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Smoke Movement and Smoke Control on Merchant Ships

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
Washington, DC 20234

December 1981

Final Report

Prepared for:
Office of Merchant Marine Safety
U.S. Coast Guard
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John H. Klote and Richard H. Zile

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

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SMOKE MOVEMENT AND SMOKE CONTROL ON MERCHANT SHIPS

John H. Klote and Richard H. Zile

Abstract

In the past ten years considerable progress has been made in developing systems to control smoke movement in building fires. At present no such smoke control systems are in use on merchant ships. This paper discusses the basic concepts of smoke movement and smoke control with emphasis upon shipboard applicability. A report of simulated smoke movement tests performed on two merchant vessels is presented. Based upon these test results potential methods of smoke control for merchant vessels are discussed. Recommendations are made for future study.

Key words: Ships; smoke control; smoke movement; stack effect; sulfur hexaflouride; tracer tests; ventilation systems.

1. INTRODUCTION

Smoke is recognized as a major killer in fire situations. Traditionally when a fire has been discovered, the heating, ventilation, and air conditioning system (HVAC) is shut down in an effort to prevent it from (1) spreading smoke and (2) supplying oxygen to the fire. This has been true for ships as well as for buildings. However, in spite of shutting down the HVAC system, smoke frequently obscures exit routes and flows to locations remote from the fire.

In the past ten years a concept of controlling smoke movement in building fires has been developed. A large number of buildings now exist with such smoke control systems. The objectives of this project were to investigate smoke movement on merchant ships and to evaluate the feasibility of conventional means of smoke control on merchant ships. This study concentrates on smoke movement and control in the ship's house, a structure on the ship that contains the galley, sleeping quarters, and recreational facilities.

Initially the study was to include the engine room. However, the large volume rates of intake air required by the engine dominates air movement in the engine room. While it is normal practice during a significant engine room fire to shut down the engines, this could not be done during these field tests. Therefore, no tests were conducted in the engine room.

This report provides a brief background of smoke movement and discusses the field tests of two merchant vessels with a focus toward the applicability of conventional smoke control measures used in buildings to merchant ships.

2. BACKGROUND

The general concepts of smoke movement and smoke control have evolved in the last few years. Unfortunately there is no one source document which presents these fundamental concepts. In general terms, a smoke control system must be designed so that it is not overpowered by the driving forces which cause smoke movement. An understanding of the concepts of smoke movement and of smoke control are necessary to the intelligent development of smoke control systems. Therefore, this section presents a brief discussion of these fundamental concepts.

2.1 Smoke Movement

The driving forces causing smoke movement are stack effect, buoyancy, wind, and the HVAC system. Discussion of these concepts as they pertain to smoke movement in buildings can be found in the literature [1-4][1]. The principles involved are also valid for smoke movement on ships. Generally, in a fire smoke movement will be caused by a combination of these driving forces. The following is a brief discussion of these driving forces.

2.1.1 Stack Effect

During winter there is frequently an upward movement of air within shafts in buildings. These shafts may be stairwells, elevator shafts, dumbwaiter shafts, mechanical shafts or even mail chutes. In these cases air flows into the lower portion of the shaft and flows out of the upper portion of the shaft. This phenomenon referred to as stack effect, is caused by differences in hydrostatic pressure due to two air columns at different temperatures. The pressure difference is expressed as:

$$\Delta P = (\rho_o - \rho)\, gh$$

where

ρ_o = air density outside the shaft
ρ = air density inside the shaft
g = acceleration due to gravity
h = distance from the neutral plane.

The neutral plane is an elevation where the hydrostatic pressure inside the shaft equals the hydrostatic pressure outside the shaft. Using the ideal gas law the above relation can be expressed as

---

[1] Numbers in brackets refer to the literature references at the end of this paper.

$$\Delta P = \frac{Pg}{R} \left(\frac{1}{T_o} - \frac{1}{T}\right) h \qquad (2.1)$$

where

P = absolute atmospheric pressure

R = gas constant of air

T_o = absolute temperature outside the shaft

T = absolute temperature inside the shaft.

Considering standard conditions of one atmosphere at 21°C (70°F), the above equation can be expressed as

$$\Delta P = 3460 \left(\frac{1}{T_o} - \frac{1}{T}\right) h$$

where

h = distance from the neutral plane (m)

T_o = temperature (°K)

T = temperature (°K)

ΔP = pressure difference (Pa)

or, $$\Delta P = 7.64 \left(\frac{1}{T_o} - \frac{1}{T}\right) h$$

where

h = distance from the neutral plane (ft)

T_o = temperature (°R)

T = temperature (°R)

ΔP = pressure difference (inches of H_2O).

For a structure such as a ship's house that is 20 m (60 ft) tall with a neutral plane at mid-height and a difference between the inside and outside temperature of 40°C (72°F), the above formula indicates that a maximum of 19 Pa (0.076 inch H_2O) pressure difference would be induced by stack effect. The condition described earlier consisting of an upward air flow in shafts in the winter is sometimes called normal stack effect. This is to distinguish it from the downward air flow in shafts encountered in the summer when the outside air temperature is greater than the inside air temperature. This downward air flow condition is called reverse stack effect. Stack effect is usually thought of as existing between a building and the outside. The air movement in buildings caused by both normal and reverse stack effect is illustrated in figure 1. In this case the pressure differences in the above equations would actually refer to the pressure difference between the shaft and the outside of the building.

In unusually tight buildings with exterior stairwells, reverse stack effect has been observed even during winter conditions [5]. In this situation, the exterior stairwell temperature was considerably lower than the building temperature; i.e., the stairwell was the cold column of air and other shafts within the building were the warm columns of air.

When considering stack effect between a building and the outside, if the leakage paths are fairly uniform with height then the neutral plane will be located near the mid-height of the building. However, when the leakage paths are not uniform, the location of the neutral plane can vary considerably, as in the case for shafts which are vented. McGuire and Tamura [4] provide methods for calculating the location of the neutral plane for some vented conditions.

Smoke movement from a building fire can be dominated by stack effect. The following are descriptions of the different types of smoke movement which can result from normal and reverse stack effect.

In a building with normal stack effect the existing air currents (as shown in figure 1) can move smoke considerable distances from the place of fire origin. If a fire is below the neutral plane, smoke moves with the building air into and up the shafts. Once above the neutral plane the smoke flows out of the shafts into the upper floors of the building. If the leakage between floors is negligible, the floors below the neutral plane will all be smoke free with the exception of the fire floor.

Smoke from a fire located above the neutral plane would be carried by the building air flow to the outside through leaks in the exterior of the building. If the leakage between floors is negligible, then all the other floors will remain smoke free. When the leakage between floors is not negligible then there would be an upward smoke movement to the floor above the fire floor.

The air currents caused by reverse stack effect are also shown in figure 1. As would be expected these forces affect smoke movement in the reverse of normal stack effect.

2.1.2 Buoyancy

High temperature smoke from a fire has a buoyancy force due to its reduced density. The pressure differential between a fire compartment and the ambient can be expressed by an equation of the same form as equation 2.1.

$$\Delta P = \frac{Pg}{R} \left(\frac{1}{T_o} - \frac{1}{T}\right) h \qquad (2.2)$$

where

T_o = absolute temperature of the surroundings

T = absolute temperature of fire compartment

h = distance from the neutral plane.

The neutral plane is the plane of equal hydrostatic pressure between the fire compartment and the ambient. For a fire with a fire compartment temperature of 750°C (1380°F) the differential pressure 1.5 m (4.9 ft) above the neutral plane is 12.6 Pa (0.0505 inch H_2O). Fang [6] has studied pressures caused by room fires during a series of full-scale fire tests. During these tests the maximum differential pressure reached was 16 Pa (0.064 inch H_2O).

In a building with leakage paths in the ceiling of the fire room, this buoyancy induced pressure causes smoke movement to the floor above the fire floor. In addition, this pressure causes smoke to move through any leakage paths in the walls or around the doors of the fire compartment. As smoke travels away from the fire, its temperature drops due to heat transfer and dilution. Therefore, the effect of buoyancy decreases with distance from the fire.

2.1.3 Wind

In many instances wind can have a pronounced effect on smoke movement within a building. The pressure, P_v, that the wind exerts on a surface can be expressed as

$$P_v = \frac{1}{2} C_w \rho_o V^2 \qquad (2.3)$$

where

C_w = pressure coefficient
ρ_o = outside air density
V = wind velocity

The pressure coefficients are in the range of -0.8 to 0.8, with positive values for windward walls and negative values for leeward walls. The pressure coefficient depends on building geometry and varies locally over the wall surface. For buildings located in relatively flat terrain, wind velocity increases with height due to the boundary layer effect. Detailed information concerning wind velocity variations and pressure coefficients is available from a number of sources [7-10].

A 60 km/s (37 mph) wind produces a pressure on a structure of 130 Pa (0.52 inch H_2O) when the pressure coefficient is 0.80. The effect of wind on air movement within tightly constructed buildings with all doors and windows closed is slight. However, the effects of wind can become important for loosely constructed buildings or for buildings with doors or windows open. Usually the resulting air flows are complicated and for practical purposes computer analysis is required for an approximation of building air flows.

Frequently in fire situations a window breaks in the fire compartment. If the window is on the leeward side of the building, the negative pressure due to the wind vents the smoke from the fire compartment. This can greatly reduce smoke movement throughout the building. However, if the broken window is on the windward side then the wind forces the smoke throughout the fire floor and frequently throughout a number of floors above and below the fire floor. This both endangers the lives of building occupants and hampers fire fighting.

Pressures induced by the wind in this type of situation can be relatively large and can easily dominate air movement throughout the building.

2.1.4 HVAC System

The HVAC system frequently transports smoke during building fires. In the early stages of a fire the HVAC system can serve as an aid to fire detection. When a fire starts in an unoccupied portion of a building, smoke is transported by the HVAC system to a space where people can smell the smoke. However, as the fire progresses the HVAC system will transport smoke to every area that it serves, thus endangering life in all those spaces. The HVAC system also supplies air to the fire space which aids combustion. For these reasons, HVAC systems have been traditionally shut down when fires have been discovered. Even with the HVAC system off smoke can flow through the HVAC ducts to endanger life at places far from the fire. If there are fire dampers in these ducts, generally considerable smoke will flow past the dampers before the fusible links melt. In addition, shutting down the HVAC system does nothing to prevent smoke movement through other paths due to stack effect, buoyancy, or wind. In the last ten years a concept has arisen which uses the HVAC system to limit smoke movement within a building. This concept will be discussed in section 2.5.

2.2 Principles of Static Smoke Control

Smoke control can be either static or dynamic. For static smoke control, components such as partitions, doors, and floors are used to stop the movement of smoke. Aboard ships the names of these components are different; however, they still can be used for static smoke control. The driving force of smoke movement for static smoke control is buoyancy, whereas the driving forces for dynamic smoke control are the HVAC system and specially dedicated fans.

The two basic principles of static smoke control are:

1. Smoke movement can be limited by components such as decks, bulkheads and hatches.

2. Smoke can be removed from a fire space by smoke vents or smoke shafts.

The effectiveness of a component in limiting smoke movement depends on the leakage paths in the component and on the pressure difference across the component. Pipe penetrations through decks or bulkheads, cracks where bulkheads meet decks, and cracks around hatches are a few of the possible leakage paths. In ship construction many of these leakage paths can be eliminated by welding components together and by sealing or gasketing other cracks. The pressure difference across these components depends upon stack effect, buoyancy, wind, and the HVAC system, as discussed in section 2.1.

The effectiveness of smoke vents and smoke shafts depends on the proximity to the fire, the buoyancy of the smoke, and the presence of other driving forces.

Elevator shafts and stairwells in buildings have been used as smoke shafts. In fires these shafts frequently distribute smoke to floors far from the fire. This problem can be eliminated by the use of smoke shafts which have essentially no leakage on floors other than the floor of the fire.

2.3 Principles of Dynamic Smoke Control

Dynamic smoke control uses the components (bulkheads, decks, hatches, etc.) of static smoke control in conjunction with pressure differentials and air velocities generated by mechanical fans. The two basic principles of dynamic smoke control are:

1. Air flow by itself can control smoke movement provided that the air velocities are of sufficient magnitude.

2. Pressure differentials across barriers can act to control smoke movement.

Because dynamic smoke control relies on air flow and pressure differentials produced by fans, it has the following advantages:

1. Dynamic smoke control is less dependent upon tight barriers. Reasonable leakage areas in barriers can be allowed for in the design.

2. Stack effect, buoyancy, and wind are less likely to overcome dynamic smoke control than static smoke control. In the absence of dynamic smoke control, these driving forces cause smoke movement to the extent that leakage paths allow. How-

ever, in dynamic smoke control these driving forces are opposed by the differential pressures and velocities of the system.

3. Dynamic smoke control can be designed to prevent smoke flow through an open doorway in a barrier by the use of air velocity. Doors in barriers are open during evacuation and are sometimes accidentally left open or propped open throughout fires. In the absence of dynamic smoke control, smoke flow through these doors is common.

Unfortunately dynamic smoke control does have the disadvantage that the system cannot operate in the event of a power failure to the system fan. The ideal solution to this problem is for the system to be designed to convert to a static smoke control system in the event of power failure.

The following sections discuss the basic principles of dynamic smoke control.

2.3.1 Air Flow

Theoretically a counter air flow can be used to stop smoke movement through any space. Two places where air velocity can be used to control smoke movement are open doorways and in corridors. The problem of preventing smoke movement through doorways is currently being researched. Thomas [11] has developed a relation for the critical velocity to prevent smoke from flowing upstream in a corridor.

$$U_c = k \left(\frac{gQ}{w\rho cT}\right)^{1/3}$$

where

U_c = critical air velocity to prevent smoke backflow
Q = energy release rate into corridor

w = corridor width

ρ = density of upstream air

c = specific heat of downstream gases

T = absolute temperature of downstream gases

k = constant of the order of 1

g = acceleration of gravity.

The downstream properties are considered to be taken at a point sufficiently far downstream of the fire for the properties to be uniform across the cross section. Considering $\rho = 1.3$ kg/m^3 (0.081 lb/ft^3), $c = 1.005$ kJ/kg°C (0.24 BTU/lb°F), $T = 27$°C (81°F), and $k = 1$ the above equation becomes

$$U_c = 0.03 \left(\frac{Q}{w}\right)^{1/3}$$

where

U_c = critical velocity (m/s)

Q = energy (W)

w = width (m)

or

$$U_c = 5.7 \left(\frac{Q}{w}\right)^{1/3}$$

where

U_c = critical velocity (ft/min)

Q = energy (BTU/hr)

w = width (ft).

The above relation can be used when the fire is located in the corridor or when the smoke enters the corridor through an open door, an air transfer grill, or other opening. For an energy release rate of 37 kw

(126,000 BTU/hr) into a corridor 1 m (3.3 ft) wide the above relation yields a critical velocity of 1 m/s (200 ft/min). However, for a larger energy release rate of 2.4 MW (8 x 10^6 BTU/hr) the above equation yields a critical velocity of 4 m/s (800 ft/min) for a corridor of the same width. This value is approximate because only an approximate value for k was used. However it is indicative of the kind of air velocities required to prevent backflow of smoke from fires of different sizes.

This illustrates that air flow can be used to control smoke movement without the benefit of partitions and doors to help stop the smoke. However, this is not the primary means of controlling smoke movement because the quantities of air required are so large. The use of air flow is important in preventing smoke movement out of a smoke zone when a door in the boundary of that smoke zone is open. However, the primary means of controlling smoke movement is by air pressure across partitions, doors and other building components.

2.3.2 Pressurization

As stated earlier, air pressure is the primary means of controlling smoke movement in buildings. In fact, pressurization creates high velocities in the small gaps around doors and in construction cracks and thereby prevents backflow through these openings.

The air flow rate through a construction crack, door gap, or other flow path is proportional to the differential pressure across that path raised to the power n. For a flow path of fixed geometery, the power n is theoretically in the range of 0.5 to 1. However, for all flow paths, except extremely narrow cracks, using n = 0.5 is reasonable and the flow can be expressed as

$$F = CA \sqrt{\frac{2\Delta P}{\rho}}$$

where

F = flow rate

C = flow coefficient

A = cross sectional area of flow path

ΔP = differential pressure across the flow path

ρ = density of air entering the flow path.

