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Investigation of Fuel Oil/Lube Oil Spray Fires On Board Vessels

Volume I

FINAL REPORT
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The U.S. Coast Guard Headquarters project sponsor is Matthew Gustafson at 202-267-0170.

16. Abstract (200 words or less)

The U.S. Coast Guard sponsored this project to assess control measures (technological advancements as well as safety management systems) for preventing or mitigating the impacts of fuel oil or lube oil spray fires on board vessels, particularly in the engine room. For this purpose, we identified a number of proposed control measures to prevent/mitigate the impacts of spray fires, and then we evaluated the reduction in risk that can be expected from the implementation of each measure. As part of our evaluation, we identified many sources of relevant incident investigation reports. These sources provided a total of 143 fires caused by releases of fuel oil/lube oil; of these 9 are known to have resulted in fatalities, and another 8 are known to have resulted in personnel injury.

Our research findings substantiated several (and refuted a few) previous findings/beliefs regarding spray fires. In addition, our investigation resulted in 18 feasible, practical control measures (recommendations) to reduce risks associated with fuel oil/lube oil spray fires in engine rooms. The first 12 recommendations address specific changes to 1) existing fuel oil/lube oil equipment and systems and 2) management issues. The next three recommendations address more significant changes to fuel oil/lube oil equipment, and they are presented for new (or significantly modified) ships. We also identified two areas that require additional research and development efforts, and we developed two recommendations to address these areas. Finally, we determined that much of the risk associated with fuel oil/lube oil spray fires stems from deficiencies in (or lack of) safety management systems. That is, the root cause of these incidents is generally the absence of, neglect of, or deficiencies in management systems.

This report consists of three volumes. Volume I contains a summary of these practices. Volume II consists of Appendix A: MISREP Events and Associated Event Trees Characterization Tables; Appendix B: MSIS Events. Volume III consists of Appendix C: LMIS Events; Appendix D: Nippon Kaiji Kyokai (NK) Events; Appendix E: TSB Events; Appendix F: MIIU Events; Appendix G: NTSB/MAR-95/04 Events; Appendix H: Preliminary Recommendations; Appendix I: Qualitative Analysis of Oil Spray Incidents; Appendix J: Evaluation of the Impact of Preliminary Recommendations; Appendix K: Resumes of Hazard Evaluation Team Members; and Appendix L: June 16-17, 1997, Trip Report.

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METRIC CONVERSION FACTORS

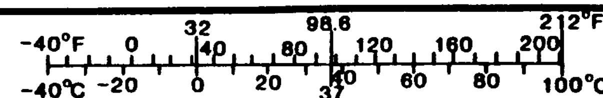
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



ACKNOWLEDGMENTS

The author gratefully acknowledges Richard Hansen, our technical contact at the Coast Guard Research and Development Center, for his support and direction, and George Cassa, CG International, Inc., for his naval engineering insights. Both participated actively throughout this investigation. We also thank Matthew Gustafson for his valuable comments during Coast Guard reviews of our investigation. We appreciate the support of the Coast Guard Marine Safety Office in Port Arthur, Texas, especially CWO Bob Stegall, for handling the logistics for ship tours and helping respond to many technical issues. CWO Bob Stegall also participated in the review and analysis of incident investigation reports. In addition, the author is thankful to several JBFA engineers (particularly Russell McNutt, Lee Vanden Heuvel, Chris Yerger, and Tom Zanin) who helped in the data collection and data analysis phases of the investigation.

The author appreciates James Rooney of JBF Associates, Inc. for performing technical review of this report. The work of Leslie Adair in editing this report and Maureen Hafford in proofreading this report is also greatly appreciated. Finally, we wish to recognize Angie Nicely, Shelia Ross, Elizabeth Hyde, and Nicole Lepoutre-Baldocchi for their skill and craftsmanship in producing this report.

SUMMARY

The purpose of this project was to help the United States Coast Guard (Coast Guard) assess control measures for preventing or mitigating the impacts of fuel oil or lube oil spray fires on board vessels, particularly in the engine room. The control measures of interest included technological advancements as well as safety management systems.

Our investigation approach consisted of eight research steps, including assessment of current practices for controlling risks of spray fires and extensive review of spray fires that have occurred worldwide on board vessels. As presented in this summary and discussed in detail in Sections 3.7 and 4 of the report, our research findings substantiated several (and refuted a few) previous findings/beliefs regarding spray fires. In addition, our research evaluated the reduction in risk that can be expected from the implementation of each proposed control measure to prevent/mitigate the impacts of spray fires.

One of the principal activities of this project was to identify a large number of incident investigation reports that could be used to provide insights into the causes of fires and potential options for frequency reduction and/or consequence mitigation. For this purpose, we identified many sources of relevant incident investigation reports: the Coast Guard; the U.S. Marine Safety Information System; Lloyd's Maritime Information Services Limited; the Japanese classification society Nippon Kaiji Kyokai; the Transportation Safety Board of Canada; the Marine Incident Investigation Unit, Inspector of Marine Accidents, Australia; and the U.S. National Transportation Safety Board.

Overall, these sources provided a total of 182 incident records. Of these, 175 involved releases of fuel oil/lube oil in the engine room on board ships (the other 7 were determined to be outside the scope of this project), and 143 releases ignited and resulted in fires. Of the 143 fires caused by releases of fuel oil/lube oil, 9 fires are known to have resulted in fatalities and another 8 are known to have resulted in personnel injury.

Our investigation provided the following insights:

- Oil releases on board ships have occurred because of a variety of human-related and/or equipment-related causes. Although each incident is unique regarding the specific cause of failure, we identified six general categories of causes of failure: (1) lack of adequate inspection or maintenance (10% of all releases), (2) personnel error during inspection or

maintenance (25%), (3) personnel error and/or equipment failure during preparation for inspection/maintenance or restoration to service after inspection/maintenance (10%), (4) design, manufacturing, or installation deficiencies (20%), (5) unknown root cause (30%), and (6) external impact (5%). Obviously, improvements in human factors and management systems are essential for reducing the frequency of releases.

- Hot surface (particularly engine exhaust manifold/pipe, turbocharger casing, and steam line) was responsible for the ignition of about 93% of all fires, 93% of all fires with injury or fatality, and 86% of the fires with fatalities. Obviously, control measures to prevent oil sprays from reaching hot surfaces are essential for reducing the frequency of oil spray fires in engine rooms.

- The skid piping, tubing, or hose for diesel engines, turbochargers, or boilers are the most common sources of spray (almost 40% of all fires). These results are interesting because skid piping/tubing/hose is usually under the control of the manufacturer (i.e., the piping/tubing/hose that comes with an engine skid or pump skid), and it is generally not subject to regulations and standards that are in place for piping outside the engine/pump skid. Obviously, control measures to prevent oil sprays from skid piping/tubing/hose are essential for reducing the frequency of oil spray fires in engine rooms.

- Duplex strainers, filters, or coalescers are the most common sources of fatal spray fires (55%). In one case, a crew member damaged the O-ring of a strainer cover, resulting in a leak. In another case, a temporary change to a duplex strainer defeated an original safeguard (safety pin) provided by the manufacturer. This eventually led to an oil spray that ignited. In two other cases, the crew was having difficulties moving the three-way transfer valve to divert flow from one strainer chamber to the other chamber so that the strainer element could be cleaned or changed. In one instance, the crew member decided to loosen the mounting bolts of the packing retaining cover to facilitate movement of the valve. This was done excessively, resulting in an oil spray through the packing retaining cover. In the other instance, the crew member decided to kick the lever on the duplex strainer. He inadvertently hit a vent valve, which ruptured and released an oil spray. In both cases, while attempting to overcome an equipment malfunction (stuck transfer valve), crew members undertook unsafe actions that caused oil sprays and fires. Obviously, control measures to prevent oil sprays from duplex strainers/filters/coalescers are essential for reducing the frequency of fatal fires in engine rooms.

- Fuel oil systems account for about 70% of all oil fires while lube oil systems account for about 30%. However, when fires with fatality are considered, these contributions are 50% for fuel oil systems and 50% for lube oil systems. This indicates that while fuel oil fires occur more often (about twice as much) than lube oil fires, the fewer lube oil fires have caused as many fatal incidents as fuel oil. This suggests that the probability of a fatality given a lube oil fire is more than twice the probability of a fatality given a fuel oil fire. *Lube oil fires are less frequent than fuel oil fires, but they tend to be more fatal when they do occur.*

- Of all 57 incidents that documented the damage incurred by a spray fire, the vessel sank in 6 of the incidents, suffered constructive total loss in 9 of the incidents, and experienced an average damage of about $293,000 in the remaining 42 incidents.

- Of all 105 incidents that documented the impact of the spray fire on the propulsion and/or steering systems, vessels experienced loss of propulsion and/or steering in 70 incidents and were able to maintain these functions in 35 incidents. These are important statistics because loss of propulsion and/or steering can lead to other incidents such as grounding and collision. These numbers indicate that the probability of loss of propulsion and/or steering is about twice the probability of not losing these functions during spray fires in the engine room.

- It has been proposed that mist detectors can be strategically located in the engine room to indicate hazardous oil spray conditions (Reference 6). Our investigation revealed a different conclusion in this regard, at least for safety-related spray fires (i.e., fires that can result in personnel injury/fatality). Specifically, we observed that most safety-related oil spray fires in engine rooms occur during maintenance activities while the crew is in the engine room. These fires tend to ignite very quickly (in a matter of seconds in many cases). There is often insufficient time for crew evacuation, thereby resulting in personnel injury/fatality. Crews need no device or alarm to alert them to the presence of an oil spray in these cases. On the other hand, oil sprays that do not ignite quickly have a tendency to not ignite at all. *Thus, mist detectors would not have helped prevent or mitigate safety-related fuel oil/lube oil fires in the engine room.* The same conclusion also appears correct for non-safety-related spray fires (i.e., fires that cause equipment/vessel damage but do not result in personnel injury/fatality).

- There is no correlation between the number of spray fires and the ship's age, size, kind (oil tanker, fishing vessel, tug/tow, etc.) and nationality.

Our investigation resulted in several feasible, practical control measures to reduce risks associated with fuel oil/lube oil spray fires in engine rooms. Eighteen (18) recommendations for reducing the risks of spray fires are listed below. Section 4 of this report presents detailed discussions of each recommendation. The first 12 recommendations address specific changes to (1) existing fuel oil/lube oil equipment and systems and (2) management issues. These recommendations include improvements to inspections and maintenance, safe work practices, training, and emergency response. The next three recommendations address more significant changes to fuel oil/lube oil equipment in engine rooms. Because they may be too difficult to retrofit to existing ships, they are presented for new (or significantly modified) ships.

We also identified two areas that require additional research and development efforts; Recommendations 16 and 17 address these areas. Finally, our investigation of the causes of previous incidents revealed that much of the risk associated with fuel oil/lube oil spray fires stems from deficiencies in (or lack of) safety and reliability management systems. That is, the root cause of these incidents is generally the absence of, neglect of, or deficiencies in management systems; Recommendation 18 presents a general recommendation for ship operators to ensure that their management practices address all elements suggested in industry standards and guidelines.

Recommendations

1. Sheath, cover, or provide deflector shielding for fuel oil/lube oil piping, tubing, and hoses.

2. Sheath hot surfaces.

3. Provide deflector shielding between the fuel oil/lube oil strainer, filter, coalescer, or purifier and potential sources of ignition.

4. Duplex devices such as strainers, filters, or coalescers should not be opened when the fuel oil/lube oil system is in operation and pressurized.

5. Provide fine-water mist systems for local application on selected equipment areas in engine rooms, including diesel engine, turbocharger, and duplex strainer/filter/coalescer areas.

6. Ensure that all alterations (i.e., modifications that are not replacements-in-kind) to fuel oil/lube oil systems are unambiguously posted/logged.

8. Establish and implement safe work practices for fuel oil/lube oil.

9. Supplement periodic training of engine room personnel with a short video on the hazards of fuel oil/lube oil systems.

10. Ensure that the inspection and maintenance programs for fuel oil/lube oil equipment includes demonstration of the operation of three-way transfer valves in duplex strainers/filters/coalescers; periodic inspection and replacement of hoses, tubings, and fittings on diesel engines and turbochargers; and provisions for periodic inspection of devices that prevent sprays of oil.

