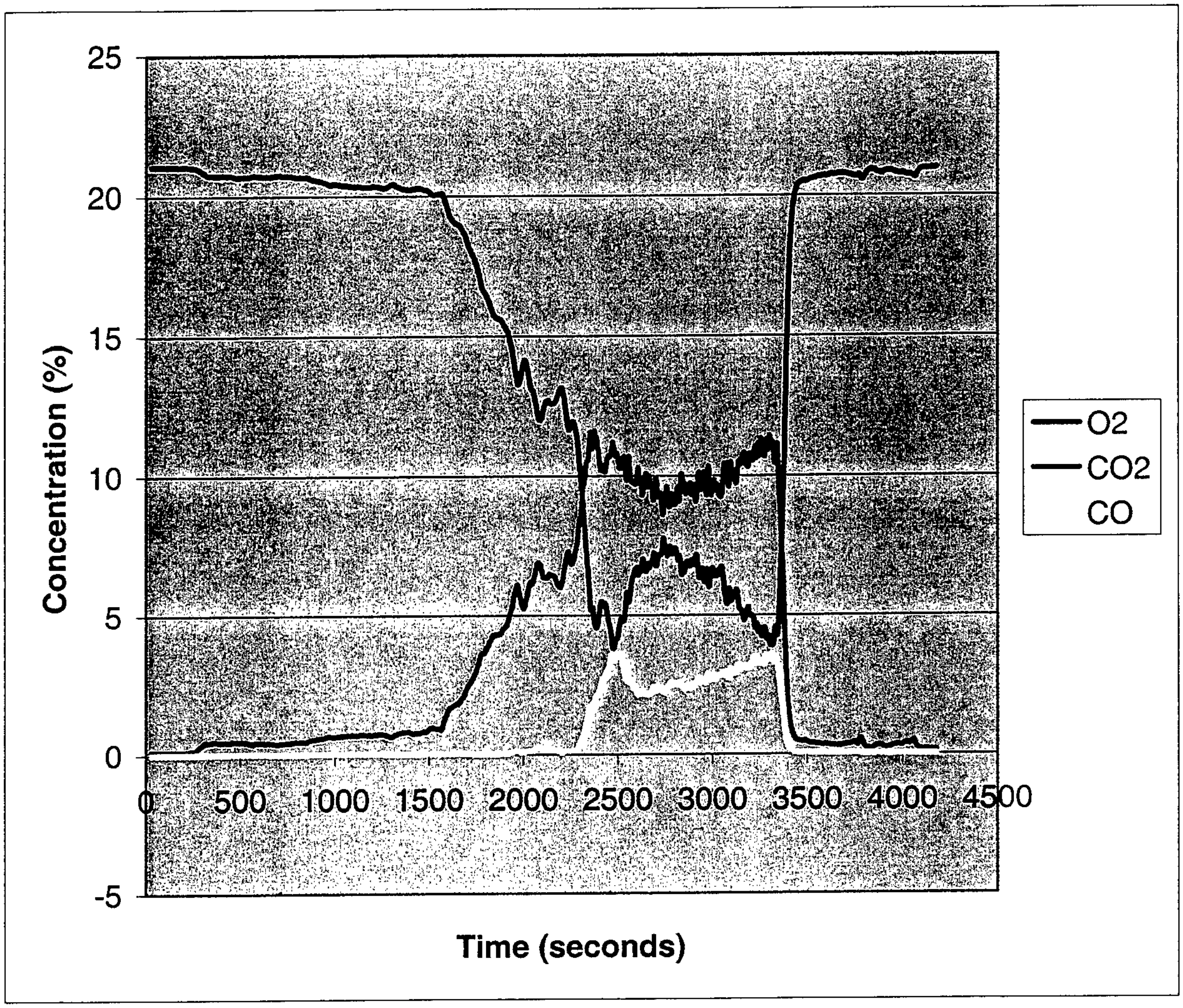

Figure 22: Concentration of gases in the OHIO class submarine plastic waste stowage compartment fire with a partially closed door.