The flow coefficient depends on the geometry of the flow path as well as turbulence and friction. In the present context, the flow coefficient is in the range of 0.6 to 0.7. For one atmosphere at 21°C (70°F) and for C = 0.65 the above equation becomes

$$F = 840\ A \sqrt{\Delta P}$$

where

F = flow rate (ℓ/s)

A = area (m^2)

ΔP = differential pressure (Pa)

or

$$F = 2600\ A \sqrt{\Delta P}$$

where

F = flow rate (cfm)

A = area (ft^2)

ΔP = differential pressure (inch H_2O)

A closed door with a crack area of 0.01 m^2 (0.11 ft^2) and with a pressure differential of 25 Pa (0.1 inch H_2O) would have an air leakage rate of approximately 42 ℓ/s (89 cfm). Several field tests have been conducted on real buildings using the gas sulfur hexaflouride as a tracer to study simulated smoke movement and to study the effectiveness of various smoke control systems [1,5,12-14]. In these tests pressure on the order of 1 Pa (0.004 inch H_2O) across partitions and closed doors has been sufficient to prevent upstream migration of the simulated "smoke".

In order to control smoke movement, the pressures produced by a smoke control system must be sufficiently large so that they are not overcome by stack effect, smoke buoyancy, and the forces of the wind. However, the differential pressure produced by a smoke control system should not be so large as to result in unreasonably high door opening forces.

2.4 Door Opening Forces

The determination of what is a reasonable door opening force is difficult. Clearly, a person's physical condition is a major factor in determining a reasonable door opening force for that person. The Life Safety Code of the National Fire Protection Association (NFPA) [15] states that the force required to open any door in a means of egress shall not exceed 222 N (50 lb). Many smoke control system designers consider this a very high value. On a merchant vessel it is probably reasonable to assume that the officers and crew are in good physical condition under normal circumstances. However, it should be realized that exposure to smoke during a fire can adversely affect a person's physical capabilities, further complicating the determination.

The force required to open a door is the sum of the forces to overcome the differential pressure across the door and to overcome the door closer. This can be expressed as

$$F_T = F_C + \frac{WA\Delta P}{2(W-t)}$$

where

F_T = the total door opening force

F_C = the force to overcome the door closer

W = door width

A = door area

ΔP = differential pressure across door

t = distance from the door knob to the knob side of the door.

This relation assumes that the door opening force is applied at the knob.

2.5 Dynamic Smoke Control Systems

The principles presented in section 2.3 have been employed to provide dynamic smoke control systems in buildings. The two most common systems are pressurized stairwells and zone smoke control and are discussed in the following sections.

2.5.1 Pressurized Stairwells

In an effort to provide smoke-free stair passages during a fire, a number of stairwells have been built with pressurization systems. Ideally these systems use air pressure to prevent smoke infiltration. A number of papers have been written concerning analysis, design and field testing of pressurized stairwells [1,2,3,5].

A stairwell pressurization system must maintain sufficient pressures to prevent smoke infiltration when all doors are closed. For this case the flow rate of pressurization air would be low because it would only consist of leakage air around the closed doors and through building cracks and any other small leakage areas. If this flow rate is too high then the resulting high levels of pressurization can result in unreasonably high door opening forces. However, a much larger air flow rate would be needed when stairwell doors are open in order to prevent smoke backflow through the open doors.

Pressurization systems have been built which achieve these different air flow rates by means of automatic control. An alternate solution is to supply the larger air flow rate to the stairwell even when all doors are closed and to vent the excessive air to prevent unreasonably high door opening forces. The excessive air can be vented through a transfer grill or a barometric damper. This alternate approach is less complicated and less expensive than using automatic controls.

In the winter, the pressures across the upper doors of a pressurized stairwell can be quite high while the pressures across the lower doors can be very low or even negative. The opposite condition can exist in the summer. An equation has been derived by Klote [15] for the air flow rate in a simple building when the outside and inside temperatures are different. The simple building consists of one without leakage paths between building levels. However, a real ship house may have leakage through the decks or vertical connections by means of shafts. In order to analyze a pressurized stairwell connected to such a ship house a computer program could be used. Such a computer program has been developed at NBS [16]. In the design of a pressurized stairwell it is recommended that initial calculations be performed on the simple building model. If the resulting pressure differentials are acceptable then no computer analysis is required because this method is conservative.

2.5.2 Zone Smoke Control

The zone system of smoke control generally uses the HVAC system to control smoke movement. Specially dedicated smoke control fans can also be used. When this system is employed a building is divided into a number of smoke zones. In the event of a fire, air is exhausted from the smoke zone where the fire is located and air is supplied to the other zones. These air flows acting over the leakage areas of a smoke zone cause pressure differences across the boundaries of the smoke zone in which the fire exists. Ideally this pressurization will prevent smoke movement to building spaces outside of the zone in which there is a fire.

When the HVAC system is used for smoke control the following events should occur when the system is activated:

1. The supply air to the zone where the fire is located should be shut off.

2. The return air system is placed in 100 percent exhaust mode for the zone where the fire is located.

3. The supply air to all zones where there is no fire is set at 100 percent outside air.

4. The return air system is shut off for all zones where there is no fire.

A number of such systems have been built and tested [12,13]. These systems are generally automatically activated with provision for manual override. However, these systems should not be activated by a pull box because such activation cannot determine the smoke zone in which the fire is located.

3. FIELD TEST PROGRAM

Methods which have been used at NBS for smoke movement and smoke control research are (1) fire tests, (2) chemical smoke tests, (3) tracer tests, and (4) pressure mapping. These field tests were to be performed on merchant ships under normal operation. Real fire tests and chemical smoke tests were eliminated because these tests would interfere with normal ship operation. Pressure mapping consists of measuring differential pressures across barriers, i.e. closed doors. This is done by placing a flexible plastic tube in a crack around the closed door and attaching one end of it to a differential pressure transducer. Unfortunately, the doors of interest on these ships were so tightfitting that the tube was crushed and differential pressures could not be measured. Therefore, field measurements were restricted to tracer tests.

The gas sulfur hexaflouride (SF_6) has been extensively used as a tracer in smoke movement and smoke control tests because it is (1) colorless, (2) odorless, (3) nontoxic[2], and (4) stable. These attributes result in tests which do not interfere with the normal operation of the facility being tested. In addition, SF_6 is virtually unused industrially in the United States. This means that SF_6 can be used as a tracer with practically no fear of interference of SF_6 from another source.

Field tests were performed on two ships and were restricted to the house which contains living quarters, galley and other service spaces.

3.1 Tracer Test Procedures

The tracer gas, SF_6, was released at a constant rate in the simulated burn room[3]. In all these tests the burn room door was open to the corridor of the ship and all of the burn room samples were taken in the doorway. It was anticipated that the tracer tests on the ship would be different than similar tests in buildings. In large buildings SF_6 is released at a constant rate. Because the volumes of the buildings are large and because of the existing air currents in buildings, the burn room concentration remains relatively constant. However, on ships it was expected that because of the lower air movement and smaller volume of the house, that the burn room concentration of SF_6 would increase throughout the test. For this reason a flow meter which operated in a lower range (0.70 to 75 mℓ of SF_6 per min) was obtained for these tests. The release rates were varied from test to test until it was determined that a release rate of 4.5 mℓ/min would yield good test results.

Air samples throughout the house were collected and analyzed to determine smoke movement in the event of a fire. Generally samples were collected at the same location three or four times during a test. In

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[2] OSHA concentration limit of SF_6 is 1000 ppm as set forth in the Federal Register, Vol. 36, No. 157, August 13, 1971. However, concentrations used in the tests described in this paper do not exceed 2 ppm.

[3] The term "burn room" will be used from here on to mean simulated burn room.

some cases spot samples were collected at a location at only one time during the test. These spot samples were collected to determine if a location were free of SF_6 or to determine the path of SF_6 movement. Gas samples were analyzed by a portable gas chromatograph having an electron capture cell fitted with a 200 mc tritium source. Data reduction was obtained by means of a calibration curve for concentrations from 0 to 180 ppb. Samples of concentration higher than 180 ppb were diluted and then analyzed.

The purpose of these tracer tests was to determine the paths of smoke movement in the event of a real fire. However, smoke from a real fire has a buoyant force that the tracer test does not simulate. The tracer tests simulate cold smoke movement which results from low energy fires[4]. The relative concentrations of smoke resulting from a high energy fire would be different; however the paths of smoke movement would most probably be the same.

The tests discussed in the following sections show that the SF_6 concentrations did increase with time as expected. The peak concentrations of SF_6 varied from 320 to 1200 ppb. For this reason the figures in this report have different scales for the SF_6 concentration. The scales were chosen for each test so that the concentrations throughout the ship could be easily compared with the burn room concentration for that test. Care should be exercised in comparing the results of different tests.

At present no method has been developed for evaluating the hazard to human life in a real fire based on the results of a tracer test. However, the presence of SF_6 at a location indicates the existence of a path which could transport smoke to that location during a real fire. The quantity of smoke thus transported would depend on the quantity and

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[4] Cold smoke movement also exists at a considerable distance from a high energy fire. However, because of the limited size of a ship house this situation is only partially relevant to this study.

temperature of smoke produced by the fire and the extent to which other driving forces such as stack effect and wind exist. For these reasons all but very small concentrations of SF_6 are of concern. For discussion in this paper, all concentrations of SF_6 greater than one percent of the maximum burn room concentration will be considered significant.

3.2 Tests on the Exxon Houston

The Exxon Houston is a sixteen year old oil tanker. The ship's house has six levels, and the general arrangements of the decks are shown in figures 2-8. The symbols used in these figures are listed on figure 4.

The HVAC system in this ship is a 100 percent outside air system. Outside air is heated or cooled as necessary and distributed throughout the house from the fan room located on 01 deck. An exhaust system draws air from equipment spaces and toilets and reuses it for spot cooling in the engine room. Additional ventilation air for the machinery room is also supplied from the outside and combustion air for the boiler is drawn from the top of the boiler room. The net effect of this is that the boiler room is maintained at a considerable overpressure with respect to both the outside and to the ship's house.

Five simulated smoke movement tests were performed on the Exxon Houston. Outside temperatures, wind data, status of the HVAC system and the flow rates of SF_6 are provided in the following table.

Table 1. Summary Data for Tracer Tests on the EXXON Houston

Test No.	Outside Temp (°C)	Wind Speed[1] (m/s)	Wind Direction	HVAC Status	SF_6 Flow (mℓ/min)
1	30	16	0°	On	.5
2	30	16	0°	On	7.5
3	32	3	5°	Off	7.5
4	31	4	5°	Off	4.5
5	25	4	5°	Off	4.5

[1] Wind data is relative to the ship

The convention for wind directions relative to the ship in this report is given in figure 9. The temperature inside the ship during all these tests was in the range of 20° to 24°C (68° to 75°F).

3.2.1 Test No. 1

In this test the burn room was located in a cabin on the main deck as shown in figure 3. The HVAC system was in normal operation. This test was performed to determine the path of SF_6 movement when the HVAC system was operating. For this reason only spot samples were collected. The SF_6 was released at a rate of 0.5 mℓ/min, resulting in burn room concentrations in the range of 0 to 15 ppb. Samples were taken on all the other decks and in a number of locations in the forward portion of the main deck. None of these samples contained any measurable quantity of SF_6. This indicated that the SF_6 release rate for this test was too low, and this test was only useful as a calibration test.

3.2.2 Test No. 2

This test was a repeat of test No. 1 except that the SF_6 flow rate was increased to 7.5 mℓ/min. In this test the burn room concentration of SF_6 rose to 900 ppb at 3 minutes. During this test spot samples were taken at a number of locations to determine the path of SF_6 movement. SF_6 flowed from the burn room through the adjacent section of corridor and into the adjacent equipment room where it entered an exhaust grill. This air was dumped into the engine room for spot cooling. At 30 minutes into the test the spot cooling supply at the main console in the engine room had 65 ppb SF_6. There were also concentrations on all the above decks in ranges from 11 to 39 ppb with the lower concentrations on the upper decks. Again a number of locations were sampled in the forward portion of the main deck such as the officer's mess and the boatswain's store and none of these samples contained any measurable quantity of SF_6. During this test the first assistant engineer stated that frequently the engineer on duty in the engine room is the first to smell smoke from a fire in the house. This is reasonable and confirms the findings, because the air exhausted from the house is supplied to the engine room as spot cooling.

3.2.3 Test No. 3

This test was similar to the second test except that the supply and exhaust systems were turned off to simulate the current practice for real fire situations. Figure 10 shows the SF_6 concentrations on different decks for this test. These samples were all measured in the corridor near the stairs. As can be seen from figure 10 the concentration decreases with deck height. In previous tests in buildings, this type of air flow has been found to be characteristic of the situation where the leakage paths are primarily between floors and not due to leakage through shafts. Samples were also collected in the forward portion of the main deck and as in test no. 2 the levels of SF_6 were negligible in all these samples.

3.2.4 Test No. 4

The burn room for this test was the first assistant engineers quarters on 03 deck. Because the volume of 03 deck was small a lower release rate of 4.5 mℓ/min was used. The supply and exhaust fans were turned off as in test no. 3. This test was made to determine the vertical SF_6 movement, and figure 11 shows SF_6 concentrations on different decks during this test. The concentrations of SF_6 on the decks directly above and below the fire room were very high. However, the levels of SF_6 on all other decks is negligible. Again this type of flow is characteristic of the situation where the leakage is primarily between the decks. Spot samples were collected at a number of locations on the main deck and the SF_6 concentrations in these samples were again negligible.

3.2.5 Test No. 5

The burn room for this test was located in the galley on the main deck. The supply and exhaust systems were again turned off as would be the case in the event of a real fire. The samples taken on the port and starboard corridors of the main deck within the first five minutes of the test had no traceable level of SF_6. Once this was realized spot samples were taken throughout the forward portion of the main deck. The primary movement of SF_6 was through the galley serving window into the crew mess and down the corridor and into the boatswain storage area. This flow path is shown in figure 3. A constant flow of air to the outside was observed through a hatch in the ceiling of the boatswain storage area. The SF_6 also migrated into the officers mess and the port corridor by the galley. The concentrations in these areas were about one-fourth the concentration in the path from the galley to the boatswain storage area. Samples were also collected in the forward corridor of the main deck as well as on all the other decks and the SF_6 concentrations in all these samples were negligible.

3.3 Tests on the Sea-Land Express

The Sea-Land Express is a new container ship with a seven level house, and the general arrangements of these decks is shown in figures 12-19. The house area was served by two HVAC systems, one for the port side and another for the starboard side of the house. The air handling units for these systems are located in two mechanical rooms on the main deck as shown in figure 13. The basic configuration of the air handling units is shown in figure 20. The system contains one fan which both supplies air to living spaces and pulls exhaust air back to the fan coil units. The proportion of return air to outside air is controlled by manually adjusting dampers. These units supply conditioned air to the ship's office on the main deck and to all the spaces on the above decks. The return air is taken from 02, 03, 04, and 05 decks. On these decks the return air inlets are located at the ends of the corridor near the doors to the outside. The return air flows from the conditioned spaces through door grilles into the corridor and then down the corridor and into the return inlets. This air then goes back to one of the fan coil units on the main deck. There are no inlets on the main deck, 01 deck, and 06 deck. All the air supplied to these decks is either vented to the outside or exhausted to the outside.

Five simulated smoke movement tests were performed on the Sea-Land Express. Outside temperatures, wind data, status of the HVAC systems and the flow rates of SF_6 are provided in the following table.

Table 2. Summary Data for Tracer Tests on the Sea-Land Express

Test No.	Outside Temp (°C)	Wind Speed[1] (m/s)	Wind Direction	HVAC Status	SF_6 Flow (mℓ/min)
1	28	10	45°	On	4.5
2	26	10	45°	Off	4.5
3	17	6	5°	On	4.5
4	13	7	323°	Off	4.5
5	11	4	270°	Off	4.5

[1] Wind data is relative to the ship.

The convention for wind directions is the same as that used for the Exxon Houston, and is given in figure 9. The temperature inside the ship during all these tests was in the range of 20° to 24°C (68° to 75°F).