11. Provide readily accessible emergency breathing apparatus to facilitate escape from engine rooms, and conduct periodic engine room fire and evacuation drills.

12. Ensure that hazard analyses are performed for systems containing pressurized fuel oil or lube oil.

13. Use diesel engines, fuel oil pumps, and lube oil pumps with integrated channels for fuel oil and/or lube oil (i.e., monolithic equipment housing).

14. When instrument signals (e.g., pressure indication) from fuel oil/lube oil systems are sent to gauge boards, pneumatic/electronic transducers should be used near the instrument tap to avoid lengthy runs of tubing or piping containing oil.

15. Duplex devices such as strainers, filters, or coalescers should not be opened when the fuel oil/lube oil system is in operation and pressurized.

16. Develop guidelines for fuel oil/lube oil fittings and nipples used in high-pressure marine applications.

17. Review existing design specifications and installation guidelines for insulation/lagging to ensure that these specifications and guidelines include provisions for preventing ignition.

18. Ship operators should ensure that their management practices are consistent with safety/environmental standards and guidelines

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1. INTRODUCTION

The purpose of this project was to help the United States Coast Guard (Coast Guard) assess control measures for preventing or mitigating the impacts of fuel oil or lube oil spray fires on board vessels, particularly in the engine room. The control measures of interest included technological advancements as well as safety management systems. The specific objectives of this research and development effort were as follows:

- Identify the risks, characterize the risks, and investigate current practices for controlling the risks of fuel oil/lube oil sprays from equipment and piping coming in contact with hot surfaces or other ignition sources in the engine room

- Make recommendations for implementing feasible, practical control measures to reduce the risks associated with ignition of fuel oil/lube oil sprays from equipment or piping in the engine room

To accomplish these objectives, the project was organized into the following three tasks:[a]

Task 1 — General Spray Protection Investigation. This task consisted of two technical subtasks: (1) identify, characterize, and understand the risks associated with marine accidents involving fuel oil/lube oil spray fires and (2) assess current practices for controlling the risks associated with these fires. The results of Task 1 are documented in Reference 1.

Task 2 — Hazard Evaluation and Risk Reduction Evaluation. This task consisted of a detailed risk analysis of incidents and proposed control measures that can be taken to reduce the risk of these incidents. (Risk reduction can be achieved by reducing the frequency of spray fires, mitigating the consequences of these fires, or both.) The principal objective in performing this task was to evaluate the risk-reduction potential associated with each proposed control measure. The control measures included technological advancements and safety management systems, and they were selected by the Coast Guard based on the results from Task 1. The results of Task 2 are documented in Reference 2.

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[a]This project also included a task for designing, developing, and implementing a testing plan for evaluating potential improvements or modifications in equipment and practices. However, the results of Tasks 1 and 2 indicated that an evaluation of potential improvement/modifications was not necessary for successfully completing this project. This project modification is documented in detail in *Recommended Task Changes for Project JBFA-101-07-94*, HMP-107-98, Letter to Richard L. Hansen, U.S. Coast Guard Research and Development Center, from Henrique Paula of JBF Associates, Inc., Knoxville, TN, April 1998.

Task 3 — Final Report. This task consisted of documenting the results of Tasks 1 and 2 in this final report.

While our investigation included some incidents involving hydraulic oil systems and some incidents that occurred outside the engine room, the scope (and emphasis) of this project was limited to fuel oil and lube oil systems in the engine rooms.

This report is organized in six sections, including Section 1 (Introduction). Section 2 presents our investigation approach. Our investigation approach consisted of eight research steps, including extensive review of spray fires that have occurred worldwide on board vessels. The analysis results appear in Section 3. The results include a review of the causes of incidents, the source of ignition, the equipment and system that caused the release, damage characterization, and, most importantly, the expected impact (i.e., potential risk reduction) of preliminary recommendations to prevent the occurrence and/or mitigate the consequences of spray fires on board vessels. (Preliminary recommendations are new or modified technological advancements and/or safety management systems that can potentially reduce risk. The preliminary recommendations with greatest risk reduction potential are the most promising control measures for implementation by the shipping industry, classification societies, administrations, International Maritime Organization [IMO], etc.) Section 4 presents our recommendations for reducing spray fire risks. Section 5 concludes our research, and Section 6 presents the references used throughout the report.

Appendixes A through G contain the incidents that we analyzed. Appendix H presents the preliminary recommendations. Appendixes I and J present qualitative and quantitative results of our review of spray fires that have occurred worldwide on board vessels. The résumés of the analysts who participated in the risk reduction evaluation appear in Appendix K. The first step in our investigation approach involved visiting vessels for observation of fuel oil/lube oil systems and locations of these systems on board vessels. Appendix L presents the trip report prepared as part of this step.

2. *INVESTIGATION APPROACH*

Our investigation approach consisted of eight steps:

- ***Step 1 — Visited vessels for observation of fuel oil/lube oil systems and locations***
- ***Step 2 — Developed a procedure for collecting and documenting previous incidents***
- ***Step 3 — Assessed current practices for controlling the risks associated with spray fires***
- ***Step 4 — Developed a database of relevant incidents***
- ***Step 5 — Developed preliminary recommendations***
- ***Step 6 — Assembled a team of specialists for the hazard evaluation***
- ***Step 7 — Assessed the impact of preliminary recommendations***
- ***Step 8 — Developed feasible, practical recommendations to reduce risks***

Steps 1 through 3 were completed during Task 1. Steps 4 and 5 were initiated during Task 1 and completed during Task 2. The remaining steps were completed in Task 2. Each step is described separately in the following sections

Step 1 — Visited Vessels for Observation of Fuel Oil/Lube Oil Systems and Locations. The objective of this step was to observe the types of systems that contain fuel oil/lube oil, the typical locations of these systems (including piping), and the typical safeguards (administrative controls and engineered features) used to help prevent/mitigate accidental spray fires.

Two project team members (Henrique Paula of JBF Associates, Inc. [JBFA] and George Cassa of CG International, Inc. [CGI]) participated in the vessel visits on June 16 and 17, 1997, in Port Arthur, Texas. These two project team members were assisted by Coast Guard Marine Safety Office personnel, including CWO Bob Stegall, who handled the logistics for the tours and helped respond to technical issues. Table 2.1 shows the vessels visited. We considered the following issues during each visit (Appendix L presents the trip report detailing these visits):

- Systems of interest (fuel oil and lube oil) and their location
- Potential causes of fuel oil/lube oil releases (e.g., hose failure)
- Potential ignition sources (e.g., hot exhaust piping from a diesel engine)
- Means of fire detection (e.g., smoke detectors, heat detectors)
- Means of release isolation (e.g., shutting off pump, closing isolation valve)
- Means of fire suppression (e.g., CO_2 system, dry chemical extinguisher)
- Potential for fire propagation to other vessel compartments
- Potential for disabling the propulsion system
- Potential for disabling the steering system
- Potential for human casualty

Table 2.1 Vessel Visits

Vessel (Visit Date)	Participants
OMS LIBERTY (June 16)	CWO Bob Stegall, George Cassa, and Henrique Paula
OMS SHELBY (June 16)	CWO Bob Stegall, George Cassa, and Henrique Paula
SS PETERSBURG (June 16)	CWO Bob Stegall, George Cassa, and Henrique Paula
CAPE VINCENT (June 17)	CWO Bob Stegall and Henrique Paula[b]

Step 2 — Developed a Procedure for Collecting and Documenting Previous Incidents. As described in Step 4, one of the principal activities of this project was to identify a large number of incident investigation reports that could be used to provide insights into the causes of fuel oil/lube oil spray fires and potential options for frequency reduction and/or consequence mitigation. The objective of Step 2 was to develop a procedure for collecting and documenting previous incidents involving spray fires in engine rooms. Having this procedure helped ensure consistency and completeness of our evaluation of previous incidents. Our procedure consists of collecting and documenting each incident in three ways:

- The incident (event) description, as documented in the original incident investigation report (we have not edited or modified these descriptions)
- An event tree, which shows the sequence of events associated with the incident
- An event characterization table, which supplements the event tree with comments (as documented in or inferred from the incident description) about the system/location, cause, ignition source, means of detection, means of release isolation, means of fire suppression, impact on propulsion, impact on steering, human casualty, and corrective action

For example, Table 2.2 shows the incident description from one of the databases. This description was extracted directly from the original incident investigation report. It occurred on October 8, 1994, and it involved the Liberian tankship SEAL ISLAND while moored at the Hess Oil Refinery in St. Croix, U.S. Virgin Islands. The incident started when engineering personnel were changing the lubricating oil strainer on the ship's service turbogenerator. Because of a faulty temporary repair that had been previously performed on this system, lubricating oil sprayed onto the hot turbine casing and a fire erupted. The fire caused the death of three crew members and serious injury to six other crew members.

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[b]George Cassa did not participate in the visit to the CAPE VINCENT. However, Mr. Cassa performed the pre-purchase reflagging survey on this vessel for the U.S. Maritime Administration and, therefore, is familiar with this vessel.

Table 2.2 Example Event Description

Event Description (See Appendix G, page G-5)
On June 10, 1994, the lubricating oil duplex strainer on the SEAL ISLAND's turbogenerator had a defective O-ring (gasket) that was leaking about 6 gallons of oil daily. To avoid shutting down the ship's service turbogenerator for 2 hours to make a permanent repair to the duplex strainer, the chief engineer devised an assembly comprising an O-ring, a metal cup, and a screw-jack. The cup was to fit around the bottom of the flow valve casing. The screw-jack was to hold the cup in place to achieve and maintain a tight fit. When the first engineer tried to attach the O-ring and cup, the valve's lower securing pin prevented his getting a tight seal. The chief engineer directed him to retract the lower securing pin ... the replacement chief engineer cautioned that it was dangerous to remove the pin without having a device to hold the flow valve in place. The chief engineer designed a strongback, which was fabricated by a machinist in about 10 hours. On June 12, all four components of the temporary assembly were fitted on the oil strainer and the oil leak stopped. On October 8, 1994, the Liberian tankship SEAL ISLAND was moored at the Hess Oil Refinery in St. Croix, U.S. Virgin Islands. About 0845, while engineering personnel were changing the lubricating oil strainer on the ship's service turbogenerator, lubricating oil sprayed onto the hot turbine casing and a fire erupted. The fire burned about 6 hours before it was extinguished. The fire resulted in the death of three crew members and serious injury of six other crew members. The fire seriously damaged the tankship's engine room; heat, smoke, water, and soot badly damaged the accommodations and pilothouse. The tankship was declared "no longer a useful carrier" and its owner, the Seal Island Shipping Corporation, had it towed to Spain where it was sold as scrap for $12 million. The National Transportation Safety Board determines that the probable cause of the fire on board the SEAL ISLAND was the chief engineer's failure to recognize the risks introduced by the temporary repair to the engine room oil strainer. Contributing to the loss of life were the suddenness and severity of the fire, the inability of the crew to use the control room emergency escape hatch, and the lack of fire and escape drills in the vessel engine room.

Figure 2.1 shows the event tree for this incident. The event tree provides a general overview of what happened during the incident and the resulting consequences. It starts with an initiating event (release of fuel oil or lube oil [generically represented by "pressurized flammable or combustible liquid"]), and then proceeds to indicate whether important functions (prevent spray ignition, prevent fire propagation to other compartments, prevent loss of propulsion or steering, and prevent human casualty) were successful or unsuccessful. Each of these functions is represented by a "branch point" in the event tree. By definition, we indicate a success for a function by moving up at the branch point for the function and a failure by moving down at the branch point for the function.