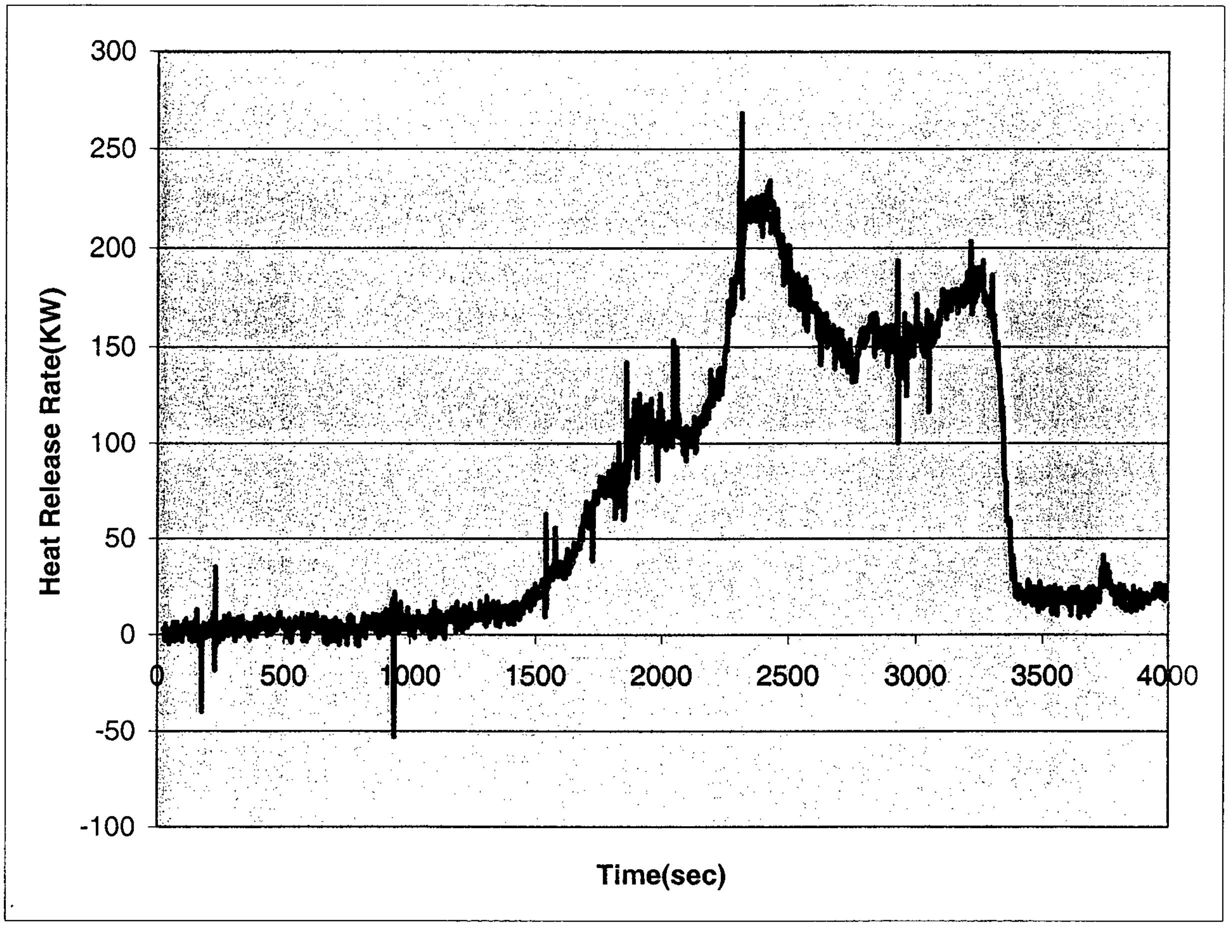

Figure 23: Heat Release Rate in the OHIO class submarine waste stowage compartment fire with partially closed door.

Figure 24: Picture of the extinguished fire in the OHIO class Submarine waste stowage compartment. Door was closed except for the top ¼.