3.3.1 Test No. 1

In this test the burn room was located in the first assistant engineer's office on 04 deck as shown in figure 17. During this test the HVAC system was in normal operation. This test was conducted to determine the extent to which the HVAC system would distribute SF_6 and to determine the threat to a crew member trapped in a cabin. The SF_6 concentrations on 04 deck are shown in figure 21. Air is drawn from the burn room down the port corridor to the exhaust grill at the end of the port corridor. This explains why the concentration at the aft end of the port corridor is so close to the burn room concentration. The concentrations at other locations on 04 deck are considerably lower. SF_6 samples were collected in the relief officer room (B) which is located at the end of the port corridor. The concentrations in this room were slightly lower than the concentration in the air leaving the supply grill in the ceiling of the room. This indicates the SF_6 in the relief officer room (B) was primarily coming from the HVAC system. This was anticipated because there was a very noticable air flow from the room to the corridor which would inhibit SF_6 infiltration to the room from the corridor.

The SF_6 concentration on the other decks of the ship's house and the burn room concentration are shown in figure 22. The concentrations on the other decks are similar to the concentrations measured in the relief officer room (B) in figure 21. The SF_6 on these other decks was transported through the HVAC system and possibly to some extent by leakage paths between decks.

3.3.2 Test No. 2

This test was the same as test no. 1 except that the HVAC system was shut off as would be the case in a real fire. A major reason for this test was to determine the SF_6 movement to the other decks, and samples were collected on all the other decks throughout the test. The SF_6 concentrations on the other decks were negligible throughout the test. This showed that there was essentially no vertical leakage within the ship's house.

In order to determine the threat to a crew member trapped in a cabin, samples were collected in the relief officer room (B) and these are shown in figure 23. The door to the relief officer room (B) had an open return air grill in it and this was obviously the primary path for the significant quantity of SF_6 that entered this cabin. The concentrations in this cabin were very similar for both tests no. 1 and 2. However, in test no. 1 the SF_6 in this cabin entered primarily through the HVAC system.

3.3.3 Test No. 3

The burn room for this test was the crew lounge on 01 level as shown on figure 14. The HVAC system was operating normally for this test and the galley exhaust fans were shut off. The SF_6 concentrations for the burn room and other locations on the 01 level are shown in figure 22. As one might expect, the SF_6 concentrations in the 01 level corridor decrease with distance from the burn room. The concentration in the galley was less, but still significant. However, the concentration of SF_6 in the hospital was insignificant. In addition, SF_6 samples were also collected on the other decks and the SF_6 concentrations of these samples were all negligible. This indicates that again there was essentially no vertical leakage within the ship's house even though the HVAC was operating. The HVAC system did not recirculate the SF_6 as in test no. 1 because there are no air returns on level 01 where the SF_6 was released.

3.3.4 Test No. 4

The crew linen locker on level 02 was used as the burn room for this test as shown in figure 15. The HVAC was shut off as would be the case in a real fire. This test was made to determine the extent of SF_6 movement on the deck of the burn room and to determine the extent of vertical SF_6 movement. In order to determine the extent of danger to a crew member trapped in a cabin samples were collected in the Chief Steward's room on 02 level with the door closed. The SF_6 concentrations on 02 deck for this test are shown in figure 25. The SF_6 concentration in the corridor of 02 deck was quite high. It can be seen from figure 25 that the SF_6 level in the Chief Steward's room was significant. As in the case of test no. 2 this cabin door had an open return air grill which was obviously the primary path for SF_6 flowing into the cabin. It is apparent from figure 25 that there was a high level of SF_6 in the corridors of 02 deck.

Samples were also collected on other decks and these concentrations are shown in figure 26. It can be seen that the SF_6 concentrations are essentially zero for all the levels sampled excepted for 05 deck. A slight quantity of SF_6 reached 05 deck, undoubtably by stack effect. A number of pressure measurements were made in a effort to find the shaft which transported the SF_6 to the 05 level. Unfortunately this was unsuccessful. In any event the concentration of SF_6 on 05 deck was so low that this unidentified leakage path probably presents no serious threat.

3.3.5 Test No. 5

For this test the first mate's office on 05 deck was used as the burn room as shown in figure 18. The HVAC system was again shut off as would be the case in a real fire. This test was made to determine if similar smoke movement would exist when the burn room was on 05 deck as happened on other decks in the test nos. 2 and 4. The SF_6 concentrations from this test are shown in figure 27. As in earlier tests the corridor concentration was high. Samples were collected in the third mate's room with the door closed. Again, as in test nos. 2 and 4, the SF_6 concentrations in the third mate's room were significant. However, the SF_6 concentrations in the officer lounge were negligible, most likely due to its distance from the burn room and the fact that it was separated from the corridor by a closed door. Air samples were also collected on the other decks and the SF_6 concentrations were negligible.

4. DISCUSSION

4.1 Horizontal Smoke Movement

The main emphasis of the tests on the Exxon Houston was vertical SF_6 movement, with the exception of test no. 5. Test no. 5 was the special case of a simulated galley fire where SF_6 was carried by the existing air currents out of the ship after passing through the crew's mess and the boatswains storage. However, on the Sea-Land Express all of the tests clearly indicated only horizontal movement. As might be expected SF_6 concentrations within the corridor decreased with distance from the burn room. Test nos. 2, 4 and 5 (sections 3.3.2, 3.3.4, and 3.3.5) all show that there is significant SF_6 movement from the corridor into cabins on the fire deck. This SF_6 movement was through the ventilation return grills located in the cabin doors.

These grills are located in the lower part of the doors and the extent of smoke infiltration would probably be somewhat less in the event of an actual fire due to buoyancy effects. Nonetheless, this poses a life threat in a real fire situation. In addition, high smoke concentrations in the corridor would hinder evacuation as well as fire fighting.

4.2 Vertical Smoke Movement

In test no. 4 on the Sea-Land Express the burn room was 02 level and the other decks had no SF_6 except for a slight quantity on 05 deck, presumably due to stack effect. There was no evidence of SF_6 movement by stack effect in any of the other tests on the Sea Land Express or on the EXXON Houston.

There was essentially no leakage of SF_6 between decks on the Sea Land Express (test nos. 2-5). However, there was considerable leakage of SF_6 between decks (test nos. 3 and 4) of the Exxon Houston. While the exact leakage paths and the events that created them could not be determined, it is important to remember that such leakage can exist. Smoke control systems that are developed for merchant vessels should probably be capable of satisfactory performance even if such leakage paths exist between decks.

4.3 Smoke Control Problem

Based upon the preceding discussion of horizontal and vertical smoke movement one possible scenario of a fire in a cabin, storage room or equipment space can be developed. The smoke flows out of the burn room into the corridor and into the HVAC return. The HVAC system spreads the smoke throughout the ship's house. Someone smells the smoke and turns in an alarm, and the HVAC system is shut off. The corridor of the fire floor is totally obscured. Possibly sleeping crew members are trapped as smoke enters the return grills in their cabin doors. If there are leakage paths between decks, smoke flows into other decks. Valuable time is wasted determining on which deck the fire is located. Once the fire deck is determined, more valuable time is wasted locating the fire through the obscured corridor. During this wasted time the fire grows larger and the threat to any trapped crew members becomes greater.

Ideally a smoke control system including smoke detectors should be part of the fire protection system in order to limit the smoke movement problems, and thus allow faster location and extinction of such fires.

4.4 Pressurized Stairwells

Pressurized stairwells (1) provide a means of exit from the fire, (2) can be used as a staging area for firefighters, and (3) provide air flow which can clear the corridor of smoke from the corridor to the burn room door. Air flow from a stairwell to a corridor exists when the stairwell door is open. In order to clear a corridor of smoke, the air flow rate into the corridor must be sufficiently large as discussed in section 2.3.1. The analysis provided in section 2.3.1 is for air flowing in one direction through a corridor that has essentially no leakage paths in the sidewalls. This is different from the case on a merchant ship which has return air grills in the doors, and further study is needed. Air for such a system could be provided by the HVAC system or a special fan.

4.5 Zone Smoke Control

The zone smoke control concept could be used to exhaust the smoke from the fire deck and pressurize the other decks. Such a system would prevent or reduce smoke leakage through decks. Even though this system would remove some smoke from the fire deck, obscuration and toxic gases would still possibly be a problem on the fire deck.

The use of existing HVAC system for zone smoke control poses problems. HVAC systems that lend themselves to zone smoke control have separate fans for supply and exhaust. The recirculating HVAC system (figure 20) has no exhaust fan. The 100 percent outside air system has both fans but modification to zone smoke control would require expensive ductwork changes and addition of smoke dampers. Considering the limited benefit of zone smoke control to the particular smoke problem described in section 4.3, it is doubtful if such a system would be justified for a retrofit situation. In the case of new ships further study of zone smoke control is in order.

4.6 Pressurized Stairwell with Zone Smoke Control

This system provides the advantages of both systems, i.e., pressurized stairwells and zone smoke control. It can prevent smoke from moving to other decks and it can provide a smoke free section of corridor from the stairwell to the burn room when the stairwell door is opened. However, the same considerations concerning retrofit for the zone smoke control also apply to this system.

4.7 Smoke Exhaust System

Test nos. 1 and 2 on the Exxon Houston showed that when the HVAC system was operating, it purged SF_6 from the ship house. This is because this ship has a HVAC system which operates on 100 percent outside air. The exhaust air from the house was used for spot cooling in the engine room.

A possible method of smoke control for such a ship would be to leave the exhaust system operating during a fire but to duct the exhaust air directly outside rather than through the engine room. However, even though this system would remove some smoke from the fire deck, obscuration and toxic gases would possibly still be a problem. And, because this system does not include pressurization of the other decks, smoke flow to those decks is also possible.

4.8 Test Methods

The tracer tests performed on these two ships provided considerable information on leakages and the paths of smoke movement in the event of a real fire. However, because the tracer lacked buoyant forces, obscuration and toxicity, these tests should not be interpreted as providing complete information regarding the actual smoke danger presented from a fire.

4.9 Engine Room Fire

As discussed in the introduction, tests could not be performed in the engine rooms during this test series. However, an important observation can be made. As in the case of the ship's house, smoke obscuration in the event of an engine room fire can prolong location and extinguishment of the fire. This problem is made more severe because of the large size of the engine room. Furthermore, the potential of an engine room fire is relatively high due to the presence of fuels and lubricants. This problem needs further investigation.

5. RECOMMENDATIONS

5.1 Fire Tests

The use of pressurized stairwells and zone smoke control is feasible for merchant vessels. Full-scale fire tests are needed (1) to determine the effectiveness of zone smoke control in reducing the levels of obscuration and of toxic gases on the fire deck and (2) to investigate the smoke clearing effect of air flowing from an open door of a pressurized stairwell into the fire deck. Emphasis is placed on the fire deck because reduction of obscuration on this deck can save valuable time during fire fighting.

5.2 Computer Analysis

It is recommended that a computer model of smoke movement and smoke control in a merchant ship's house be developed. This model could be used as a research tool to gain a better understanding of smoke control on the fire deck, to extend the test results to other geometries, and to develop design guidelines.

5.3 Engine Room Fires

It is recommended that a study of smoke control in engine rooms be undertaken. In these large spaces, buoyancy would be a major driving force of smoke movement. Accordingly, tracer tests would not be appropriate because of absence of any buoyant force in such tests. The most appropriate tests would be full-scale fire tests. Possibly a system which used power venting would be appropriate for engine room fires.

5.4 Passenger Ships

It is recommended that future studies be made concerning smoke movement and smoke control on passenger ships. The passenger ship is more complex due to the larger number of people, the more complicated architecture, and the more complex HVAC systems. Basic information concerning flow paths and leakages is needed for passenger vessels and SF_6 tests would be an appropriate way in which to obtain this information.

5.5 Military Ships

The basic concepts of smoke control discussed in section 2 are also applicable to military ships. Basic information concerning flow paths and leakages can be obtained from SF_6 tests. Specific solutions to the smoke control problems on these ships would depend upon specific details as to the ship's function, interior ship layout, and type of HVAC system. Obviously, different solutions would be appropriate for different ships. The primary goal of such a study would be to reduce smoke obscuration so that the fire could be located and extinguished as quickly as possible.

6. ACKNOWLEDGEMENTS

Thanks are due to the Exxon Company and the Sea Land Company who allowed NBS to test on their merchant ships. In particular, we extend our appreciation to Captain Ford of the Exxon Houston and Captain Berger of the Sea-Land Express for their cooperation and for the cooperation of their officers and crews. Appreciation is also expressed to William Stull of NBS for his help in performing the tests on the Exxon Houston.

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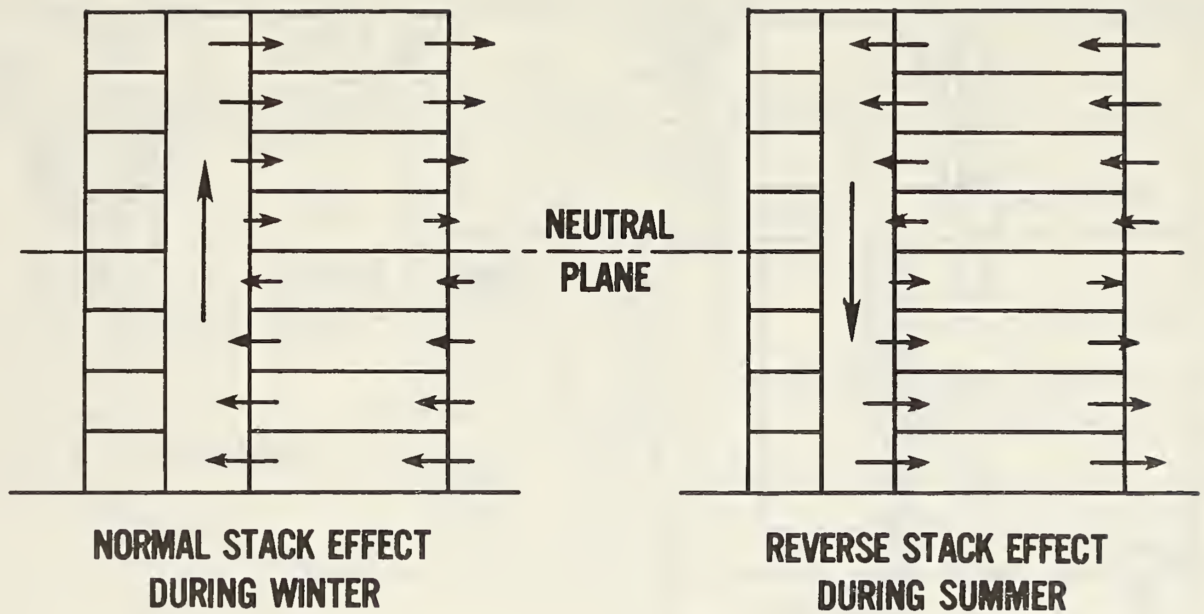