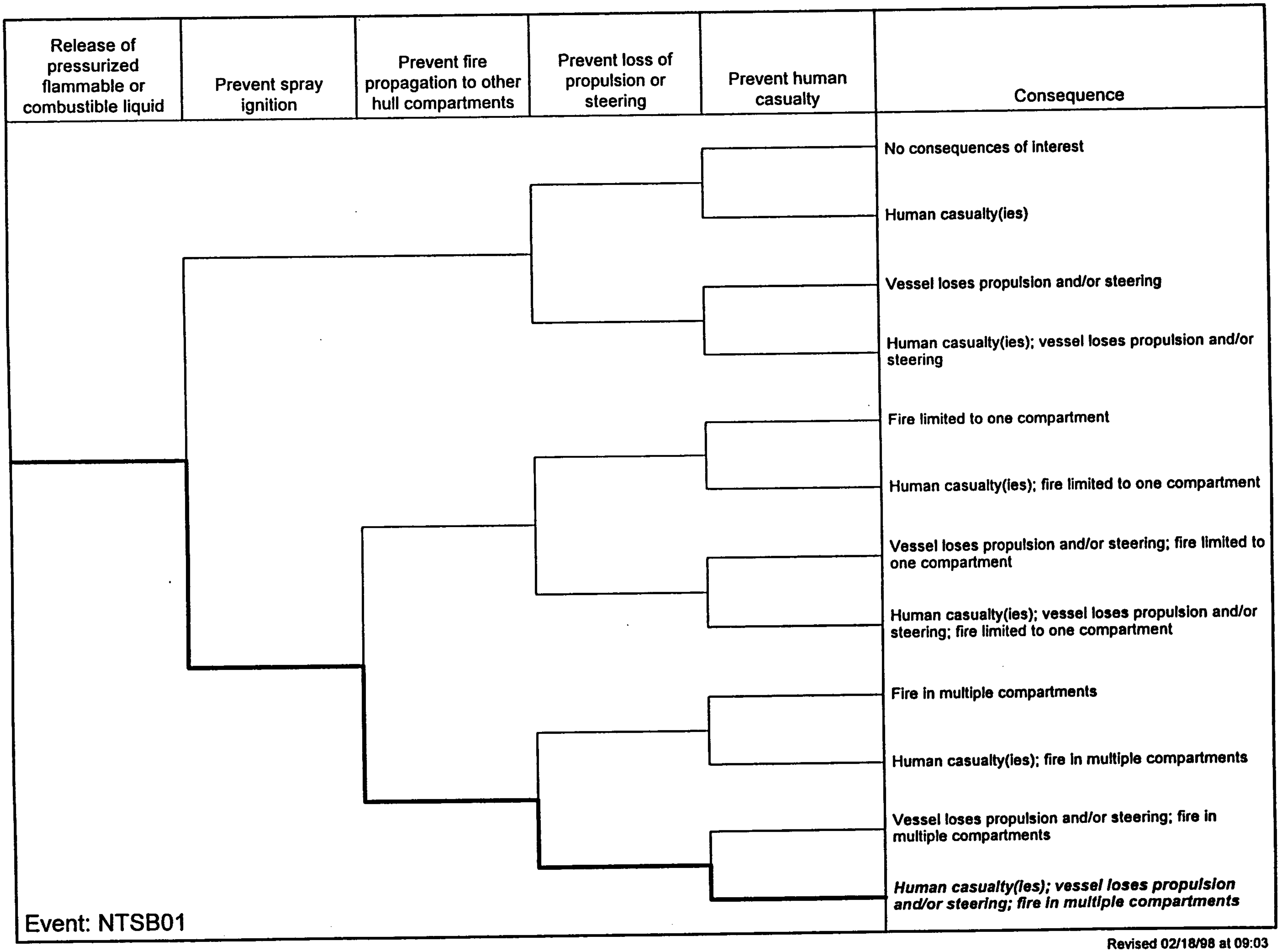


Figure 2.1 Example Event Tree

For example, the event tree in Figure 2.1 indicates that (1) a release of pressurized flammable or combustible liquid (the initiating event) occurred in this event and (2) the spray ignited (downward path for the first branch point in the event tree). Also, the event tree indicates that there was fire propagation to other hull compartments, loss of propulsion or steering, and human casualty (downward path for the second, third, and fourth branch points in the event tree, respectively). The ultimate consequence of the release is indicated in the consequence column in the event tree. For the event tree in Figure 2.1, the ultimate consequence was "Human casualty(ies); vessel loses propulsion and/or steering; fire in multiple compartments."

Table 2.3 shows the event characterization table, which supplements the event tree with more detailed information about the system/location, cause, ignition source, means of detection, means of release isolation, means of fire suppression, impact on propulsion, impact on steering, human casualty, and corrective actions to prevent recurrence. The event characterization table has two separate columns to enter information that was explicitly documented in the report and information that was inferred from the descriptions provided in the report.

Step 3 — Assessed Current Practices for Controlling the Risks Associated with Spray Fires. The objective of this step was to review industry practices, standards, and regulations to become familiar with administrative and engineered controls that can help reduce the risks associated with fuel oil/lube oil spray fires. Obviously, the Coast Guard regulations for U.S.-flag ships are of great interest to our research. For example, 46 CFR Chapter I, Subchapter F (Marine Engineering) has several regulations that are relevant in our analysis of hazards associated with oil systems:

- 46 CFR 56.50-60 — *Systems Containing Oil*
- 46 CFR 56.50-65 — *Burner Fuel-oil Service Systems*
- 46 CFR 56.50-75 — *Diesel Fuel Systems*
- 46 CFR 56.50-80 — *Lubricating-oil Systems*

Also, the Coast Guard has several regulations regarding firefighting equipment:

- 46 CFR 34 — *Firefighting Equipment* (applies to Subchapter D Tank Vessels)
- 46 CFR 76 — *Fire Protection Equipment* (applies to Subchapter H Passenger Vessels)
- 46 CFR 95 — *Fire Protection Equipment* (applies to Subchapter I Cargo Vessels)
- 46 CFR 118 — *Fire Protection Equipment* (applies to Subchapter K Small Passenger Vessels Carrying more than 150 Passengers or with Overnight Accommodations for more than 49 Passengers)
- 46 CFR 132 — *Fire Protection Equipment* (applies to Subchapter L Offshore Supply Vessels)
- 46 CFR 181 — *Fire Protection Equipment* (applies to Subchapter T Small Passenger Vessels Under 100 Gross Tons)
- 46 CFR 193 — *Fire Protection Equipment* (applies to Subchapter U Oceanographic Research Vessels)

Table 2.3 Example Event Characterization Table

Event Number: NTSB01	Event Characterization	
	As Documented in the Event Report	**As Inferred from the Event Report**
System/Location	Lube oil/engine room	
Cause	On October 8, 1994, the crew removed the strongback on the lubricating oil duplex strainer to replace the strainer element on the aft strainer. After replacing the element, the crew moved the directional flow control valve handle to the aft basket. Lube oil suddenly sprayed upward from the duplex strainer The reason for the spray was that the lower securing pin for the flow control valve had been removed to install a temporary assembly to stop a leak. A strongback kept the flow control valve in place during normal operation, but it had to be removed to replace the strainer element. Changing the strainer element without a device in place to restrain the upward movement of the control valve was poorly thought out and created a hazard that ultimately led to the fire	
Ignition Source	Hot surface (turbogenerator casing)	
Detection	Crew	
Release Isolation	The turbine tripped automatically on low lubricating oil pressure	
Fire Suppression	Unsuccessful	
Impact on Propulsion	Loss of propulsion (the ship had to be towed)	
Impact on Steering		None

Table 2.3 Example Event Characterization Table (cont'd)

Event Number: NTSB01	Event Characterization	
	As Documented in the Event Report	**As Inferred from the Event Report**
Human Casualty	Three fatalities and six serious injuries[c] When the fire started, nine people were in the engine room. The first engineer, an electrician, and a machinist died. All six survivors suffered burn and inhalation injuries during their escape	
Corrective Action to Prevent Recurrence	All ships maintain readily accessible emergency breathing apparatus to facilitate escape from the engine room Periodic engine room fire and escape drills International Maritime Organization should develop a standard for engine room fire and escape drills that will include, at a minimum, how to locate and don breathing apparatus and how to find and use emergency exits in simulated fire conditions Test all modes of fire pump starting systems, including electric, hydraulic, and pneumatic, during fire and boat drills Install spray shields around lubricating and fuel oil strainers	

[c]Serious injuries are injuries that (1) require hospitalization for more than 48 hours, commencing within 7 days from the date the injury was received, (2) result in a fracture of any bone (except simple fractures of fingers, toes, or nose), (3) cause severe hemorrhages or nerve, muscle, or tendon damage, (4) involve any internal organ, or (5) involve second- or third-degree burns, or any burn affecting more than 5% of the body surface.

The International Maritime Organization (IMO) also has regulations, guidelines, and proposed guidelines relevant to our analysis:

- *International Convention for the Safety of Life at Sea (SOLAS) 1974, as Amended, Reg. II-2 Construction — Fire Protection, Fire Detection and Fire Extinction, Part A/Regulation 15 — Arrangements for Oil Fuel, Lubricating Oil and Other Flammable Oils, Paragraphs 1 through 6*, International Maritime Organization. (Reference 3)

- *Adoption of the Amendments to the International Convention for the Safety of Life at Sea (SOLAS), 1974*, Resolution MSC.31(63), International Maritime Organization. (Reference 4)

- *Guidelines to Minimize Leakages from Flammable Liquid Systems*, Maritime Safety Committee (MSC) Circular 647, International Maritime Organization. (Reference 5)

- *Analysis of Fire Casualty Records (Draft MSC Circular on Fuel Systems — Submitted by the United Kingdom)*,FPL/2/12/1, Sub-committee on Fire Protection, 42nd Session, Agenda Item 2, International Maritime Organization. (Reference 6)

We have also reviewed industry standards such as those published by the National Fire Protection Association (NFPA):

- *Flammable and Combustible Liquids Code*, NFPA 30, National Fire Protection Association, Quincy, MA, 1996.
- *Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines*, NFPA 37, National Fire Protection Association, Quincy, MA, 1994.

In addition, we considered standards and practices from the American Petroleum Institute (API), Chemical Manufacturers Association, and from selected petrochemical/oil refining companies. Of particular interest from the chemical, petrochemical, and oil industries were the standards or recommended practices regarding safety management systems:

- API Recommended Practice 75, *Recommended Practices for Development of a Safety and Environmental Management Program for Outer Continental Shelf (OCS) Operations and Facilities*, American Petroleum Institute (Reference 7)
- *The Process Safety Code of Management Practices*, Chemical Manufacturers Association (Reference 8)

- API Recommended Practice 750, *Management of Process Hazards*, American Petroleum Institute (Reference 9)
- Occupational Safety and Health Administration, *Process Safety Management of Highly Hazardous Chemicals*, 29 CFR 1910.119. (Reference 10)

Our review of standards and practices also included the International Safety Management (ISM) Code, prepared by the IMO (References 11 through 14). The ISM code became international law on July 1, 1998, and it applies to passenger ships, oil and chemical tankers, bulk carriers, gas carriers, and high-speed cargo craft of 500 gross tonnage or more. The ISM code will also apply to other cargo ships and mobile offshore drilling units of 500 gross tonnage or more by July 1, 2002. This code focuses on management systems and company organizations (both on shore and on board ships). The ISM code became international law through incorporation into the International Convention for the Safety of Life at Sea (SOLAS), 1974, as a new Chapter IX. (SOLAS is accepted by 128 countries and applies to more than 97% of world merchant shipping tonnage.)

Step 4 — Developed a Database of Relevant Incidents. The objective of this step was to identify a large number of incident investigation reports that could be used to provide insights into the causes of fuel oil/lube oil spray fires and potential reduction/mitigation options. We identified seven databases that contained relevant incident investigation reports:

- **MISREP** — A computerized Coast Guard database (Reference 15). In this database, a mishap is any unplanned, unexpected, or undesirable event causing injury, occupational illness, death, material loss, or damage. (In the Mishap Reporting [MISREP] database, the term "mishap" is used in lieu of "accident" and/or "occupational illness.") We performed computer searches to identify the mishaps in the MISREP database from 1990 to 1996 that involved sprays of flammable or combustible liquids on board vessels. Appendix A presents a total of 55 incidents from the MISREP database.

- **MSIS** — Records from the Marine Safety Information System (MSIS) were compiled for this project by the Data Administration Division of the Coast Guard according to our specifications (Reference 16). Specifically, we requested incidents involving fuel oil, lube oil, and hydraulic oil systems on board ships of all sizes exceeding about 100 gross tonnage. Also, we requested a variety of owners/operators, flag states, and classification societies. Appendix B presents a total of 38 incidents from the MSIS database.