4.0 CONCLUDING REMARKS

The tests described in this report were conducted to assess the fire growth characteristics and the ease of fire control in the proposed VIRGINIA class submarine waste stowage compartment and in the OHIO class submarine PWB stowage compartment with a partially closed door. Fire severity was measured in terms of heat release rate, temperatures, and gas (oxygen, CO_2 and CO) concentrations inside the fire compartment. The test results are summarized as follows:

VIRGINIA class compartment:

1. The door open: Fire growth was slow initially and produced very thick smoke. Smoke production was worse when the ventilation was not on. The heavy smoking would, however, be an obstacle to fire fighting at this early stage. The fire eventually grew to a maximum heat release rate of about 600 KW without ventilation and about 400 KW with ventilation. The maximum temperatures near the compartment ceiling with ventilation off and on were about 1100 K (1520 °F) and about 950 K (1250°F), respectively. In each case, the fire was extinguished at the worst condition with less than one unit of AFFF or a ¾ inch water hose line in less than one minute.
2. The door closed: The fires grew at a slow rate at the early stage. However, the rate was faster when the ventilation was on compared to when the ventilation was off, since the ventilation provided the much-needed oxygen. With the door closed, the fire was oxygen limiting whether the ventilation was on or off. When the ventilation was on, the maximum temperature near the ceiling was about 900 K (1160°F) while it was about 750 K (890°F) with the ventilation off. The maximum heat release rate in both cases was about 160 KW and 100 KW, respectively. In either case, the fire was extinguished at the worst condition with less than one unit of AFFF or water from a ¾ inch hose line in less than one minute.

OHIO class compartment:

In the only test conducted with this compartment, the door was closed except for the top one quarter. The fire was oxygen limiting. Burning took place mainly in the bags near the closed door where limited oxygen was available through the openings around the door. Fire growth was slow especially in the beginning. The fire eventually peaked at about 200 KW and the oxygen concentration inside the compartment dropped to about 5%. Fire fighting was more difficult in this test since one could not see clearly where to aim the agent because of the partially closed door. The fire was extinguished with a little more than one unit of AFFF.

Finally, the results indicate that a fire in the proposed VIRGINIA class submarine PWB stowage compartment will grow slowly but has the potential of growing to a big fire if the door is open. Fire growth was faster with the ventilation on. In most of the test conditions, the fire could be controlled readily with one bottled AFFF unit or water from a ¾ inch hose line. However, a minimum of two AFFF extinguisher units may be needed to provide complete extinguishments, to protect against re-flash and to extinguish residual smoldering plastic waste.

5.0 ACKNOWLEDGEMENTS

The contributions of Miss Karla Bell and Mr. Jim Hicks in conducting the fire tests and processing the data are appreciated.

6.0 REFERENCES

1. Back G.G., Scheffey, J.L., White, D.D., Tatem, P.A. and Williams, F.W., "Fire Assessment of the Storage of Processed Plastic Waste on Submarines" NRL Report August 1999.

2. Leonard J.T., DiNenno P.J., White D.A., and Nelson H.E., "Fire Assessment of Shipboard Plastic Waste Disposal Systems," Naval Research Laboratory Memorandum Report NRL/MR/6184-94-7452 February 1994.

3. Tatem P.A., Williams F.W., Brown, R.A. and Ndubizu C. C., "Fire Hazard Assessment for on Board Stowage of Plastic Waste" NRL Ltr. Report Ser 6180/0680 Nov. 1999.

4. Janssens, M.L., "Calorimetry," In SFPE Handbook of Fire Protection Engineering. DiNenno P.J., et.al (Eds.) SFPE, Boston Mass. pp.3-16 (1995).

5. Janssens, M.L., "Measuring Heat Release Rate by Oxygen Consumption" *Fire Technology* vol.**27** No.3 pp. 234-249 Aug.1991

6. Huggett, C., "Estimation of the Rate of Heat Release by Means of Oxygen Consumption," *Fire and Materials,* **12** pp. 61-65 (1980)

7. Tewarson, A., "Generation of Heat and Chemical Compounds in fires," In SFPE Handbook of Fire Protection Engineering. DiNenno, P.J et.al (Eds.) SFPE, Boston Mass., pp.3.78 (1995).

APPENDIX A

CALIBRATION OF THE CALORIMETER AND GAS ANALYZERS

The oxygen consumption calorimeter is based on the principle that heat release rate is proportional to the rate of oxygen depletion in the combustion air. For organic solids Huggett [6] found that the proportionality constant is approximately 13.1 KJ/g of oxygen. The basic requirement for the use of this calorimeter is that all the combustion products should be collected and removed though a duct where it is mixed and both flow rate and oxygen depletion is measured.