Figure 1. Air movement resulting from normal and reverse stack effect

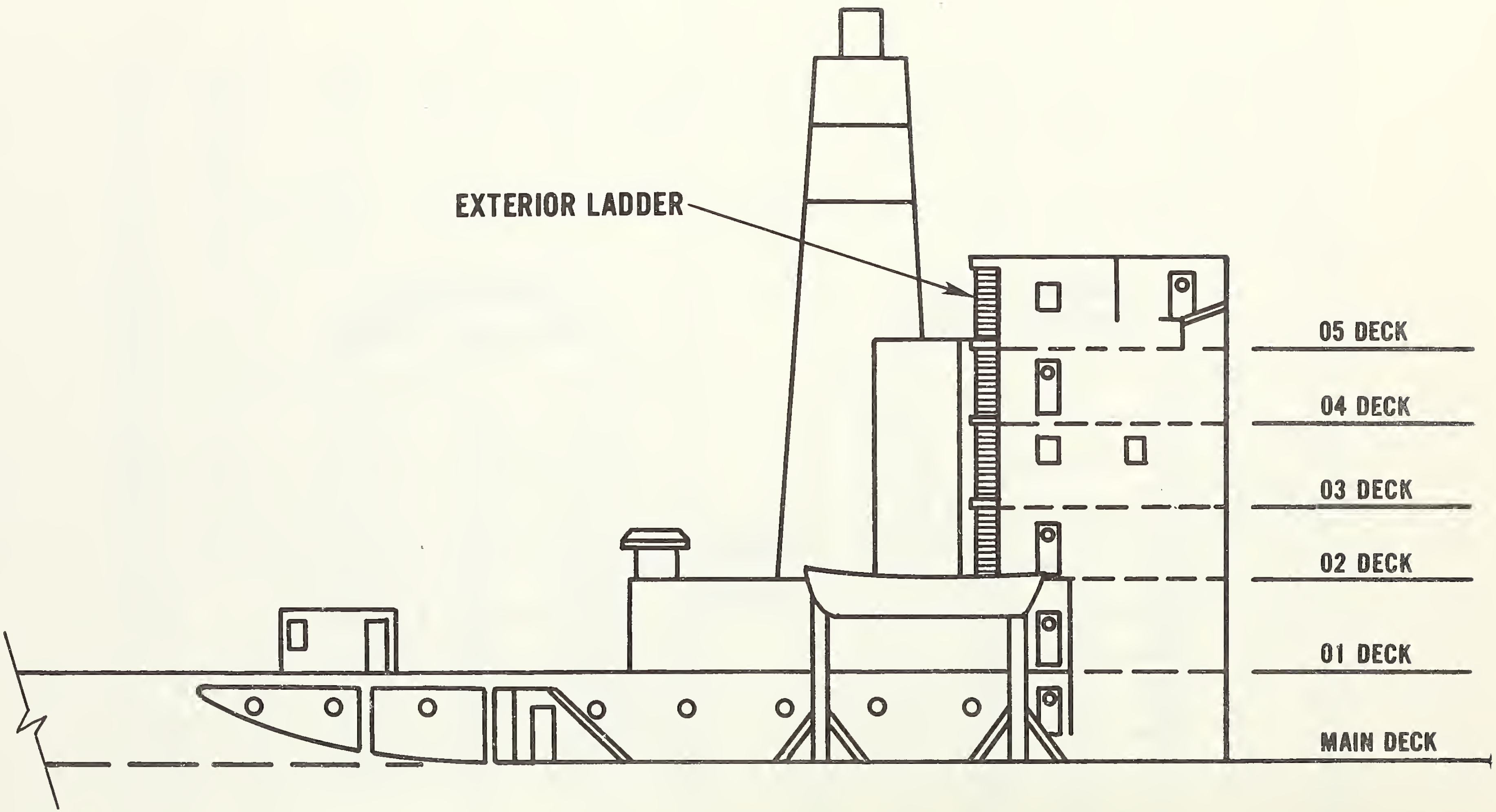
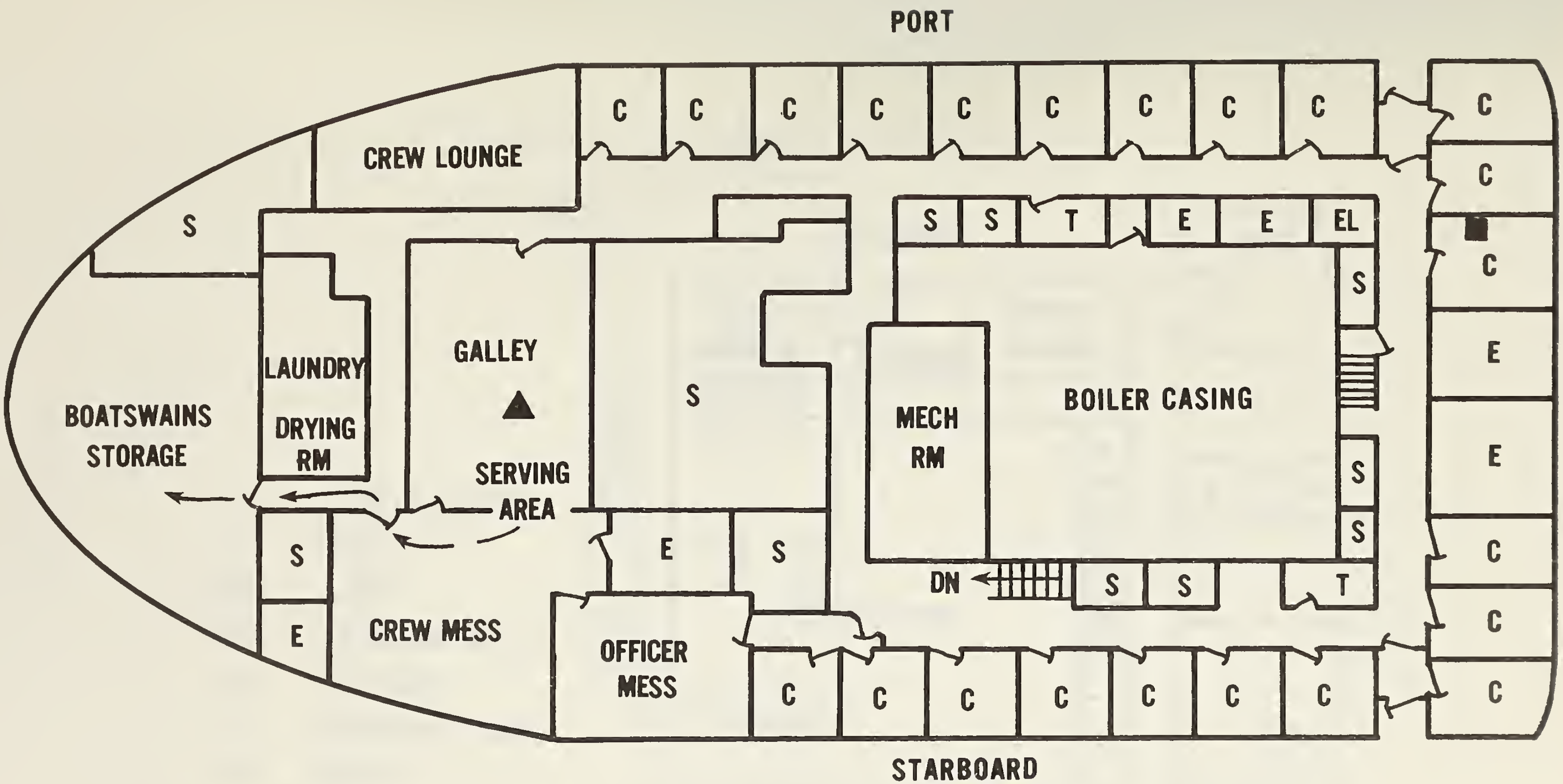


Figure 2. Elevation of ship's house on the Exxon Houston



■ LOCATIONOF BURN ROOM FOR TEST NO'S 1, 2 AND 3.

▲ LOCATION OF BURN ROOM FOR TEST NO. 5.

Note: ARROWS SHOW PRIMARY PATH OF SF_6 MOVEMENT FOR TEST NO. 5.

Figure 3. Main deck of the Exxon Houston

ABBREVIATIONS:

C	CABIN
CAPT.	CAPTAIN
DN	DOWN
E	EQUIPMENT ROOM
EL	ELEVATOR
ES	EXTERIOR STAIR
RM	ROOM
T	TOILET
S	STORAGE ROOM

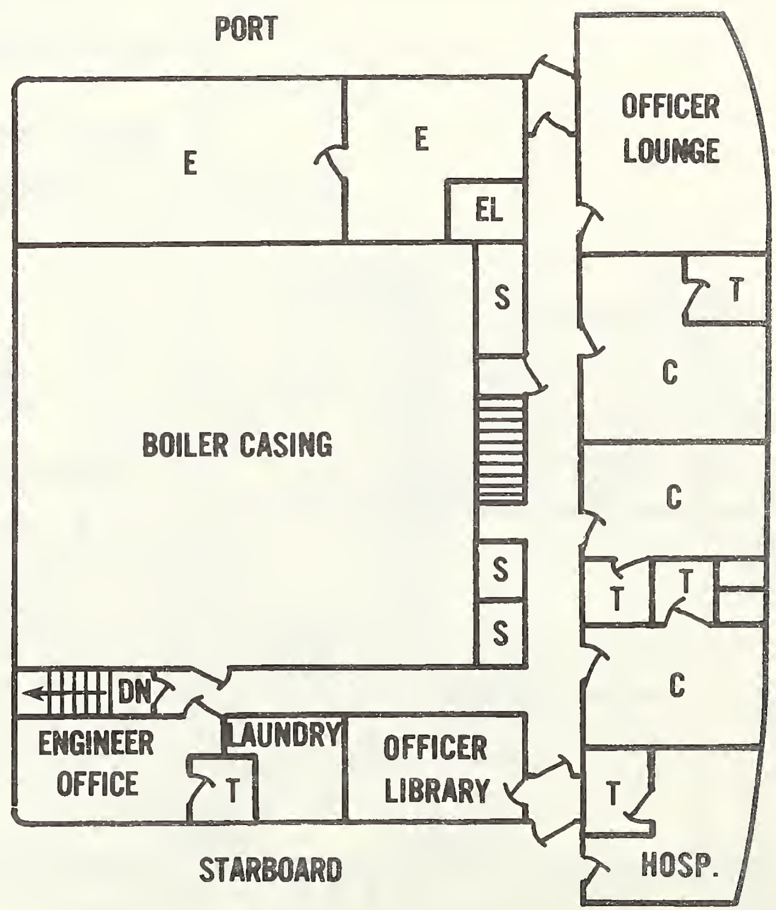


Figure 4. The 01 deck of the Exxon Houston

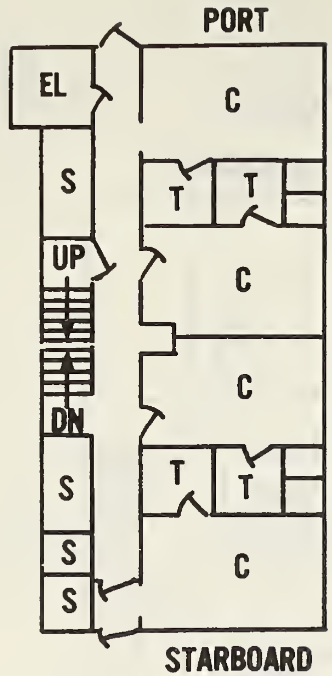


Figure 5. The 02 deck of the Exxon Houston

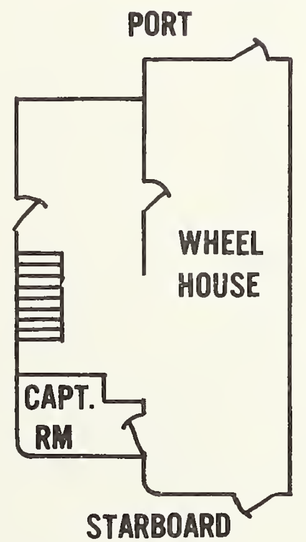


Figure 8. The 05 deck of the Exxon Houston

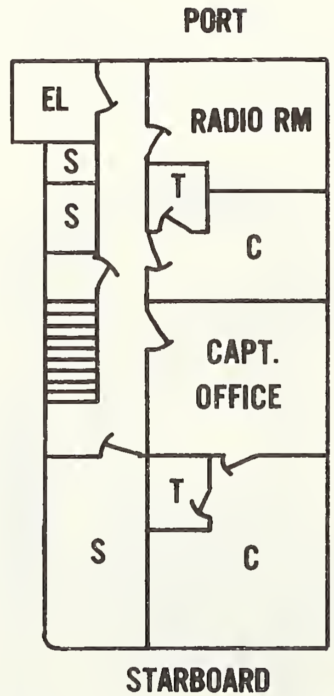


Figure 7. The 04 deck of the Exxon Houston

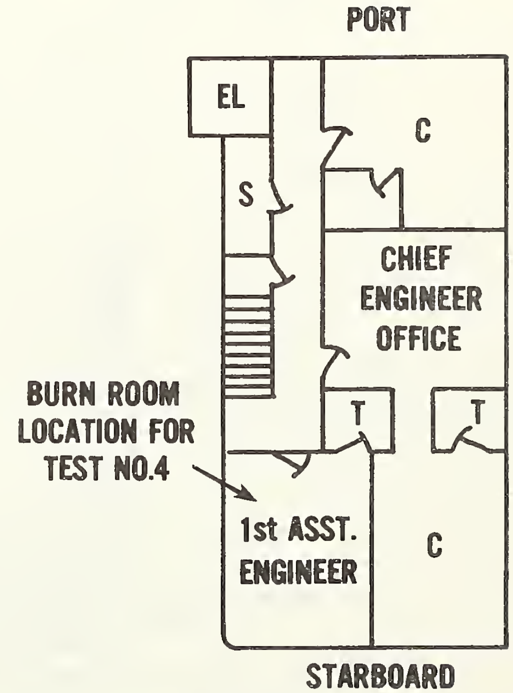
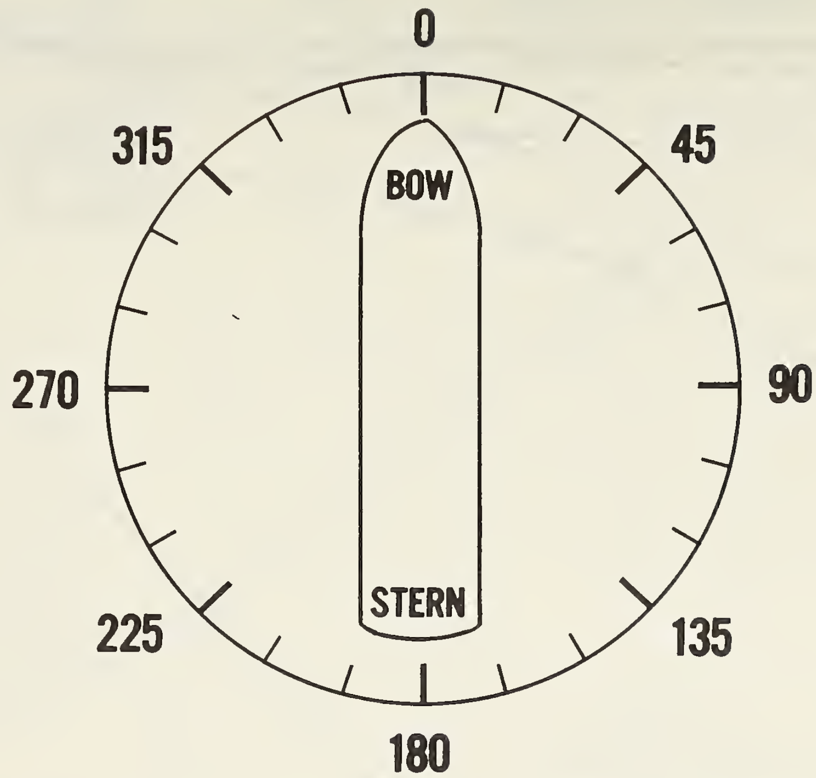


Figure 6. The 03 deck of the Exxon Houston



NOTE: Wind velocity is relative to the ship and wind direction in this report is given by this diagram.