- **LMIS** — A database developed and maintained by Lloyd's Maritime Information Services Limited (LMIS) (Reference 17). LMIS is a private limited company owned jointly by Lloyd's Register of Shipping and Lloyd's of London Press Limited. The LMIS database contains information about reported serious casualties to propelled seagoing merchant ships in the world of 100 gross tonnage and above from January 1, 1978. Also, the database contains all reported incidents (i.e., serious and nonserious) to tankers, including combination carriers and gas carriers/tankers, since January 1, 1975. The database is maintained on a mainframe computer at Lloyd's Register, and it is updated from reports received daily from Lloyd's agents and Lloyd's Register surveyors located in more than 130 countries. At our request, LMIS performed computer searches to identify all events in the database where a fire/explosion occurred and the incident involved fuel oil and/or lube oil systems. Appendix C presents a total of 42 incidents from the LMIS database (Reference 18).

- **NK** — We compiled this database from the information in *Engine Room Fire Guidance to Fire Prevention* (the "NK Report"), published by the Japanese classification society Nippon Kaiji Kyokai (NK), Tokyo, Japan, September 1994 (Reference 19). The NK Report investigated actual conditions and causes of more than 70 engine room fires in NK-classed ships during 13 years from 1980 to 1992. Of these fires, a total of 39 (about half) involved fuel or lube oil systems in the engine room. The NK Report does not include a description of most events, but it does provide the cause of each fire. Appendix D presents a total of 39 incidents from the NK database.

- **TSB** — This database was compiled from incidents provided by the Transportation Safety Board (TSB) of Canada. We reviewed the titles of dozens of TSB reports (published in the last two decades) on marine-related accidents to identify those that involved fire on board vessels. All fire-related reports were then reviewed to identify incidents involving spray of flammable or combustible liquids on board vessels (a total of only two incidents). Appendix E presents both incidents from the TSB database.

- **MIIU** — This database consists of incidents provided by the Marine Incident Investigation Unit (MIIU), Inspector of Marine Accidents, Australia, which investigates marine incidents as defined by the Australian navigation (marine casualty) regulations. The purpose of an MIIU investigation is to identify the circumstances of an incident and determine its causes. All reports of investigations are published to make the causes of an accident known within the industry, so as to help prevent similar occurrences. We reviewed the titles of all MIIU reports on marine-related accidents for the last two decades to identify those that involved fire on board. These selected reports were then reviewed to identify those that documented fires in the engine room involving either fuel oil or lube oil systems (a total of only three incidents). Appendix F presents all three incidents from the MIIU database.

- **NTSB** — We compiled this database from the reports published by the U.S. National Transportation Safety Board (NTSB), an independent federal agency dedicated to promoting aviation, railroad, highway, marine, and hazardous materials safety. Established in 1967, the agency investigates transportation accidents, determines the probable cause of accidents, issues safety recommendations, studies transportation safety issues, and evaluates the safety effectiveness of government agencies involved in transportation. NTSB makes public its actions and decisions through accident reports (e.g., Reference 20), safety studies, special investigation reports, safety recommendations, and statistical reviews. We reviewed the titles of more than 100 NTSB reports on marine-related accidents to identify those that involved fire on board ships. These selected reports were then reviewed to identify a total of three fire incidents in the engine room involving either fuel oil or lube oil systems. Appendix G presents all three incidents from the NTSB database.

Overall, Appendixes A through G contain a total of 182 incident records. Of these, 175 involved spray of fuel oil/lube oil in the engine room on board ships (the other 7 were determined to be outside the scope of this project), and 143 sprays ignited and resulted in fires. Of the 143 fires caused by sprays of fuel oil/lube oil, 9 fires are known to have resulted in fatalities and another 8 are known to have resulted in personnel injury.

Step 5 — Developed Preliminary Recommendations. The objective of this step was to identify a set of preliminary risk-reduction options (preliminary recommendations) that had the potential for reducing risks from sprays of pressurized fuel oil/lube oil. Most of the effort involved in this step was also accomplished in Task 1, and several of the preliminary recommendations considered were selected from the Task 1 results (Reference 1). Specifically, our preliminary conclusion in Task 1 was that most of the risk associated with pressurized fuel oil/lube oil systems stems from deficiencies in (or lack of) safety and reliability management systems. That is, the root cause of these incidents is generally the absence, neglect, or deficiencies of management system features. Therefore, the Task 1 Letter Report provided a number of recommendations that address improvements in management systems.

We also reviewed several reports (particularly the NK Report [Reference 19] and reports by NTSB [Reference 20]) that also presented recommendations for helping prevent spray-related fires on board ships. Several of the recommendations from these reports were similar to the recommendations from Task 1 (i.e., addressed improvements to management systems). However, these reports also suggested several hardware-related recommendations (e.g., deflector shielding) in addition to improvements in management systems.

The hazard analysis team also developed and considered a few new recommendations (e.g., using water-mist systems) during the hazard evaluation meeting (Step 7). These new recommendations became evident during the review of incidents.

Each preliminary recommendation was documented in a table that included the description of the recommendation, comments about the potential benefits of implementing the recommendation, potential limitations, and additional comments about implementation. Table 2.4 is an example of the documentation of each preliminary recommendation. Appendix H presents a total of 28 preliminary recommendations that were compiled for this study.

Table 2.4 Example Preliminary Recommendation

Preliminary Recommendation 4: *Provide deflector shielding (e.g., metal plate) between fuel oil/lube oil strainer, filter, coalescer, or purifier (which can be sources of high-pressure fuel/lube oil sprays) and potential sources of ignition (e.g., engine exhaust manifold or pipe, turbine casing, turbocharger casing, steam line). Shielding should be installed in such a way that it does not have to be removed for performing equipment maintenance, which would make shielding ineffective during maintenance (several fires occurred when the crew was performing maintenance on the equipment)* [d, e, f, g]		
Comments and Potential Benefits	Potential Limitations	Comments About Implementation
Hot surfaces are by far the most common source of ignition of sprays of combustible liquids in engine rooms. Providing deflector shielding between the potential sources of sprays and the potential sources of ignition should help prevent direct contact of sprays with the most common source of ignition. This should help reduce the probability of ignition	Some conceptual shielding designs consist of a metal "box" that encapsulates the strainers, filters, etc. The box has a top, three closed walls, and one open side (with or without a cover). The open side allows for equipment maintenance. However, these designs may direct sprays that occur during maintenance onto the crew member performing this activity	Maintenance personnel sometimes fail to reinstall shielding after maintenance. (Shielding can be useful in helping prevent fires, but it requires strict control to be effective) The hazard analysis team considers this preliminary recommendation one of the most useful in reducing spray-related risks. *The expected impact of implementing this recommendation is about 50% reduction in the frequency of fatal incidents from spray fires*

[d]National Transportation Safety Board (NTSB), *Marine Accident Report Engineroom Fire On Board the Liberian Tankship SEAL ISLAND While Moored at the Amerada Hess Oil Terminal in St. Croix, U.S. Virgin Islands, October 8, 1994*, NTSB/MAR-95/04, December 1995.

[e]Recommendation by the U.S. Coast Guard investigating officer regarding the fire on board the U.S. LASH ship STONEWALL JACKSON, as described in NTSB/MAR-95/04.

[f]Recommendation by the NTSB to the U.S. Maritime Administration (the vessel's owner) regarding the fire on board the Massachusetts Maritime Academy training ship BAY STATE, as described in NTSB/MAR-95/04.

[g]*Engine Room Fire Guidance to Fire Prevention*, page 65, Nippon Kaiji Kyokai (NK), Tokyo, Japan, September 1994.

Step 6 — Assembled a Team of Specialists for the Hazard Evaluation. We assembled a hazard analysis team of specialists with significant experience in the design, operation, and maintenance of ships as well as safety/reliability/risk analysis. The team was composed of a Marine Inspector from the Coast Guard Marine Safety Office (CWO Bob Stegall), a Naval Engineer from CGI (George Cassa), and two engineers from JBFA (Henrique Paula and Tom Zanin) with experience in safety and reliability analysis and risk assessment. Appendix K presents the résumés for these specialists.

Step 7 — Assessed the Impact of Preliminary Recommendations. We conducted a 4-day meeting (February 23 through 26, 1998) to review the incident investigation reports that we have collected from the seven databases. The hazard evaluation meeting was then followed by several weeks of additional analysis of the incidents/preliminary recommendations by JBFA and CGI. Our objectives for the hazard evaluation were to evaluate the preliminary recommendations that have been made for reducing/mitigating sprays of fuel oil/lube oil on board vessels. To accomplish this, we considered the potential benefits of implementing these recommendations by (1) analyzing the incident investigation reports and (2) considering the likelihood that the recommendations could have prevented/mitigated the previous occurrences.

We also made observations about potential difficulties in implementing the recommendations (included in Appendix H), and we compiled information on whether the release ignited, the source of ignition, whether there was loss of propulsion/steering, whether there was human casualty, the equipment involved, the system involved, and the total damage. When some of this information was not available for an incident, we specified that the information was "Not Stated." Appendix I presents the results of this analysis.

For each of the 175 fuel oil/lube oil sprays documented in Appendixes A through G, we reviewed the incident description and estimated the likelihood that the incident would have been avoided had each of the preliminary recommendations been implemented. We made this assessment for each preliminary recommendation individually and then for all 28 preliminary recommendations combined. (A total of 29 × 175 = 5,075 individual assessments.) Appendix J presents the results of this analysis. To facilitate our assessment and help ensure consistency, we used categories of likelihood as follows:

Category	Likelihood
A	0.01
B	0.01
C	0.1
D	0.5
E	1.0

Also, when insufficient information was available to select a category, a Category I was assigned. To illustrate the procedure, consider the first incident (MISREP01) documented in Appendixes A (pages A-5 through A-7) and J (page J-3). The hazard evaluation team assigned Category C for Preliminary Recommendation 1. This indicates that the team believed that the likelihood that Preliminary Recommendation 1 would have prevented Incident MISREP01 is about 0.1. Another way of interpreting this assessment is that the team believed that Preliminary Recommendation 1 would have prevented 9 out of 10 incidents similar to Incident MISREP01. That is, Preliminary Recommendation 1 is expected to reduce the frequency of similar incidents to 10% of the frequency of these incidents without the benefit of the recommendation. This assessment was repeated for each of the other 27 preliminary recommendations (a total of 28 individual assessments) and then for the combined impact of all preliminary recommendations.

In evaluating the combined impact of all preliminary recommendations, the primary consideration is whether the different recommendations are redundant (i.e., the benefit of a recommendation is reduced or eliminated after credit is given to the benefits of the other recommendations) or whether they complement each other (i.e., the benefit of a recommendation is in addition to the benefits of the other recommendations). In the former case, the impact of multiple recommendations is the same as the impact of the best recommendation. For example, two preliminary recommendations (1 and 19) were judged to have a Category C impact on MISREP14 (see Appendix J, page J-3). We considered that the impact of these two recommendations is redundant (not complementary), and, therefore, the combined impact for MISREP14 is Category C. Had we assumed that these two recommendations complemented each other, the combined impact would have been Category B.

Step 8 — Developed Feasible, Practical Recommendations to Reduce Risks. We used the results of Step 7 to develop the final recommendations presented in Section 4 of this report.