Figure 5 is a schematic of the oxygen consumption calorimeter. At the measurement location in the duct, the temperature was measured with a K-type thermocouple. A gas sampling probe collected samples for gas analysis and a Setra model 264 bi-directional pressure probe was used to measure the pressure drop in the flow which is proportional to the flow velocity of the combustion products. The sampled gas is drawn through a water trap inside an ice bath. The pressure transducer has a range of 0 to 62.16 Pa. (0 to 0.25 inches of water) and a linear output of 0 to 5 volts. Hence the LabVIEW program converted one-volt output from the pressure transducer to a pressure drop (ΔP) of 12.43 Pa. The output of the gas analyzers, pressure transducer and the thermocouple were continuously monitored with a LabVIEW program. The cross sectional area of the duct (A) was measured to be 0.6567 m^2.

A bottle of certified pure grade propane supplied the calibration fuel. It sat on an electronic balance such that its weight would be measured continuously. By recording the weight at the beginning and at the end of a known time interval during the steady state period of the test, the fuel mass supply rate could be determined. With 43.7 KJ/g as the (chemical) heat of combustion of propane [7], the calculated average heat release rate was obtained.

The calorimeter was calibrated by first calibrating the gas analyzers as described below. Then the calorimeter fan was turn on and the fan speed was set. The sampling pump was turned on. The LabVIEW program was started and background data were collected for about 60 seconds. Propane was turned on to a known flow rate and immediately ignited. The fire was allowed to burn at a steady rate for five to ten minutes. The fuel was turned off and the LabVIEW program was allowed to run for an additional two minutes before it was stopped. The data were fed into another LabVIEW program that calculated the measured heat release rate with time, using equation 2 and $E = 12.80$ KJ/g of oxygen [7]. A typical plot of the measured heat release rate is shown in Figure A1. The average of the data during the steady burning period is compared with the calculated heat release rate. The test was repeated at various calorimeter fan speeds and various propane flow rates. The flow rate range includes the range of heat release rate we anticipated in the PWB tests. The results of the calibration tests are summarized in Table A1. It shows that the fan speed