Figure 9. Wind direction diagram

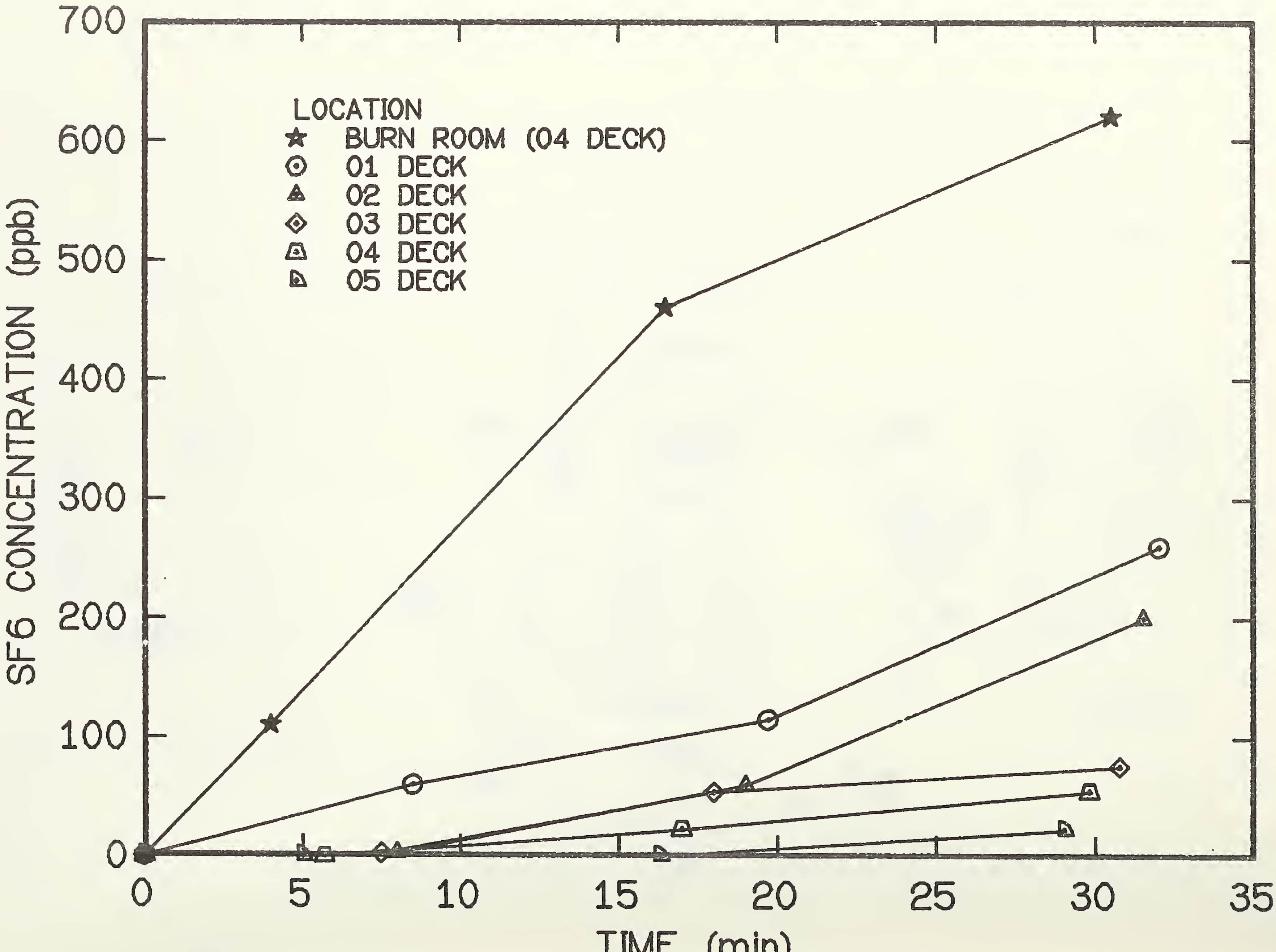


Figure 10. SF_6 concentrations for test No. 3 on the Exxon Houston

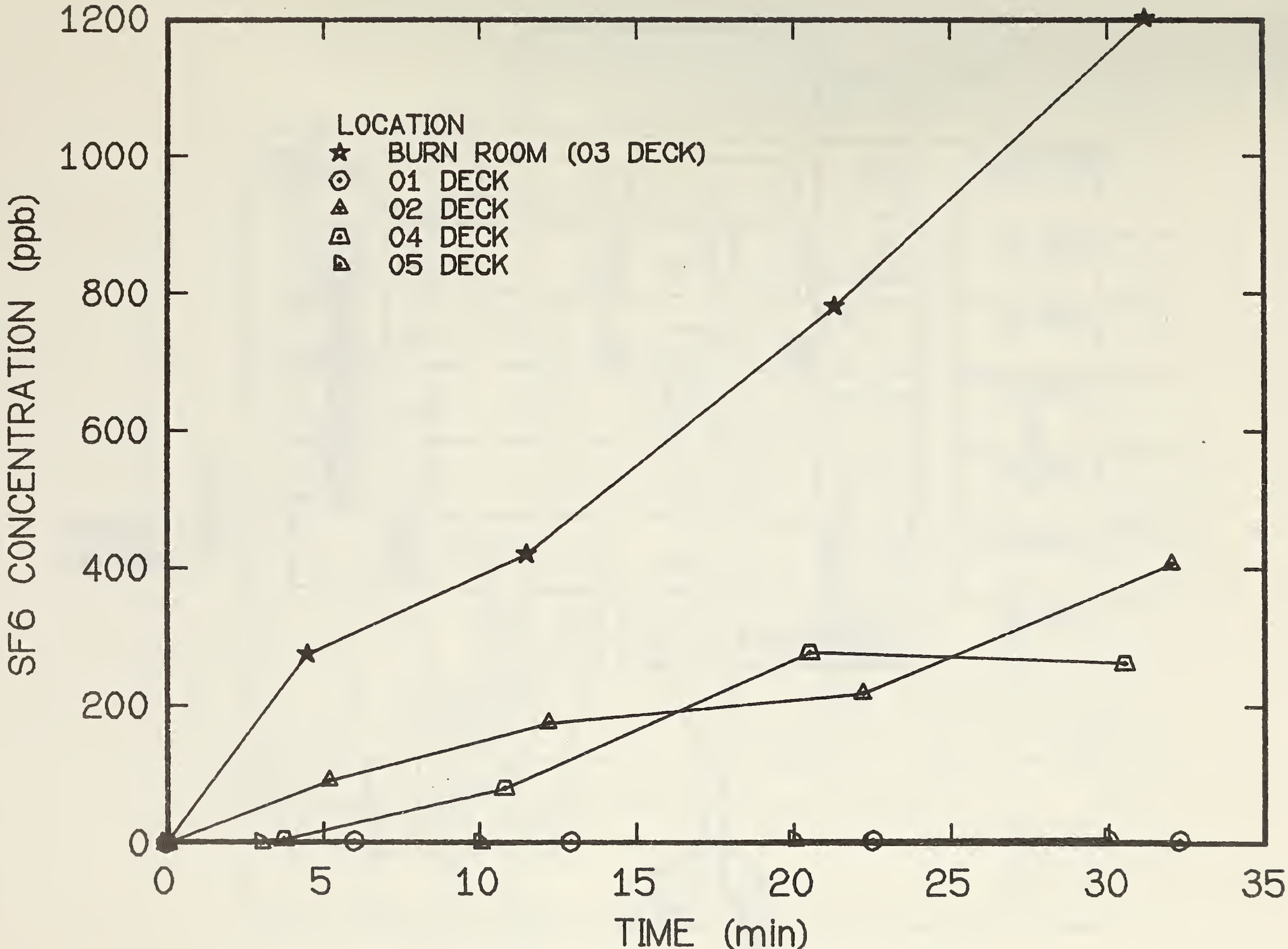


Figure 11. SF_6 concentrations for test no. 4 on the Exxon Houston

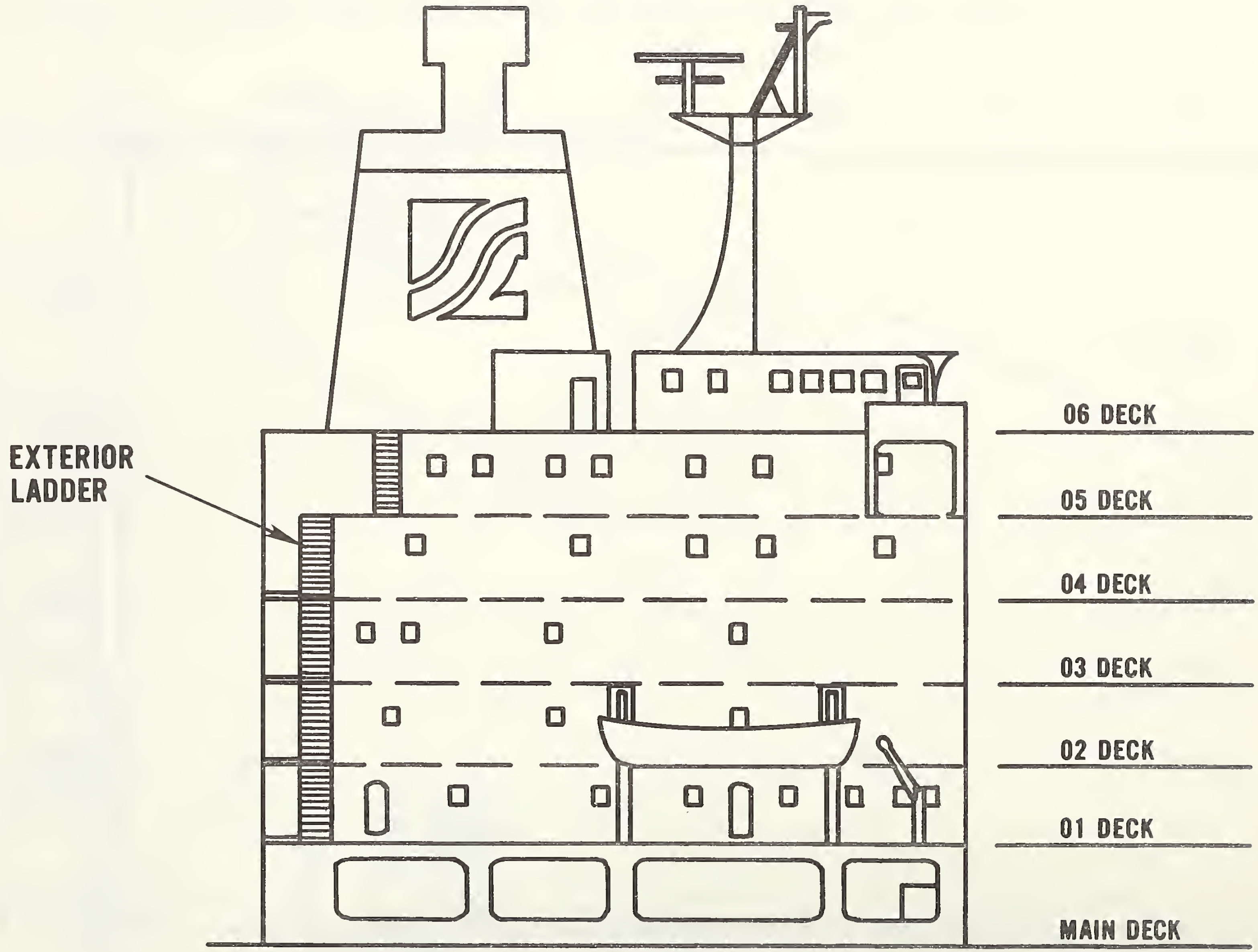


Figure 12. Elevation of ship's house on the Sea-Land Express

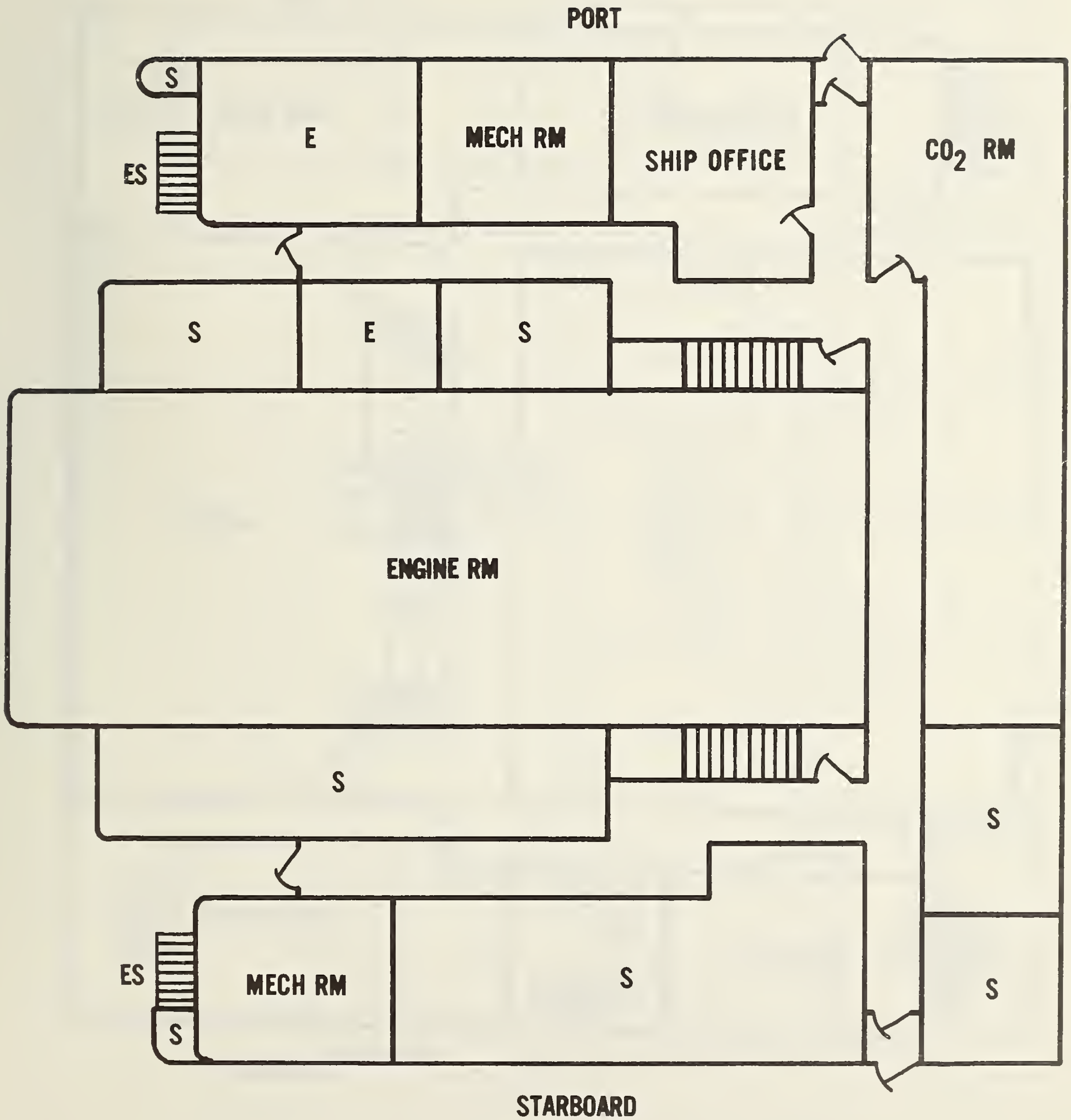


Figure 13. Main deck of the Sea-Land Express