3. ANALYSIS RESULTS

This section presents the results of our analysis in seven subsections:

3.1 — Review of the causes of fuel oil/lube oil spray fires
3.2 — Sources of ignition of fuel oil/lube oil spray fires
3.3 — Equipment involved in fires caused by the release of fuel oil/lube oil
3.4 — System involved in fires caused by the release of fuel oil/lube oil
3.5 — Damage characterization
3.6 — Impact of preliminary recommendations
3.7 —Miscellaneous results and observations

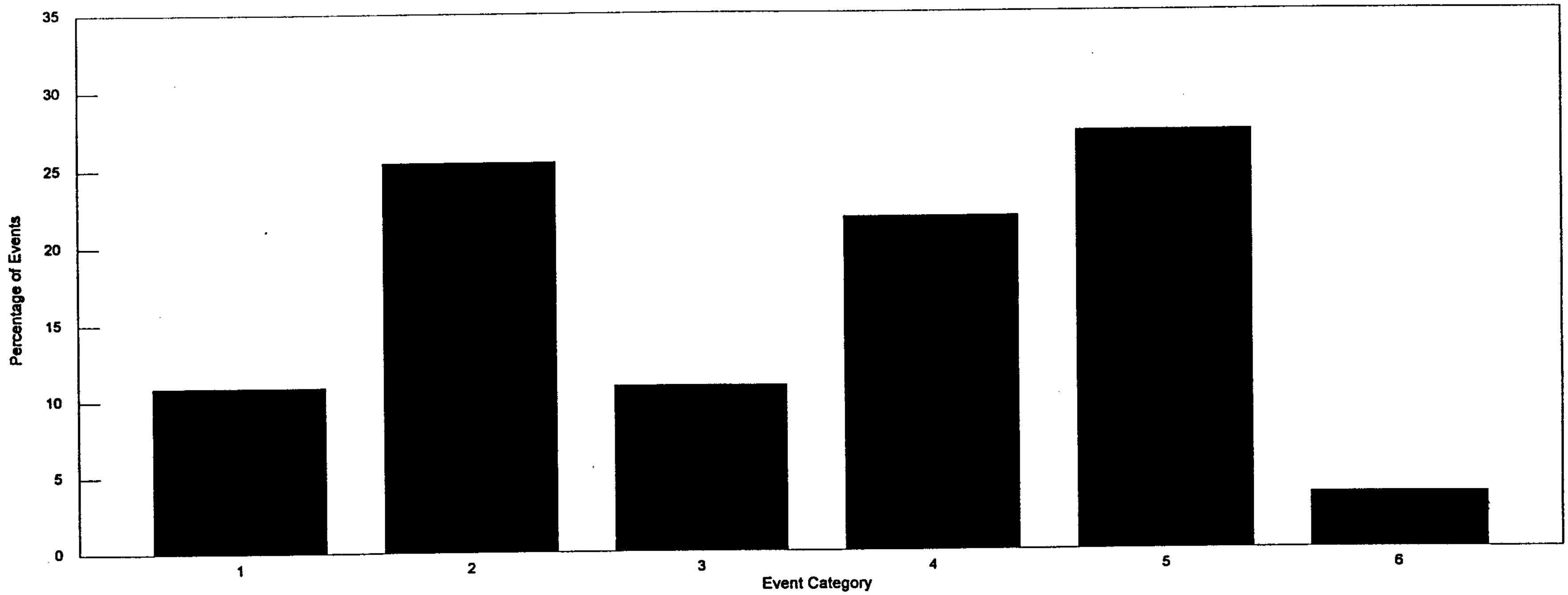
As described in Section 2, the results of our research were based on extensive review of previous incidents (releases of fuel oil/lube oil on board vessels). Appendixes A through G contain a total of 175 incident records that involved spray of fuel oil/lube oil in the engine room on board ships, and 143 of these sprays ignited and resulted in fires. Of the 143 fires, 9 fires are known to have resulted in fatalities and another 8 are known to have resulted in personnel injury. Obviously, we attempted to use all applicable incident records in the development of the results presented for each of the subsections in this section. However, incident records are often incomplete regarding one or more of the issues addressed in each subsection. The results presented in each subsection were developed based on the database(s) that provided sufficient information relevant to the specific issue considered in the subsection.

3.1 Review of the Causes of Fuel Oil/Lube Oil Spray Fires — In Task 1 (Reference 1), we examined the causes of fires that resulted from releases of oil on board vessels. This investigation considered a few releases of hydraulic oil in addition to many releases of fuel oil and lube oil. (These are the only results in Section 3 that considered a few hydraulic oil system releases.) The Task 1 review was based on the incident investigation reports in Appendix A (MISREP reports). However, when available, information from the other appendixes (e.g., E, F, and G) about the cause of the incidents is very consistent with our findings in Task 1.

Spray fires have occurred because of a variety of human-related and/or equipment-related causes. Although each incident is unique regarding the specific cause of failure, it is convenient for the purpose of discussion to assign them to one of six general categories of causes of failure. Figure 3.1 presents the percentage of incidents that resulted from each general category. Next we discuss and illustrate each category.

Category 1: Lack of adequate inspection or maintenance. About 10% of all incidents in Appendix A involved lack of inspection and/or maintenance of equipment and piping, including incidents typically attributed to "aging," "wear," or "overdue for replacement." We included these causes in Category 1 because equipment and piping will wear out over time because of erosion, corrosion, friction,

Figure 3.1 General Categories of Causes of Fuel Oil/Lube Oil Spray Fires



Category 1 - Lack of adequate inspection or maintenance

Category 2 - Personnel error during inspection or maintenance

Category 3 - Personnel error and/or equipment failure during (1) preparation for inspection or maintenance or (2) restoration to service after inspection or maintenance

Category 4 - Design, manufacturing, or installation deficiencies

Category 5 - Unknown root cause

Category 6 - External impact

fatigue, vibration, etc., and it is essential to establish programs for inspecting and maintaining these components according to applicable industry guidelines. Otherwise, the equipment and piping are expected to eventually fail because of aging, wear, etc. In fact, for most incidents in this category, the event description indicates that there was no ongoing inspection and maintenance program for the equipment or piping. That is, the equipment and piping were under a "breakdown" maintenance program. In one of these incidents (Event 94175011, page A-101), there was a program for inspecting and maintaining lube oil piping systems for blowers, but the piping system for one of the blowers had not been inspected and maintained because it was unaccessible. The piping eventually ruptured because of corrosion and vibration, causing the blower to disintegrate.

Category 2: Personnel error during inspection or maintenance. Almost 25% of all incidents in Appendix A were associated with personnel errors and/or equipment failure during inspection or maintenance activities, and about half of these incidents resulted in human casualty. (Failure to use adequate personal protective equipment [PPE] is almost invariably mentioned as a contributing factor for human casualties.) Many of these events were caused by a lack of understanding of the design and operation of vessel systems and components. For example, in Event 1141196011 (page A-193), while trying to remove a valve handle, a crew member inadvertently removed two screws that secured the valve stem holding plate. The stem shot out of the valve, covering the crew member with oil and spraying oil in the machinery space. In Event 1342496001 (page A-213), during replacement of a temperature gauge, a thermo bulb was kinked and broke when it was moved, again spraying lube oil on a crew member. A third example is Event 95141027 (page A-145), which involved two crew members clearing a blocked gauge line with a thin wire. When they succeeded in unblocking the line, a hot mixture of soot and oil sprayed out onto the crew.

Some of the other releases in this category were caused by maintenance personnel leaving vent/drain valves open and without a cap (e.g., Event 95299003, page A-183, and Event 1151396003, page A-201). Another common personnel error in this category is the use of improper materials, parts, and components. For example, Event 1151296001 (page A-197) involved a filter that fractured because an improper pump had been installed, and Event 94153013 (page A-97) discusses a catastrophic failure of an incorrect gasket type.

Finally, there were a few incidents in this category caused by improper craftsmanship or incorrect repair. For example, in Event 95278003 (page A-177) maintenance personnel cut a piece of flexiglass tube with uneven ends for use as sight glass replacement. When the sight glass was pressurized, it leaked and sprayed fuel oil. As another example, Event 9421008 (page A-113) involved a fuel rod repair/modification performed by crew members that eventually caused an overspeed condition on the emergency diesel generator engine, resulting in catastrophic failure of the engine.

Category 3: Personnel error and/or equipment failure during (1) preparation for inspection or maintenance or (2) restoration to service after inspection or maintenance. About 10% of all incidents in Appendix A were associated with preparation for/restoration from maintenance, and about half of these incidents resulted in human casualty. (Again, failure to use adequate PPE is almost invariably mentioned as a contributing factor for human casualties.) The majority of these events were caused by personnel error. For example, Event 93193011/93223002 (page A-37) involved a release caused by crew members failing to verify that a filter/coalescer was depressurized by venting and draining it before removing the top cover.

Although less common than personnel errors, some of the events in this category did result from equipment failures (or combinations of human and equipment failure). For example, Events 13221 (page A-33) and 93293039 (page A-53) involved failures of the key that connects the strainer spool (or bale) to the handle. In both events, the crew moved the handle to the position required to isolate the strainer for maintenance, but because of the failure of the key, the strainer remained pressurized. In both cases, there was no independent way of verifying that the strainer was indeed depressurized.

Category 4: Design, manufacturing, or installation deficiencies. About 20% of all incidents in Appendix A were attributed to incorrect design, deficiencies in manufacturing, and/or errors during installation. For example, Event 9404 (page A-9) involved an internal failure of a turbocharger that may have resulted from a flaw in the quality control procedures used in the recent rebuilding of the equipment. Regarding design deficiencies, the description for Event 5628 (page A-5) suggests that the design of a cover was deficient, allowing (or facilitating) the cover latch to catch the hoses from the choke and pull them off along with the cover. As a final example of Category 4 incidents, Event 94209003 (page A-109) involved a hydraulic oil release that was ultimately the result of the installation of oversized bolts.

Category 5: Unknown root cause. Almost 30% of all incidents in Appendix A were attributed to causes such as "line cracked," "O-ring failure," "internal engine failure," "gasket failure," etc. For example, each of the Events 94079019 (page A-81), 94112024 (page A-85), 95198011 (page A-153), 95221006 (page A-161), 95236005 (page A-165), and 95275008 (page A-173) lists the failure of a line, joint, fitting, or gasket as the cause of the incident, and Event 94151009 (page A-93) lists "crankcase explosion" as the cause of an oil spray. These events are categorized as "unknown root cause" because a component (e.g., engine) or piece-part (e.g., gasket) is listed as the cause of the occurrence, and the reason or reasons for the component or piece-part failure is not provided in the incident descriptions. For example, a gasket may have failed because it was the wrong type of gasket for the application, but the event description does not show this information. That is, the root cause of these events is unknown either because it was never determined during the investigation or because it was not properly documented.

Category 6: External impact. Almost 5% of all incidents in Appendix A involved damage to a pressurized system caused by an external impact from activities that take place in the vicinity of the system piping and equipment. Specifically, the description for Event 9476 (page A-13) speculates that an elbow in the turbocharger oil supply line failed because of physical damage that resulted from somebody stepping on the line. Event 12531 (page A-29) discusses a winch accident that caused a cage to hit (and rupture) a hydraulic line.

3.2 Sources of Ignition of Fuel Oil/Lube Oil Spray Fires — Figures 3.2 through 3.4 show the sources of ignition for the 143 spray fires, 17 spray fires with injury or fatality, and 9 spray fires with fatality, respectively. "Engine Exhaust Manifold or Exhaust Pipe" is by far the most common source of ignition (almost 50% of all fires in Figures 3.2 and 3.3 and about 22% of all fires in Figure 3.4). The "Not Stated" category is also an important contributor in all three figures. Other important contributors in all cases, particularly in Figure 3.4, are "Turbocharger Casing" and "Steam Line." It is clear that hot surfaces dominate risks of ignition within engine rooms on board ships.

To further illustrate the dominance of hot surface, Figures 3.5 through 3.7 show the relative contribution of categories of sources of ignition, defined in Table 3.1.