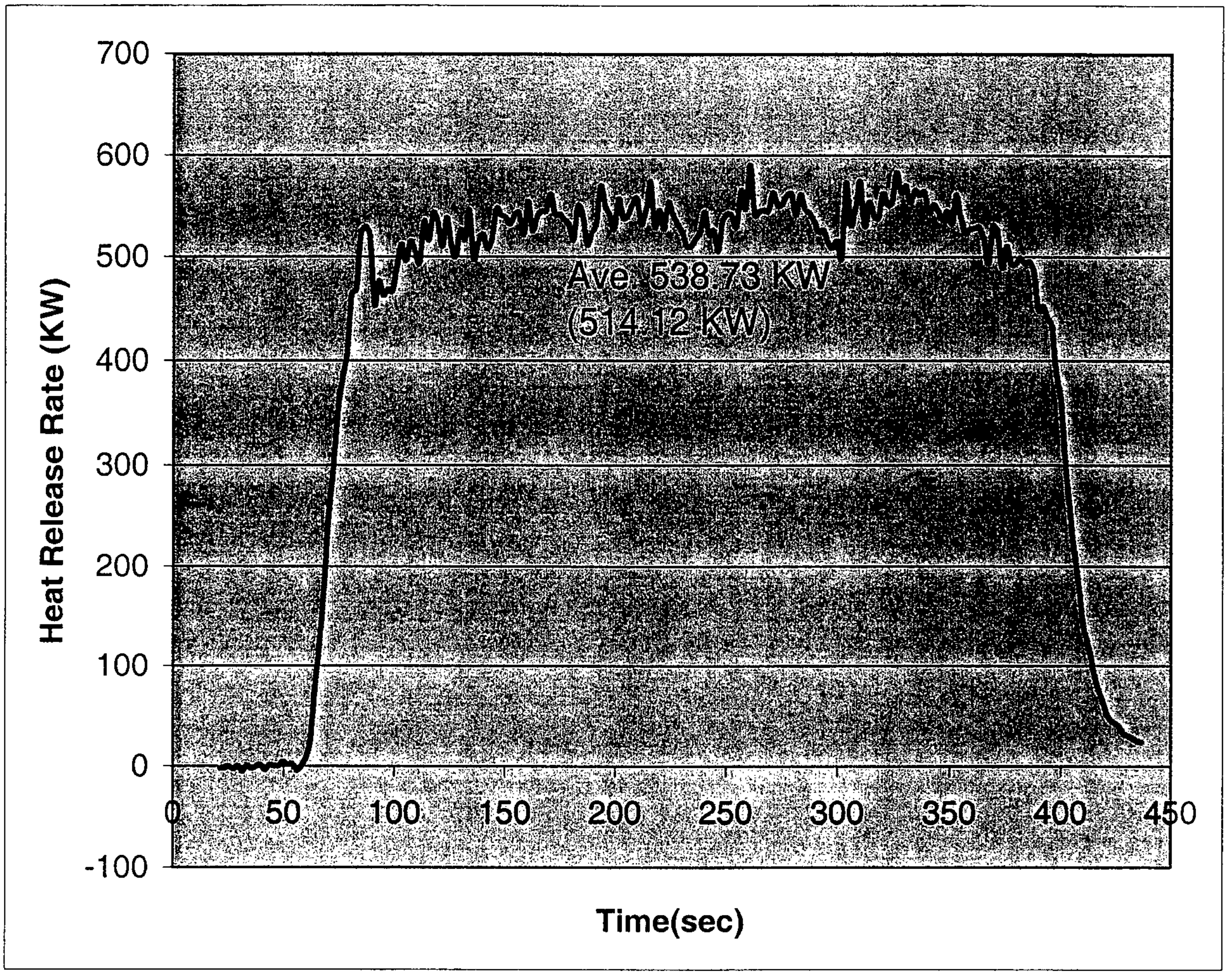

Figure A1: Heat release rate with CP grade Propane, Blower at 11% max. speed. Calculated Heat release rate = 514.12KW

of about 10 % of the maximum gave the best result and that when the speed was about 31% of the maximum the results have an error of about 20%.

The Gas Analyzers

There were two sets of gas analyzers, one for the sample from the calorimeter and the other for the sample from the test compartment. Table A2 lists the analyzers and their calibration ranges. To calibrate an analyzer, first, pure nitrogen was passed through the analyzer and its output was adjusted (if necessary) to read zero. Next, a calibration gas of known oxygen, CO or CO_2 concentration was passed through the analyzer and its output was adjusted (if necessary) to read the known value. Finally ambient air was passed through the analyzer and its output should be close to the expected ambient concentration of the particular gas.

To synchronize the values of temperature, heat release rate and species concentrations in the fire compartment it was necessary to shift the compartment concentration data by the time it took the gases to flow from the compartment to the gas analyzers. In addition it was necessary to shift the species concentration in the calorimeter by the time it took for the combustion products to flow from the fire compartment, through the calorimeter measurement location to the gas analyzers. To obtain these times, a balloon was filled with nitrogen through a valve. The valve was closed and then the balloon was attached to the gas-sampling probe either in the compartment or at the calorimeter measurement location. On opening the valve the nitrogen flowed to the analyzer and the time it took for the analyzer to respond to the nitrogen concentration was noted. The combustion products' flow time from the compartment to the calorimeter measurement location was obtained by measuring the time difference between the point of fire ignition and the time the thermocouple in the duct recorded a higher temperature.

Table A1: Comparison of Calculated and measured Heat Release Rates at Various Calibration Conditions

Percent of Full Calorimeter Flow, (%)	Propane mass flow rate (gm/sec)	Calculated Heat Release rate (KW)	Measured Heat Release Rate (KW)	Measurement Error (%)
31	4.0	174.8	214.12	22.5
31	7.46	326.0	409	25.5
32	11.98	523.4	627.5	19.9
32	4.54	198.6	236.9	19.3
25	7.5	327.8	417.5	27.4
20	4.54	198.6	238	19.8
10	4.54	198.6	201	1.2
11	11.76	514.12	538.73	4.8

Table A2: Parameters for the gas analyzers

	Model	Range	Sample source
Oxygen analyzer	Servomex	0 – 25% (0 – 1v)	Calorimeter
Oxygen analyzer	Beckman	0 – 25% (0 – 1v)	Compartment
CO_2 Analyzer	Beckman Model 865	0 – 20% (0 – 1v)	Calorimeter
CO_2 Analyzer	Rosemount Model 880	0 – 20% (0 – 5v)	compartment
CO Analyzer	Rosemount Model 880	0 – 2% (0 – 5v)	Calorimeter
CO Analyzer	Beckman Model 865	0 – 5% (0 –1v)	Compartment

APPENDIX B

FIRE FIGHTING DOCTRINE

555-36.13 PLASTIC WASTE STOWAGE FIRE.