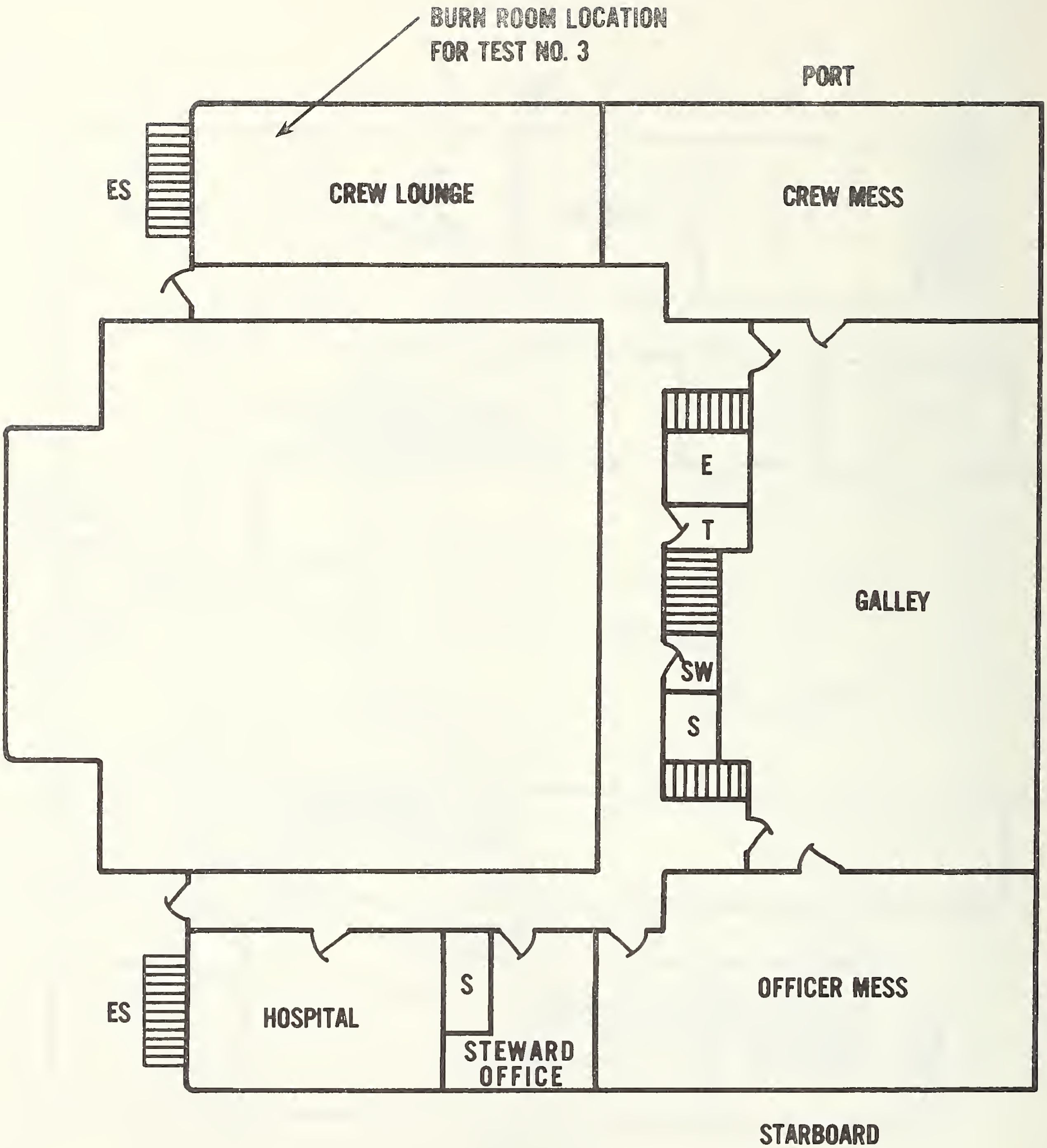


Figure 14. The 01 deck of the Sea-Land Express

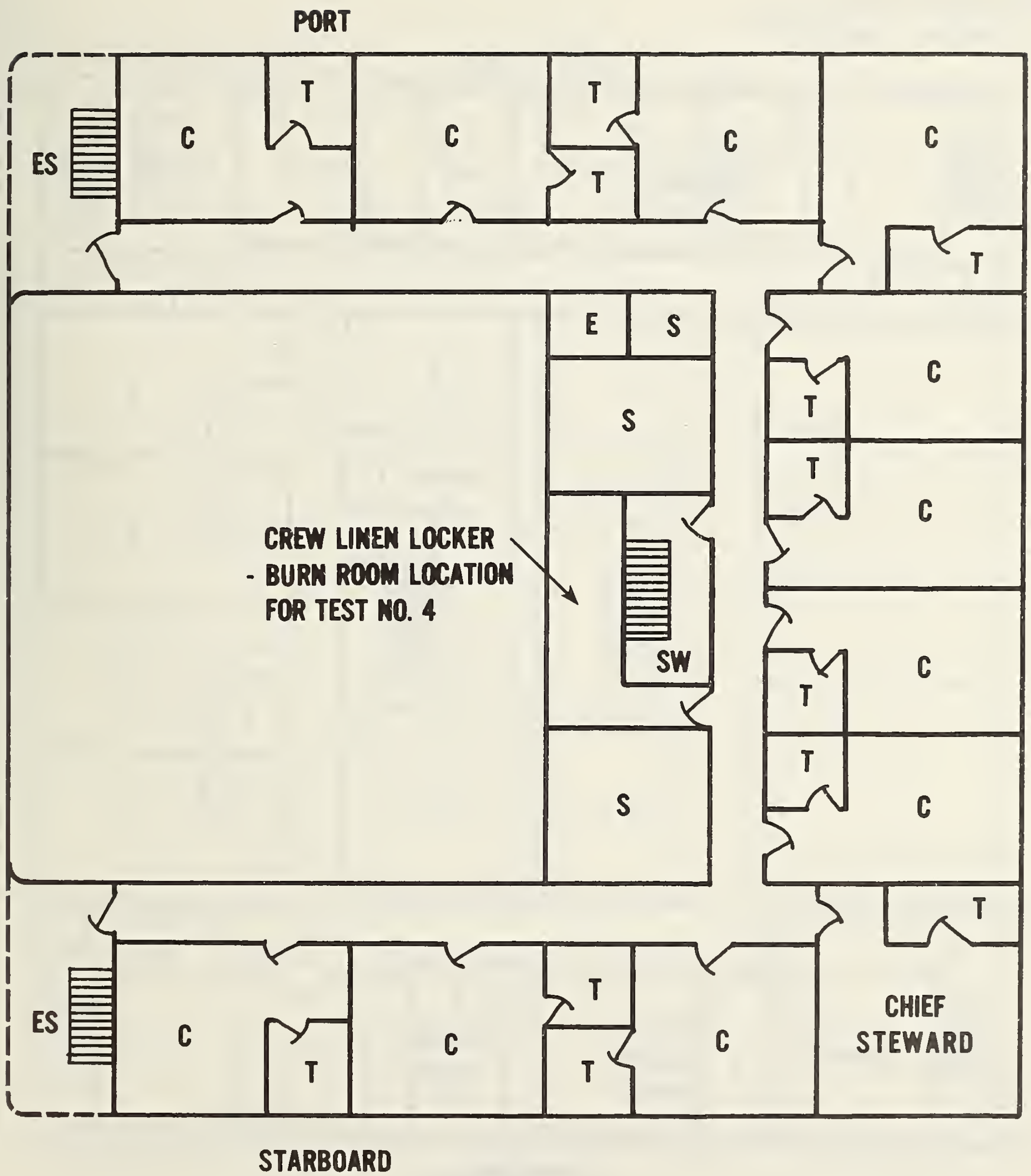


Figure 15. The 02 deck of the Sea-Land Express

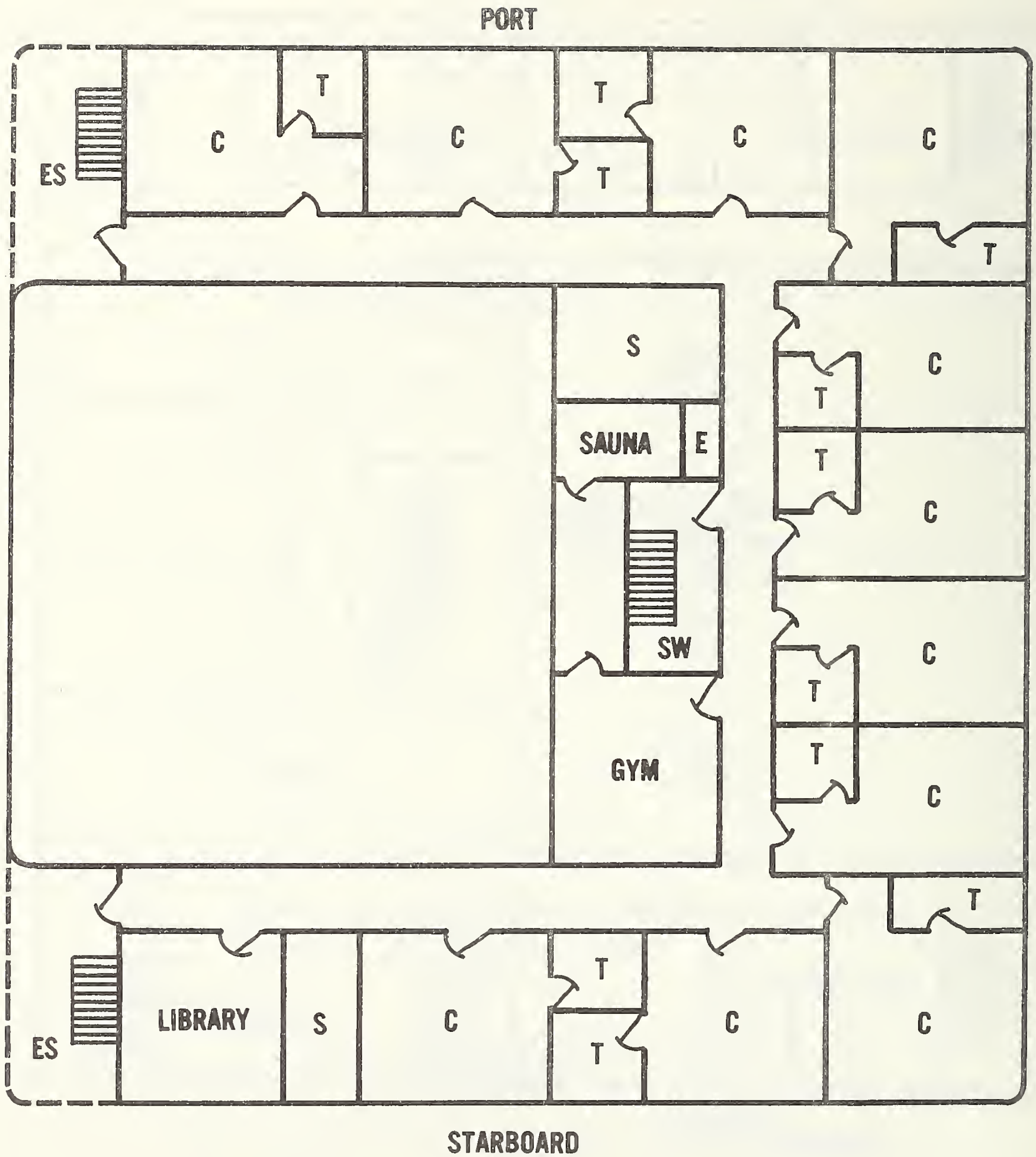


Figure 16. The 03 deck of the Sea-Land Express

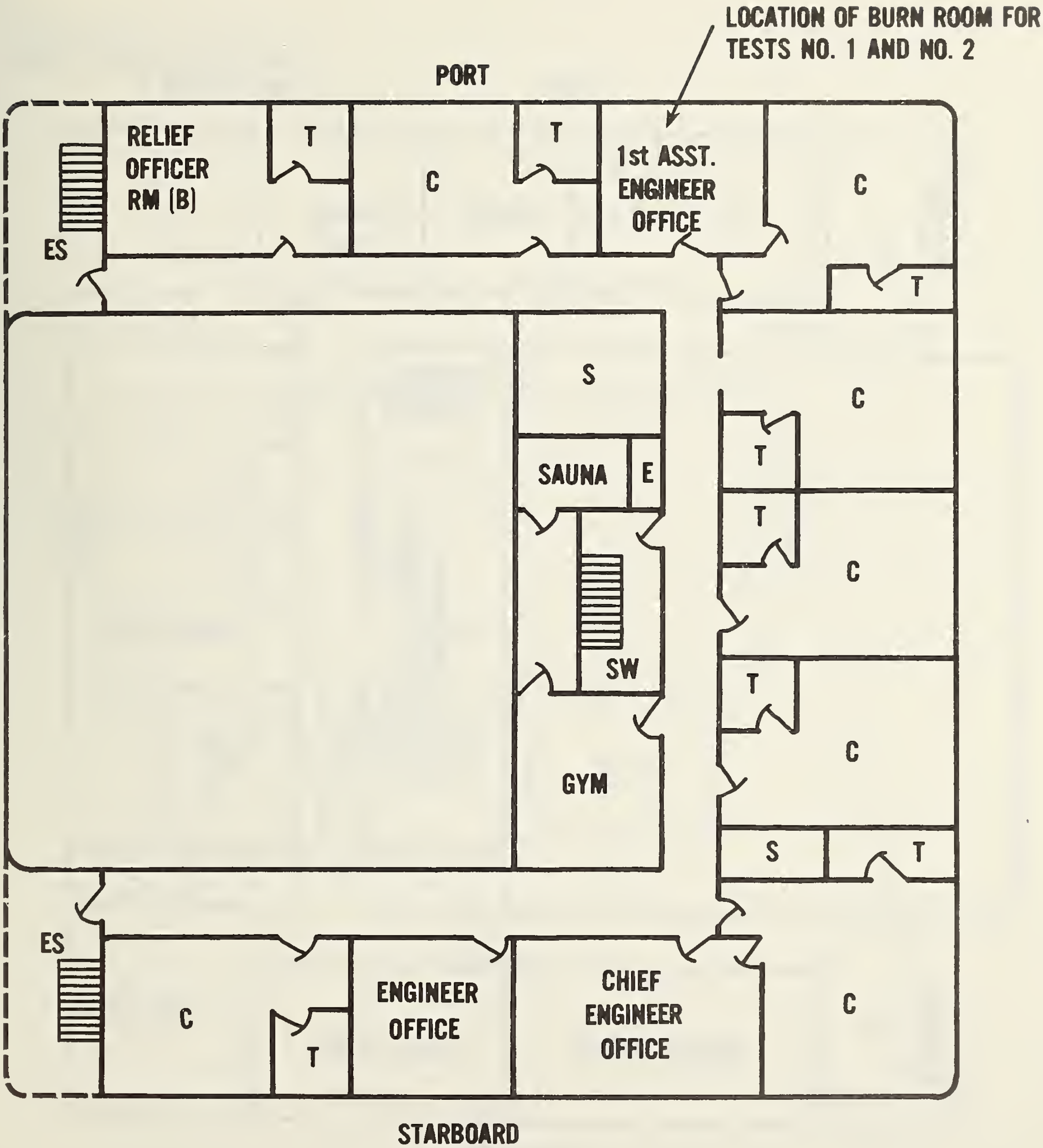


Figure 17. The 04 deck of the Sea-Land Express

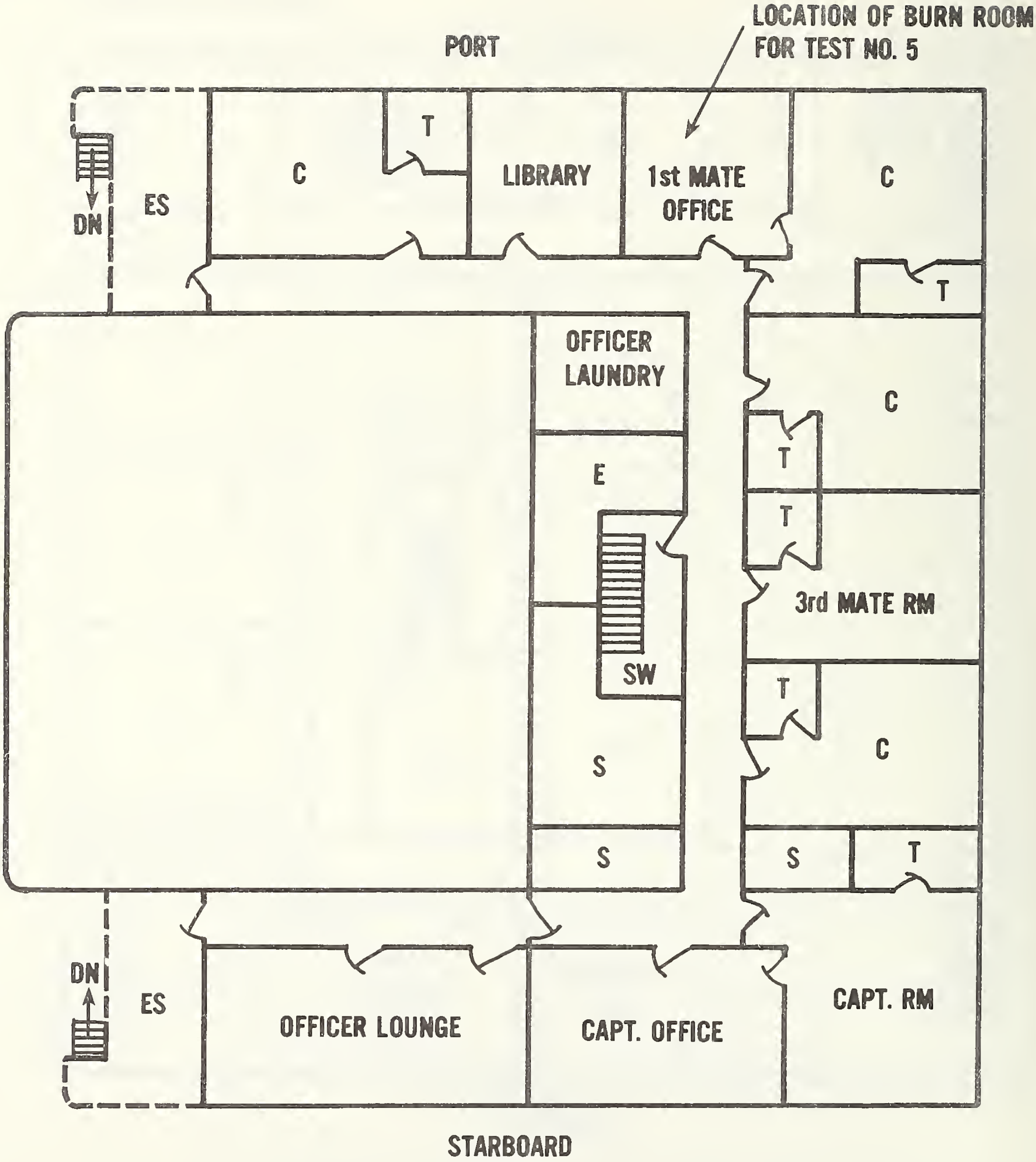


Figure 18. The 05 deck of the Sea-Land Express