Table 3.1 Categories of Sources of Ignition

Category	Sources of Ignition Included in the Category (Excludes "Not Stated")
Hot Surface	Engine exhaust manifold or exhaust pipe Turbocharger casing Turbine casing Hot surface and/or open flame Steam line Hot surface or electrical equipment (only half of all events)
Explosion	Boiler explosion Explosion
Electrical	Electrical fixture Electric heater Hot surface or electrical equipment (only half of all events)
Other	Spark from friction Handheld torch

Figure 3.2 Source of Ignition: All Oil Fires

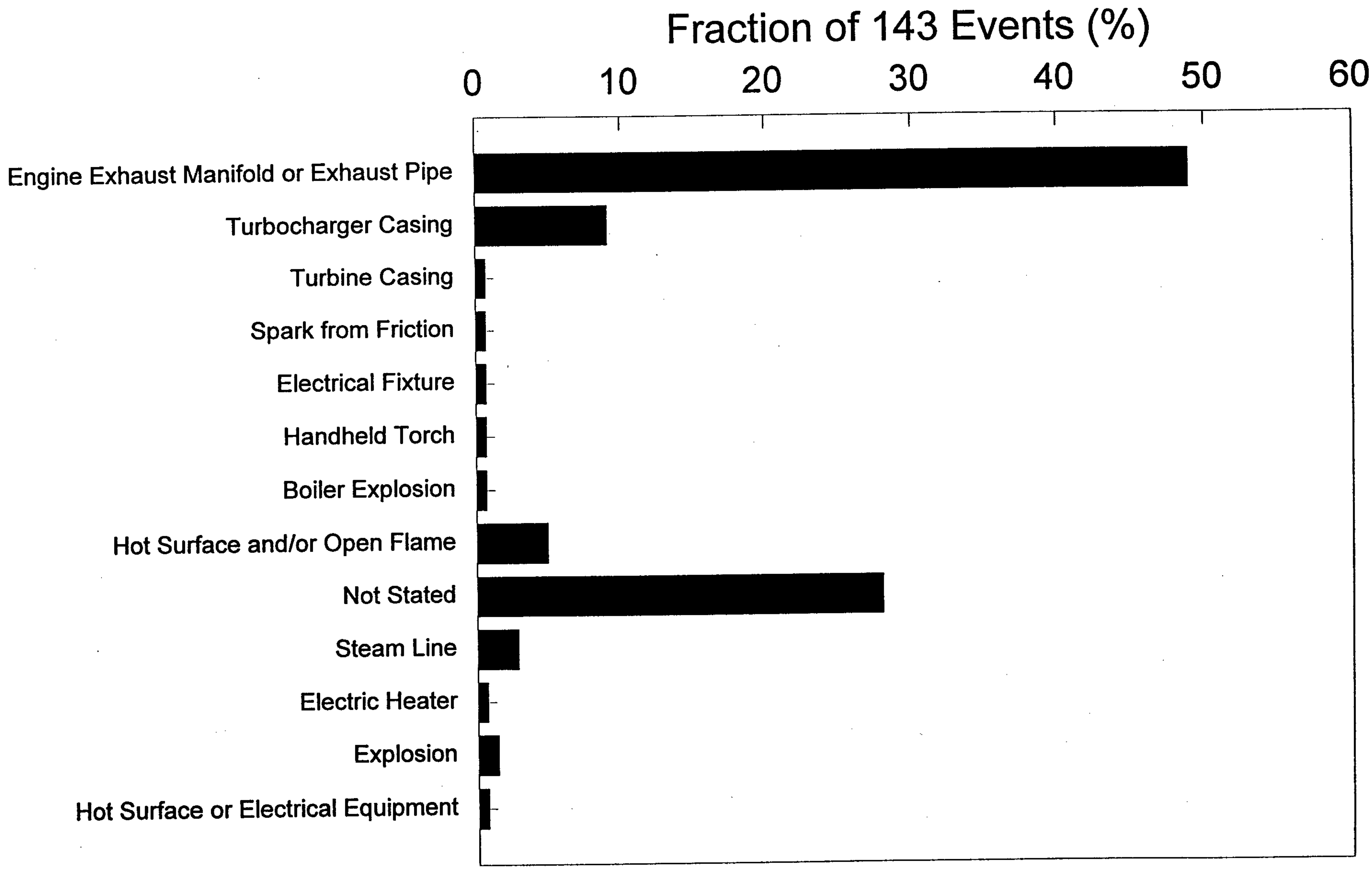


Figure 3.3 Source of Ignition: All Oil Fires with Injury or Fatality

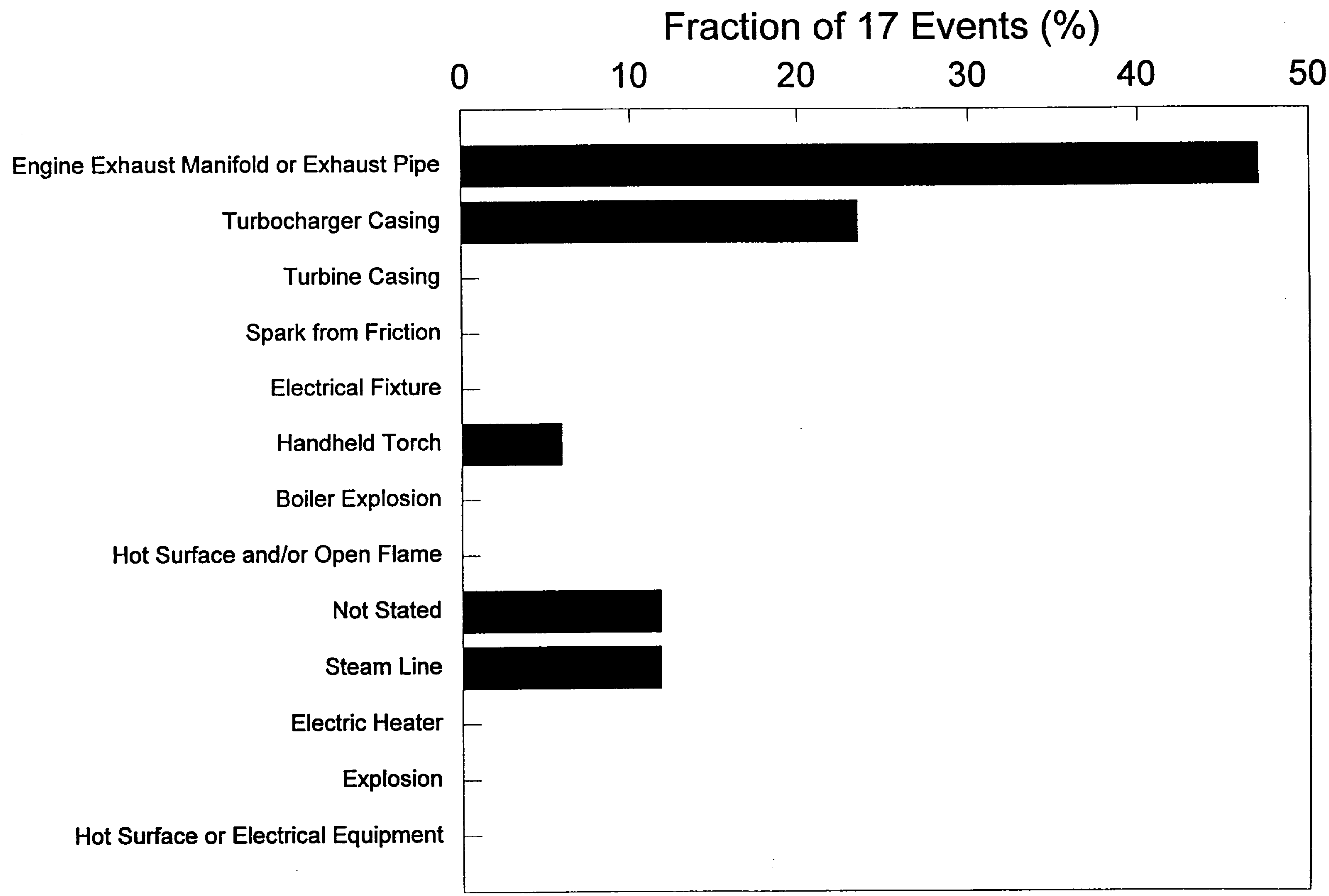


Figure 3.4 Source of Ignition: All Oil Fires with Fatality

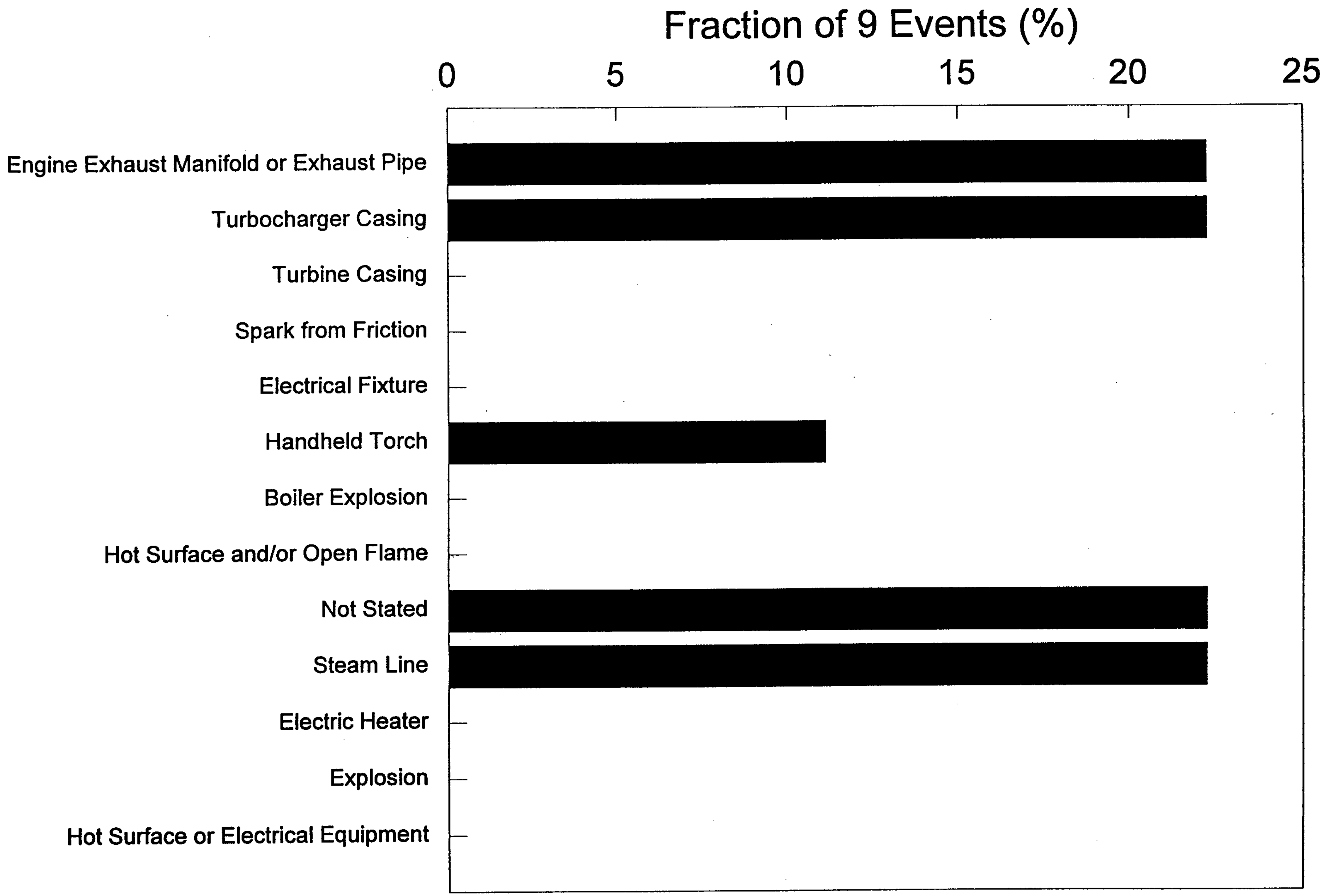


Figure 3.5 Sources of Ignition by Categories: All Oil Fires

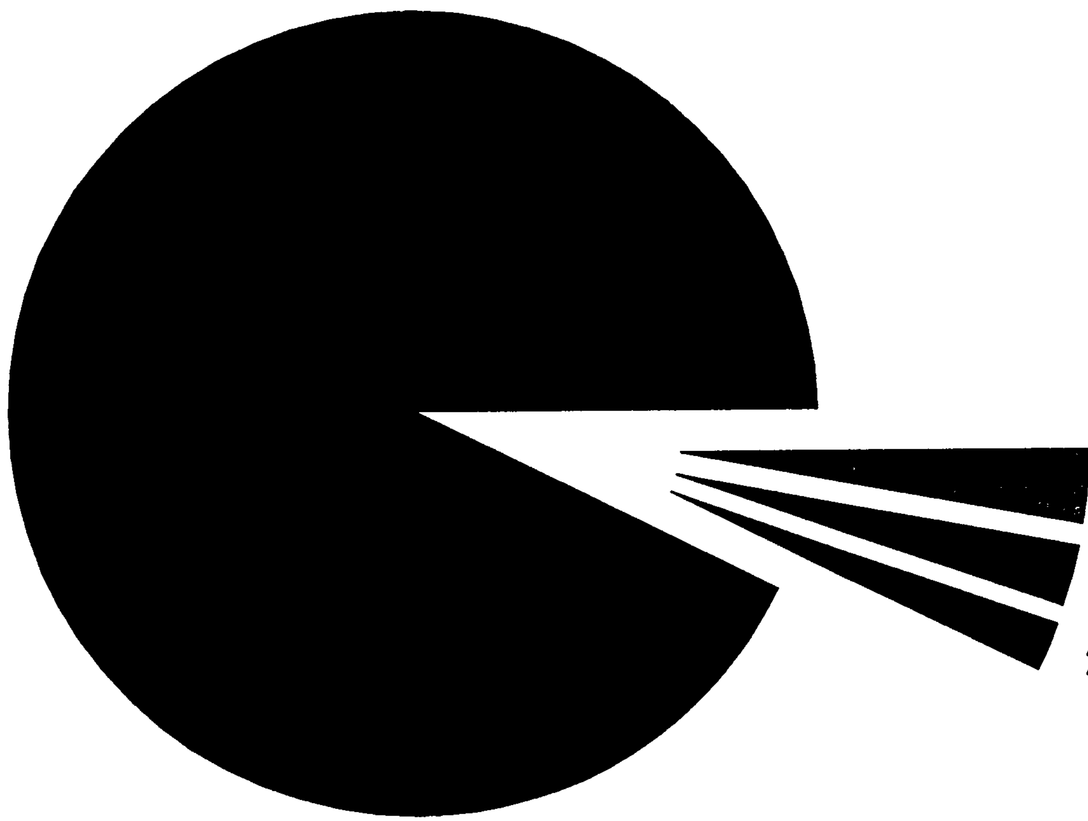


Figure 3.6 Sources of Ignition by Categories: All Oil Fires with Injury or Fatality

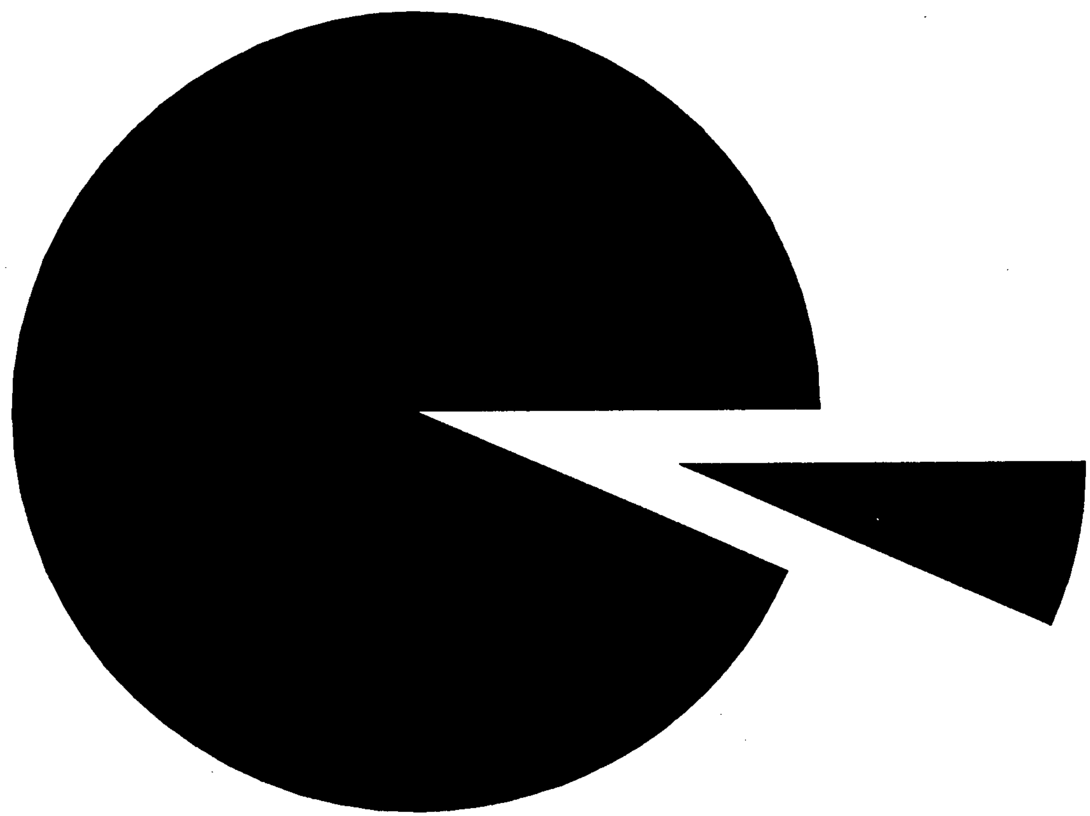


Figure 3.7 Sources of Ignition by Categories: All Oil Fires with Fatality

The category "Hot Surface" is responsible for the ignition of about 93% of all fires, 93% of all fires with injury or fatality, and about 86% of the fires with fatality. For the latter (fires with fatality), the one incident ignited by a handheld torch represents about 14% of all fires because there are only seven fatal fires in which the source of ignition has been determined and documented.

3.3 Equipment Involved in Fires Caused by the Release of Fuel Oil/Lube Oil — Figures 3.8 through 3.10 show the equipment involved in the release of fuel oil/lube oil and its contributions to all fire incidents (Figure 3.8), all fires with injury or fatality (Figure 3.9), and all fires with fatality (Figure 3.10), respectively. "Skid Piping, Tubing, or Hose" dominates risks in Figures 3.8 and 3.9, and it is important in Figure 3.10. (The piping outside the engine or pump skid [e.g., piping from oil tanks to strainers and piping from strainers to diesel engines] is considered separately in the category "Piping.") These results are interesting because skid piping/tubing/hose is usually under the control of the manufacturer (i.e., the piping/tubing/hose that comes with an engine skid or pump skid), and it is generally not subject to regulations and standards that are in place for piping outside the engine/pump skid.