555-36.13.1 GENERAL. OPNAVINST 5090.1(series) requires that all plastic waste be stored onboard the submarine for shore disposal by 31 December 2008. The compacted plastic waste is contained in two plastic odor barrier bags made of nylon and polyethylene. Typically, the bags are approx. 10 inches diameter, 24-30 inches long, and stacked horizontally in closable metal lockers or designated storage. Plastic waste exhibits a wide range of behavior relating to ignition and combustion but is generally classified as an ordinary combustible Class A fuel. Consequently, extinguishing methods suitable for fires involving wood and other ordinary combustibles (Class A fires) should be used to extinguish burning plastic.

555-36.13.1.1 Ignition. Navy nylon and polyethylene odor barrier bags typically will not ignite from a small spark source or cigarette but can be ignited by a sustained open flame or by a high temperature surface contact source. Measures should be taken to prevent an ignition source from coming into contact with the plastic waste.

555-36.13.1.1 Flame Spread and Fire Growth. Once ignited, flame spread radially into the bag is initially limited due to compaction. The burning rate increases substantially as the bag surfaces burn and compaction relaxes. In a closed locker, fire growth inside the container is limited by air supply. Close stacking of the bags inhibits air circulation between bags retarding fire growth. At the early stage, smoke will typically escape from the openings around the door and will be the first indicator of fire. For the USS VIRGINIA Class, the storage space is ventilated and smoke will be initially disbursed through the compartment. The storage space ventilation on USS VIRGINIA may be initially kept on to assist initial fire attack or secured to reduce smoke spread and oxygen supply to the fire.

555-36.13.2 FIRE ATTACK. For class A fires involving plastic waste the initial response should be with one or more AFFF extinguishers or a hose-reel, when available. If readily available, CO_2 or PKP extinguishers will provide flame knock down and short term control but the fire can be expected to reflash.

> **WARNING**
> Smoke from burning plastics can be irritating or toxic at low levels. Breathing protection should be required for personnel safety.

WARNING
Fire fighters for OHIO Class submarines should be equipped with breathing protection prior to entering the Dry Provision Storeroom in the event of a fire when there is heavy or irritating smoke present.

WARNING
Fire fighters for VIRGINIA Class submarines should be equipped with breathing protection prior to entering the Trash Room/Environmental Space in the event of a fire when there is heavy or irritating smoke present.

The initial responders should open the storage access door, if germane, and immediately discharge AFFF or water on the plastic waste. After open burning is extinguished, inserting the extinguisher nozzle tube or hose nozzle between bags and discharging will further extinguish deep seated smoldering to assist in preventing a reflash. It is possible that some plastic waste (e.g., polyurethane) may melt and form a pool of fire with similar characteristics to a flammable liquid (class B) fire. AFFF or water from a portable extinguisher or hose reel can also be used to control and extinguish these pool fires. A hose line or hose-reel, if available, may also be used for those fires that may be more fully involved to complete final extinguishing and overhaul.

555-36.13.3 OVERHAUL. After open burning is extinguished and the bags are cooled by the extinguishing agent, the bags and plastic waste contents will re-solidify into a strong interconnected lattice. This re-solidified lattice will be very difficult to break apart to access residual deep seated burning. Layers of bags and waste content should be removed as soon as practical to permit access to deep seated smoldering debris. A fire axe or crow bar will be helpful in removing layers of individual bags and waste content to access deep seated burning or smoldering pockets. Smoldering pockets in the waste bags and obstruction of agent by debris can be readily extinguished as the layers of bags and waste are removed from the storage areas. A portable AFFF extinguisher, hose reel or fire hose should be used during overhaul to protect against reflash and to extinguish smoldering debris pulled from the storage area.