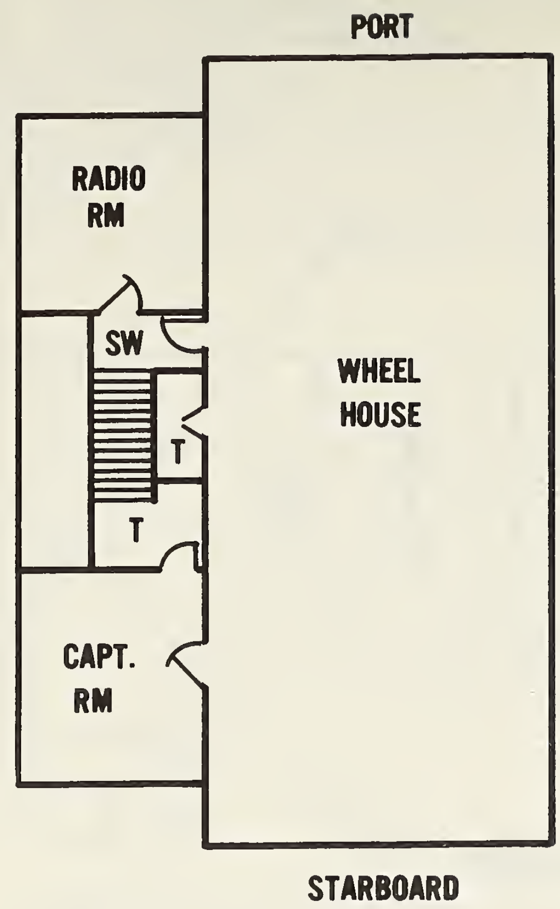


Figure 19. The 06 deck of the Sea-Land Express

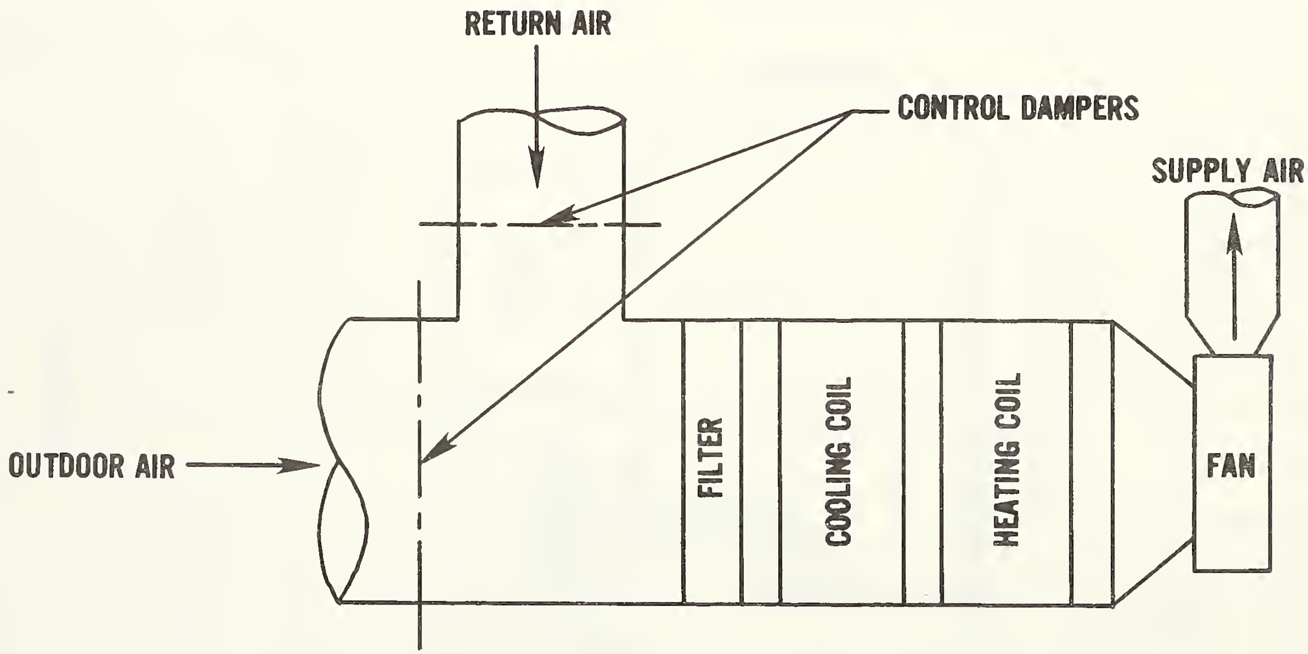


Figure 20. Fan coil unit on the Sea-Land Express

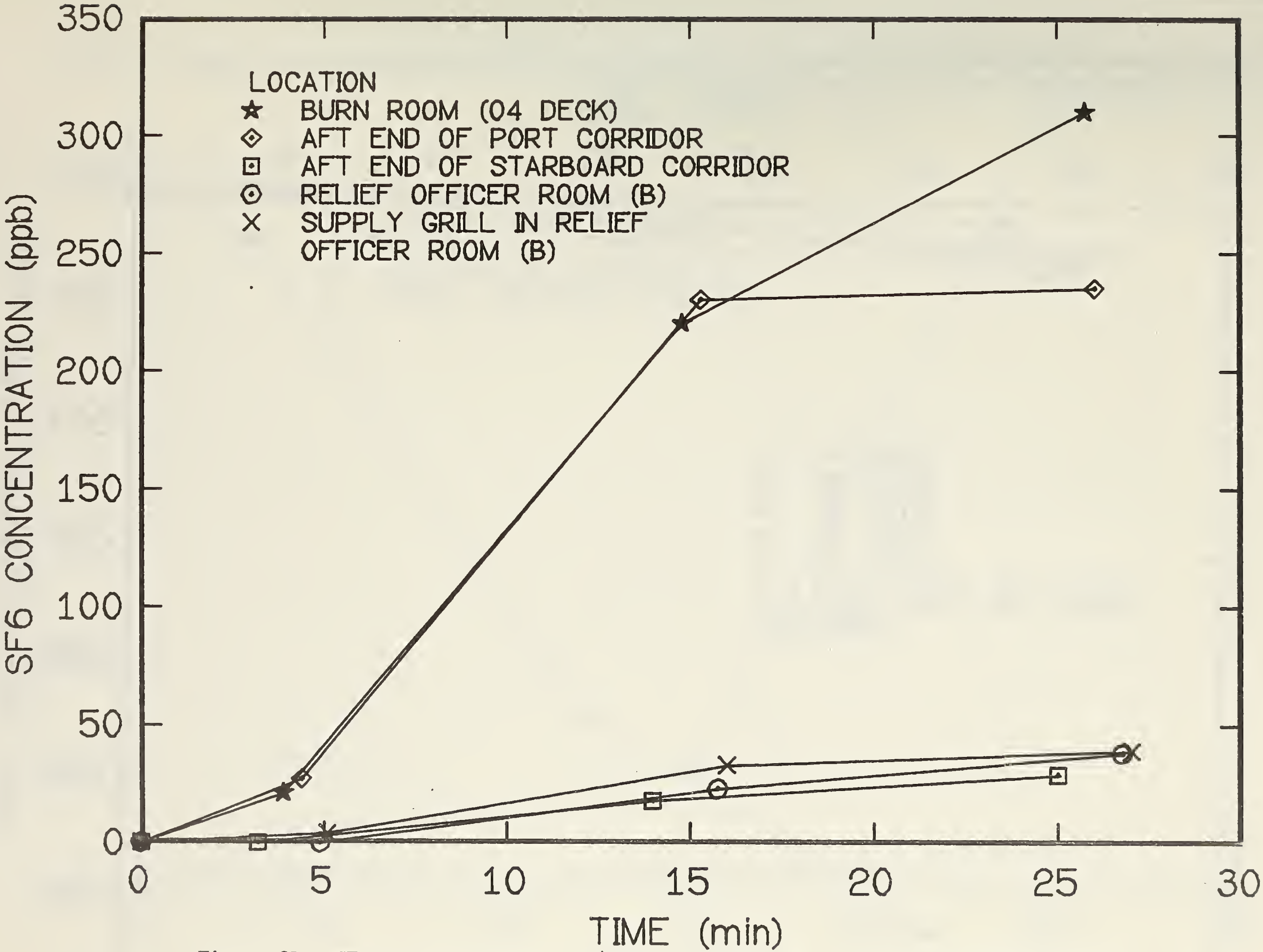


Figure 21. SF_6 concentrations on 04 deck for test no. 1 on the Sea-Land Express

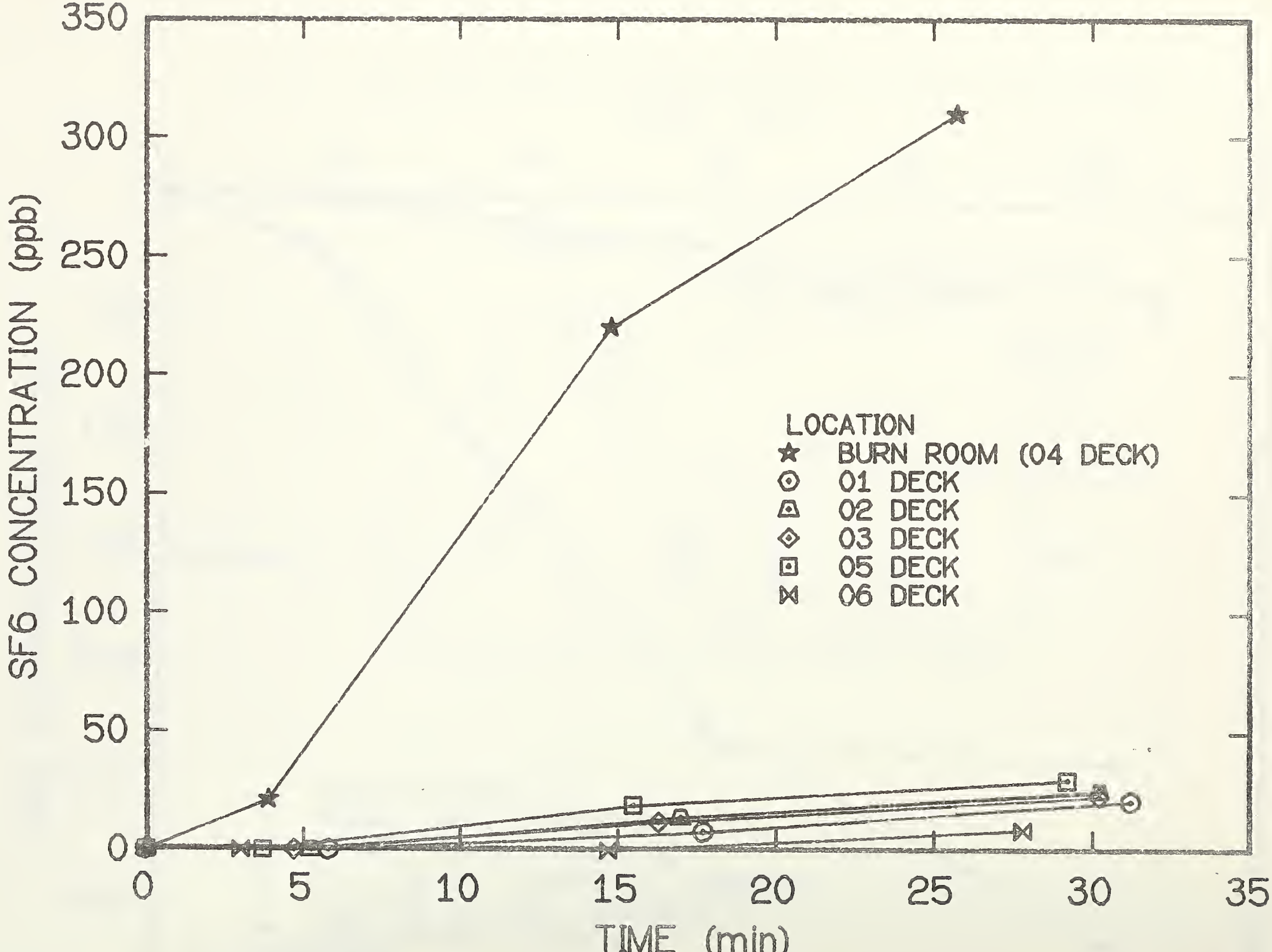


Figure 22. SF_6 concentrations on different decks for test no. 1 on the Sea-Land Express