However, the equipment category "Duplex Strainer, Filter, or Coalescer," which is the second most prevalent in Figures 3.8 and 3.9, dominates risks in Figure 3.10. *That is, spray fires involving "Duplex Strainer, Filter, or Coalescer" have been more fatal than fires involving other types of equipment.* In fact, the equipment category "Duplex Strainer, Filter, or Coalescer" is responsible for 55% of all fuel oil/lube oil spray fires with fatality (Figure 3.10).

Table 3.2 shows a synopsis of the causes of each of the nine fatal fuel oil/lube oil spray fires. Appendixes A through G provide more details for some of these events. As shown in Figures 3.2 through 3.7, hot surfaces ignited most of these incidents. Thus, providing sheathing for hot surfaces or other means (e.g., deflector shielding) to prevent oil sprays from reaching hot surfaces should help reduce the frequency of these incidents.

The first incident in Table 3.2 (MSIS22) occurred during preparation of the ship for the winter. The ship's second assistant engineer was removing bunker C heavy oil from fuel lines, but one of the lines was plugged. He used a propane torch and solvent to heat and loosen the line plug. When the plug dissolved, diesel oil was released through a drain valve, coming in contact with the flame of the propane torch. It is difficult to avoid this type of accident because it involved an unsafe work practice. Better standard operating procedures (SOPs), safe work practices, and training (awareness of oil spray fire hazards) are probably the only ways to prevent this type of incident.

Few details are provided for the second (LR26) and third (LR38) incidents in Table 3.2. The fourth incident (NK04) involved a temporary change (the use of a vinyl hose in the fuel oil piping system). The vinyl hose was inadequate for this application; it ruptured and caused an oil spray that ignited on the main