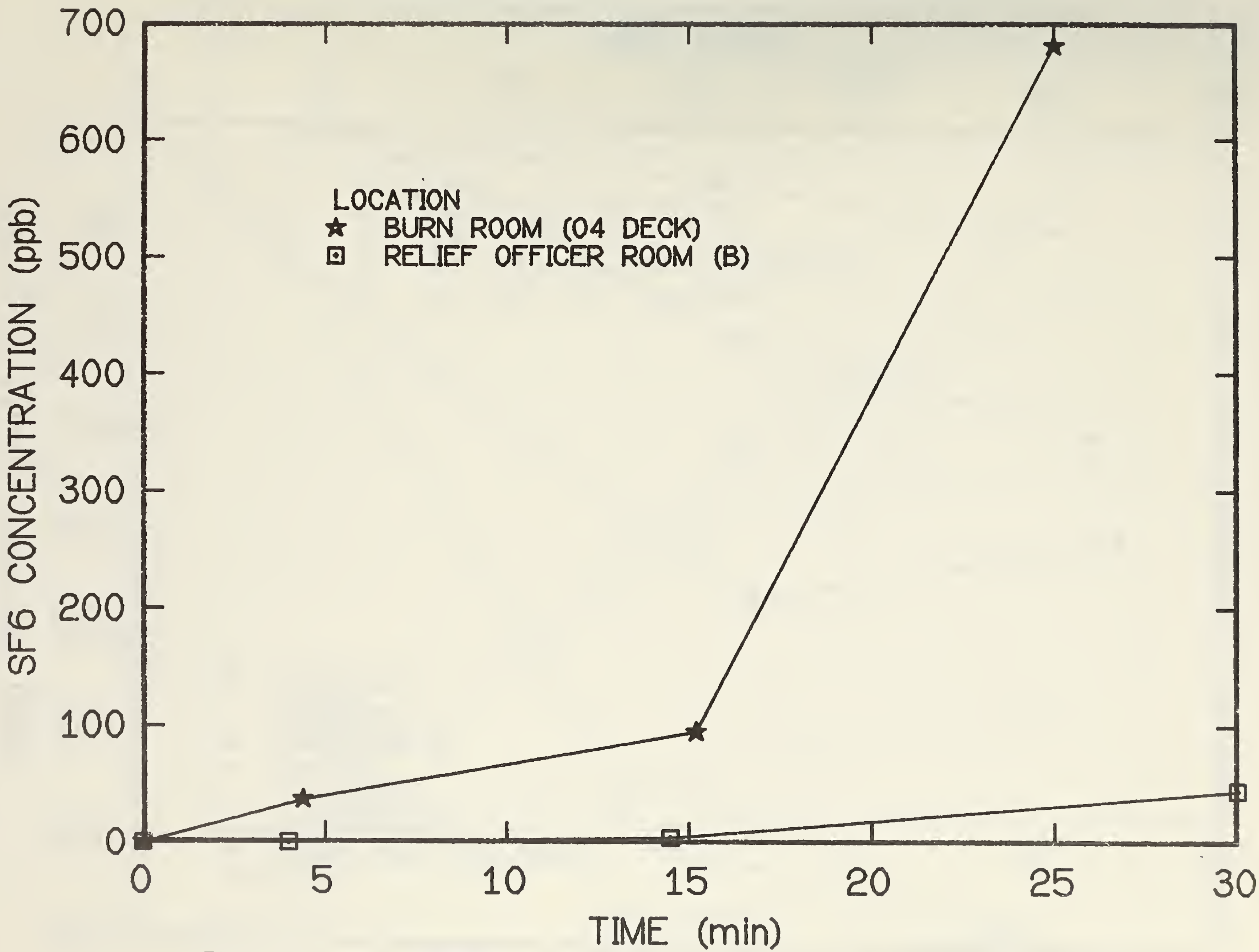


Figure 23. SF_6 concentrations on 04 deck for test no. 2 on the Sea-Land Express

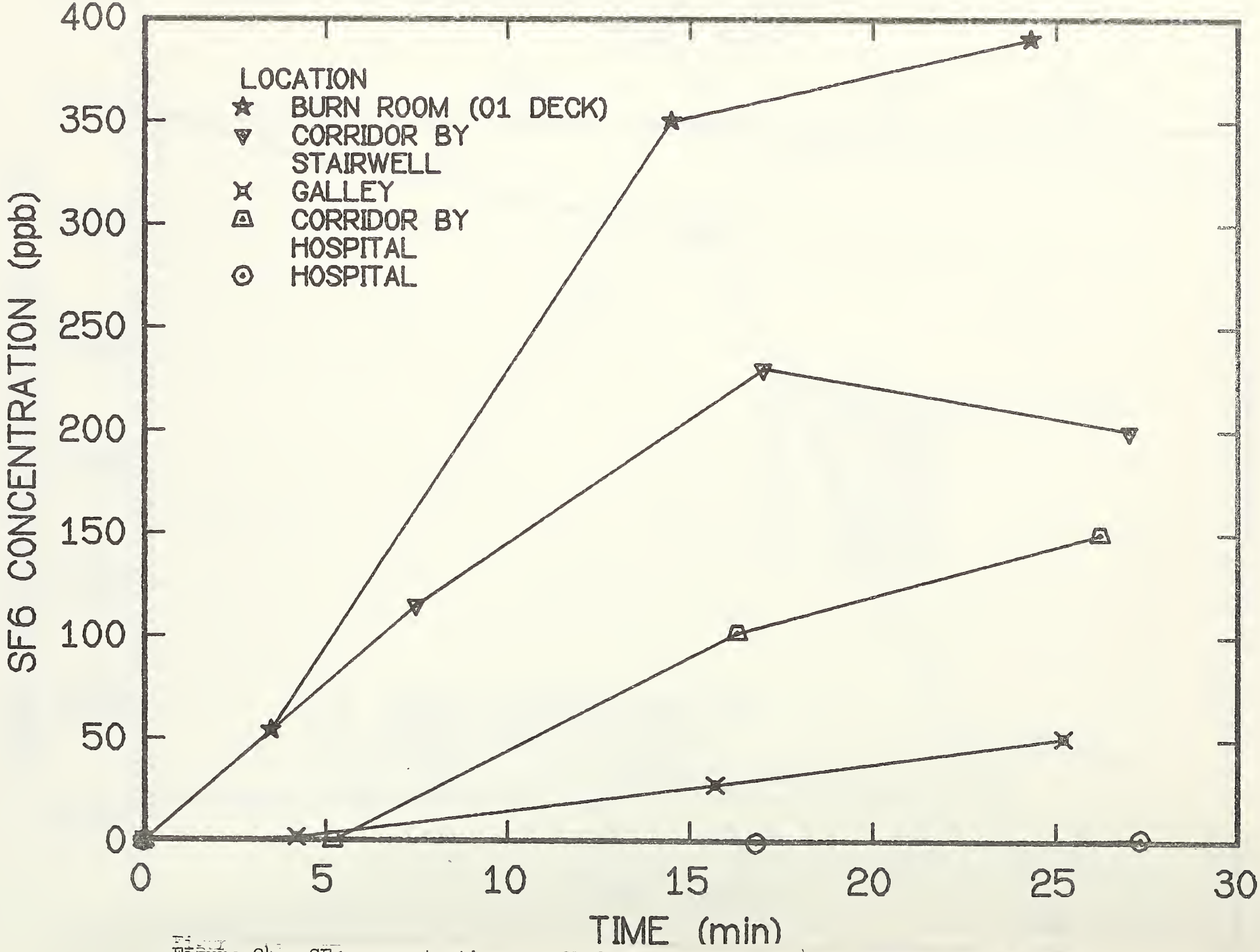


Figure 24. SF_6 concentrations on 01 deck for test no. 3 on the Sea-Land Express

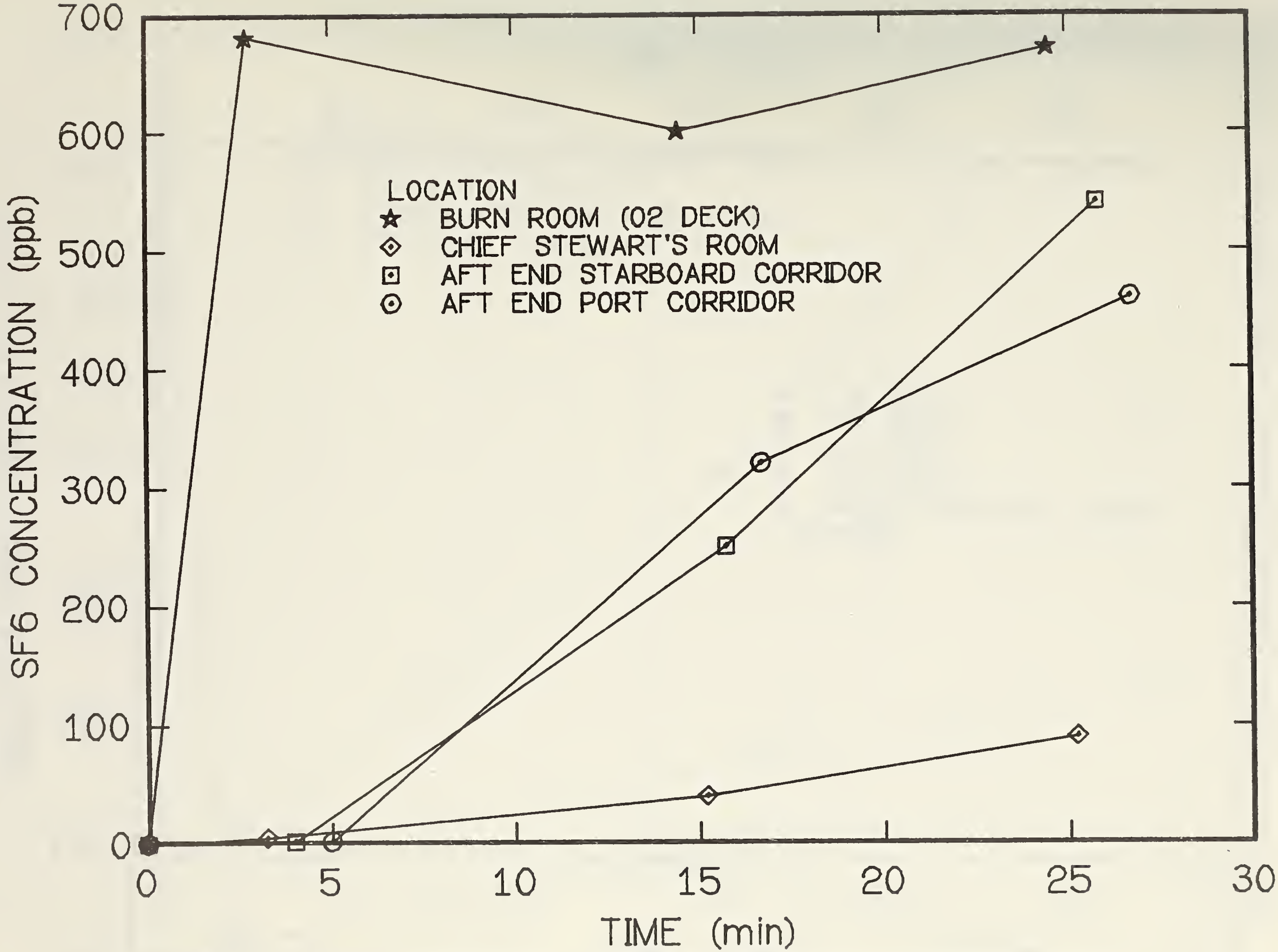


Figure 25. SF_6 concentrations on 02 deck for test no. 4 on the Sea-Land Express

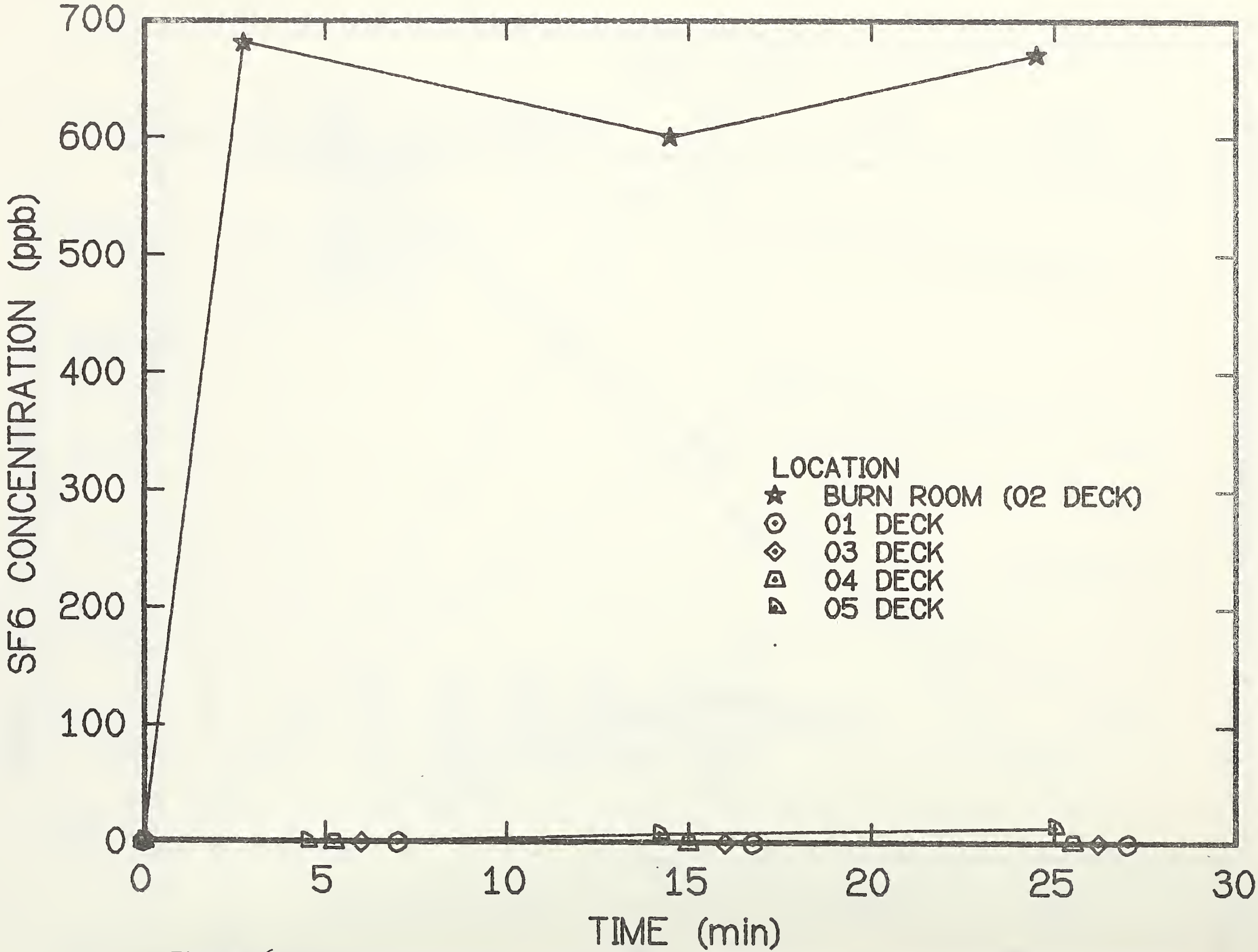


Figure 26. SF_6 concentrations on different decks for test no. 4 on the Sea-Land Express

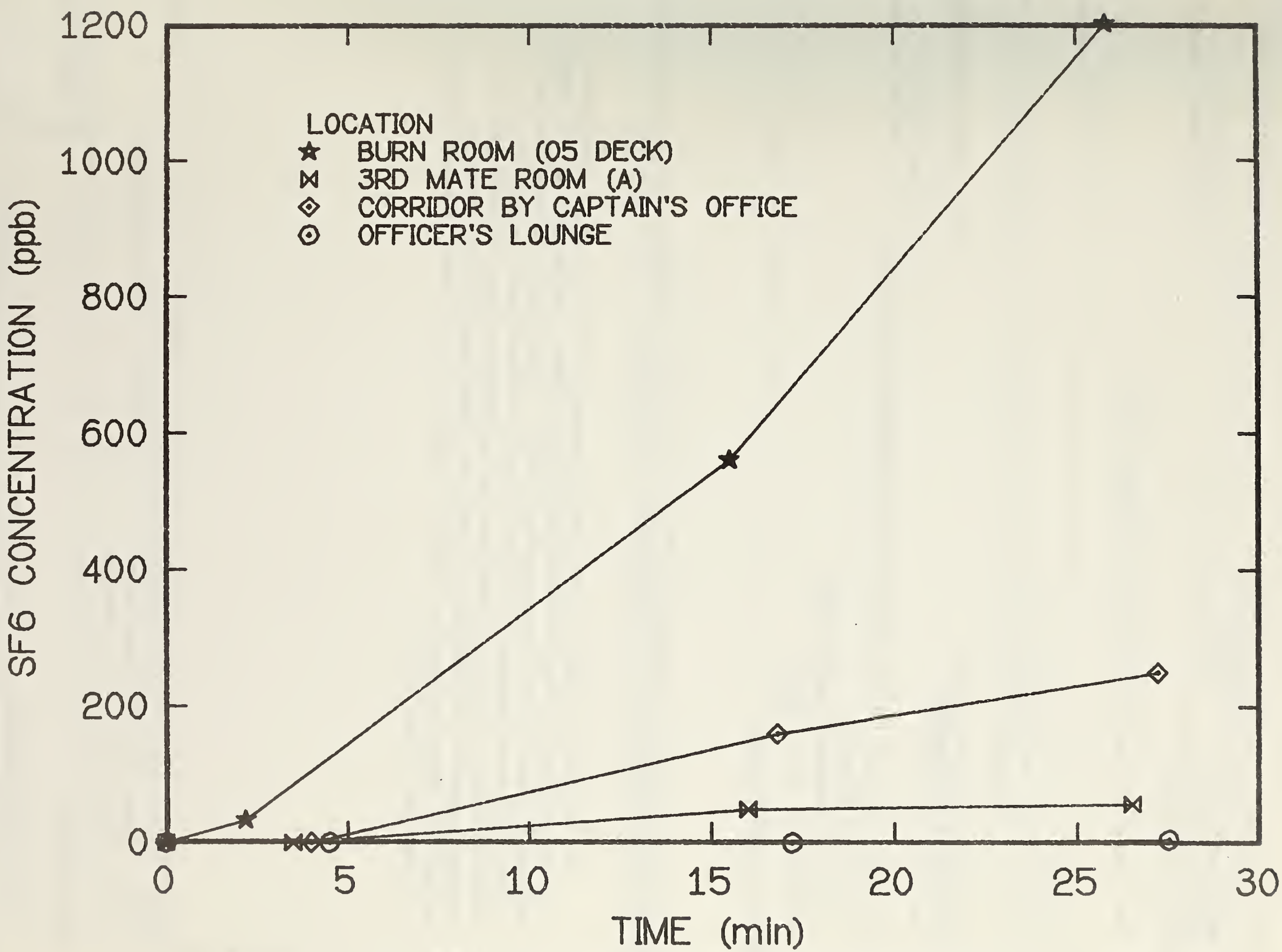


Figure 27. SF_6 concentrations for test no. 5 on the Sea-Land Express

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

In the past ten years considerable progress has been made in developing systems to control smoke movement in building fires. At present no such smoke control systems are in use on merchant ships. This paper discusses the basic concepts of smoke movement and smoke control with emphasis upon shipboard applicability. A report of simulated smoke movement tests performed on two merchant vessels is presented. Based upon these test results potential methods of smoke control for merchant vessels are discussed. Recommendations are made for future study.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Ships; smoke control; smoke movement; stack effect; sulfur hexaflouride; tracer tests; ventilation systems.

13. AVAILABILITY

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