Figure 3.8 Equipment Involved in the Release: All Oil Releases

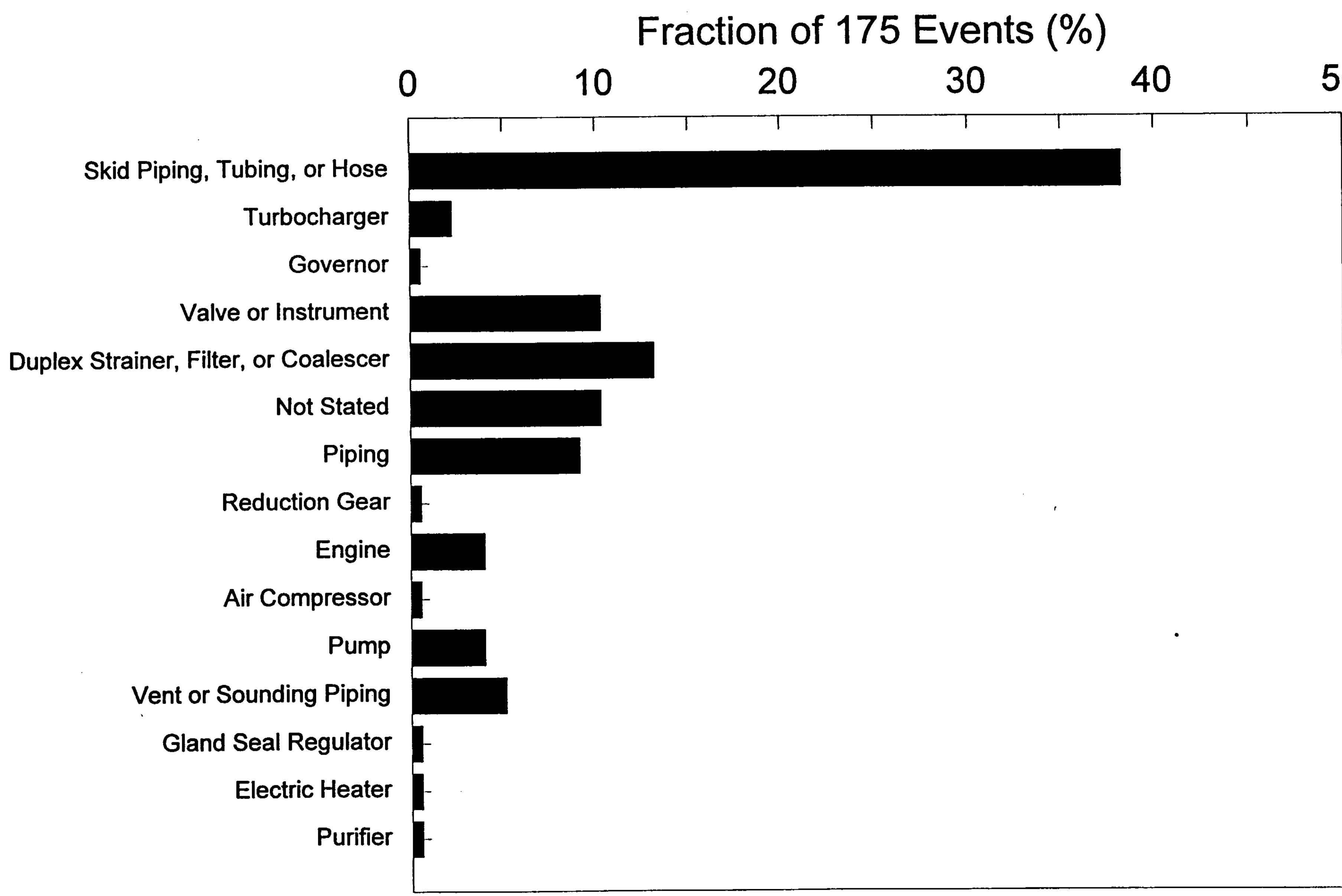


Figure 3.9 Equipment Involved in the Release: All Fires with Injury or Fatality

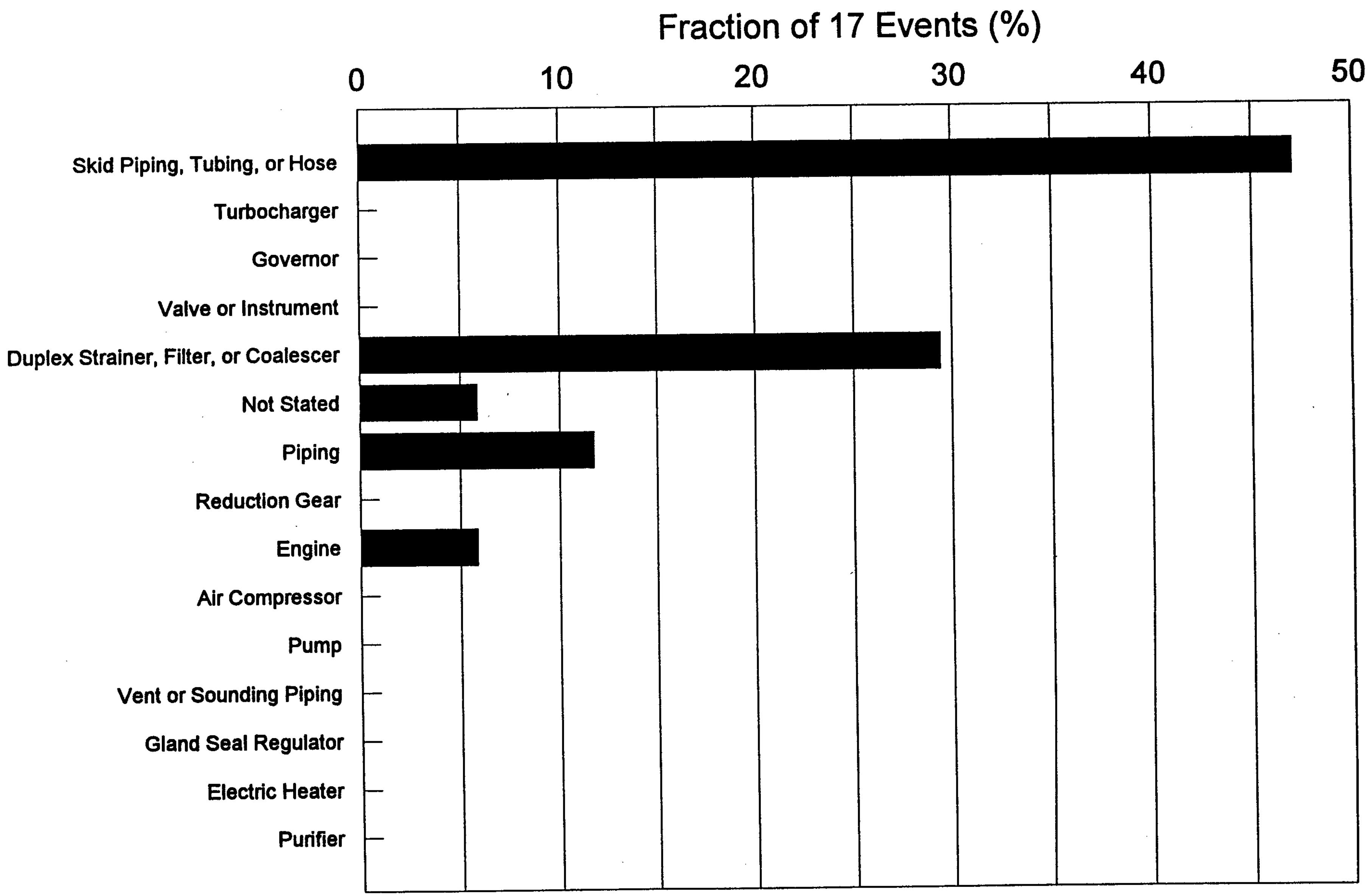


Figure 3.10 Equipment Involved in the Release: All Oil Fires with Fatality

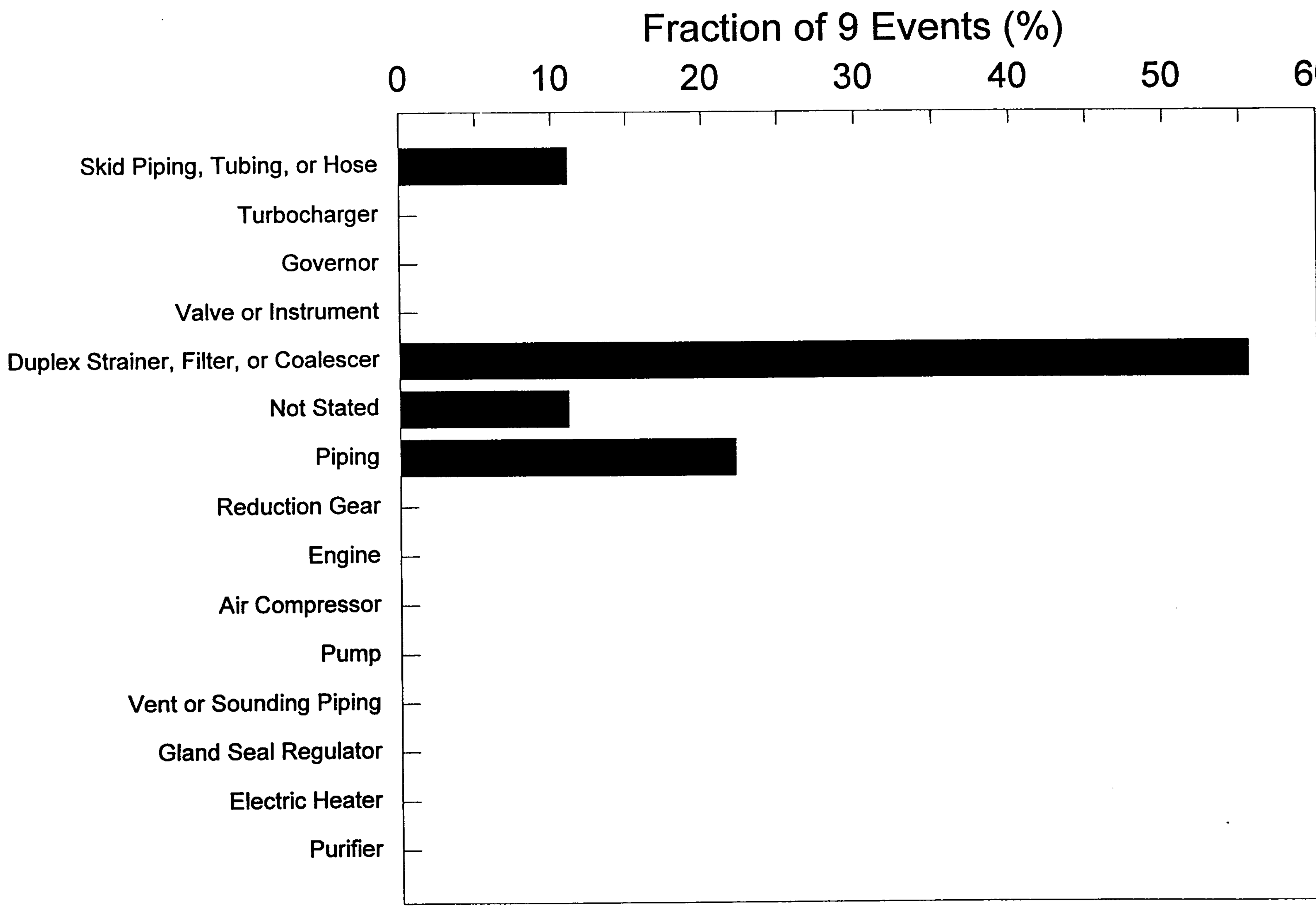


Table 3.2 Synopsis of the Causes of Fatal Fuel Oil/Lube Oil Spray Fires

Event Identifier	Synopsis
MSIS22 (Appendix B, pages B-91 through B-93)	At the time of the fire, the ship was being winterized, and the ship's second assistant engineer was removing bunker C heavy oil from fuel lines. He used a propane torch and solvent to heat and loosen a line plug. When the plug dissolved, a mixture of #2 diesel oil and #6 diesel oil was released through a drain valve, coming in contact with the flame of the propane torch
LR26 (Appendix C, pages C-55 through C-56)	Explosion in the main engine cooling system. (No details provided)
LR38 (Appendix C, pages C-79 through C-80)	A fuel pipe fractured. (No details provided)
NK04 (Appendix D, page D-11)	Disconnection of a vinyl hose in the fuel oil return piping for the main engine, allowing fuel oil to leak onto the main engine exhaust gas pipe and ignite. The vinyl hose had been temporarily fitted to the bottom of the fuel oil mixing column
NK34 (Appendix D, page D-71)	The O-ring for the strainer cover of the lubricating oil secondary strainer was removed by a crew member and was damaged while being restored. Oil leaked out from the strainer cover, dispersed, came in contact with the high temperature parts of the main engine turbocharger, and caught fire
NK37 (Appendix D, page D-77)	During the changeover operation for the lubricating oil duplex strainer of the turbocharger, the mounting bolts of the packing retaining cover were loosened excessively, resulting in oil leaking from the cover
NTSB01 (Appendix G, pages G-5 through G-8)	The lower securing pin for the flow control valve on a duplex strainer was removed to install a temporary assembly to stop a leak. A strong-back kept the flow control valve in place during normal operation, but it had to be removed to replace the strainer element. Changing the strainer element without a device in place to restrain the upward movement of the control valve was poorly thought out and created a hazard that ultimately led to an oil release and fire
NTSB02 (Appendix G, pages G-9 through G-11)	Oil sprayed upward from the duplex lubricating oil strainer while the engineers were attempting to clean and change the strainer elements. (No details provided)
NTSB03 (Appendix G, pages G-13 through G-15)	While attempting to move a strainer's directional flow valve handle, an engineer kicked at the lever with his foot. His foot slipped, striking and breaking off a brass vent cock valve from the cover of the forward strainer basket, which was in service

engine exhaust gas pipe. This is another type of incident that is difficult to avoid. Once a crew member has decided to undertake an unsafe action (the use of inappropriate pipe material), the original safeguards built into the design of the piping system will be defeated. Controlling changes to fuel oil/lube oil systems (e.g., requiring documentation of alterations) is one way to help prevent this type of incident, along with training (awareness of oil spray fire hazards).

The last five incidents (NK34, NK37, NTSB01, NTSB02, and NTSB03) in Table 3.2 involved duplex strainers. In NK34, a crew member damaged the O-ring of a strainer cover, resulting in a leak. Not much detail is provided for NTSB02, except that it happened when the crew was cleaning and changing the strainer elements. In NTSB01, a temporary change to the strainer defeated an original safeguard (safety pin) provided by the manufacturer. This eventually led to an oil spray that ignited. As for NK04, controlling changes to fuel oil/lube oil systems (e.g., requiring documentation of alterations) is one way to help prevent this type of incident, along with training (awareness of oil spray fire hazards).

In both NK37 and NTSB03, the crew was having difficulties moving the three-way transfer valve to divert flow from one strainer chamber to the other chamber so that the strainer element could be cleaned or changed. In NK37, a crew member decided to loosen the mounting bolts of the packing retaining cover to facilitate movement of the valve. This was done excessively, resulting in an oil spray through the packing retaining cover. In NTSB03, a crew member decided to kick the lever on the duplex strainer. He inadvertently hit a vent valve, which ruptured and released an oil spray. In both cases, while attempting to overcome an equipment malfunction (stuck transfer valve), crew members undertook unsafe action that caused oil sprays and fires.

3.4 System Involved in Fires Caused by the Release of Fuel Oil/Lube Oil — Figure 3.11 shows that fuel oil systems account for about 70% of all oil fires while lube oil systems account for about 30%. However, when fires with fatality are considered, these contributions are 50% for fuel oil systems and 50% for lube oil systems. This indicates that while fuel oil fires occur more often (about twice as much) than lube oil fires, the fewer lube oil fires have caused as many fatal incidents as fuel oil. Figure 3.12 further illustrates this point. The probability of a fatality given a fuel oil fire is about 4% while the probability of a fatality given a lube oil fire is about 10% (more than twice as much). *Therefore, lube oil fires are less frequent than fuel oil fires, but they tend to be more fatal when they do occur.*

Figure 3.11 System Involved in the Fire

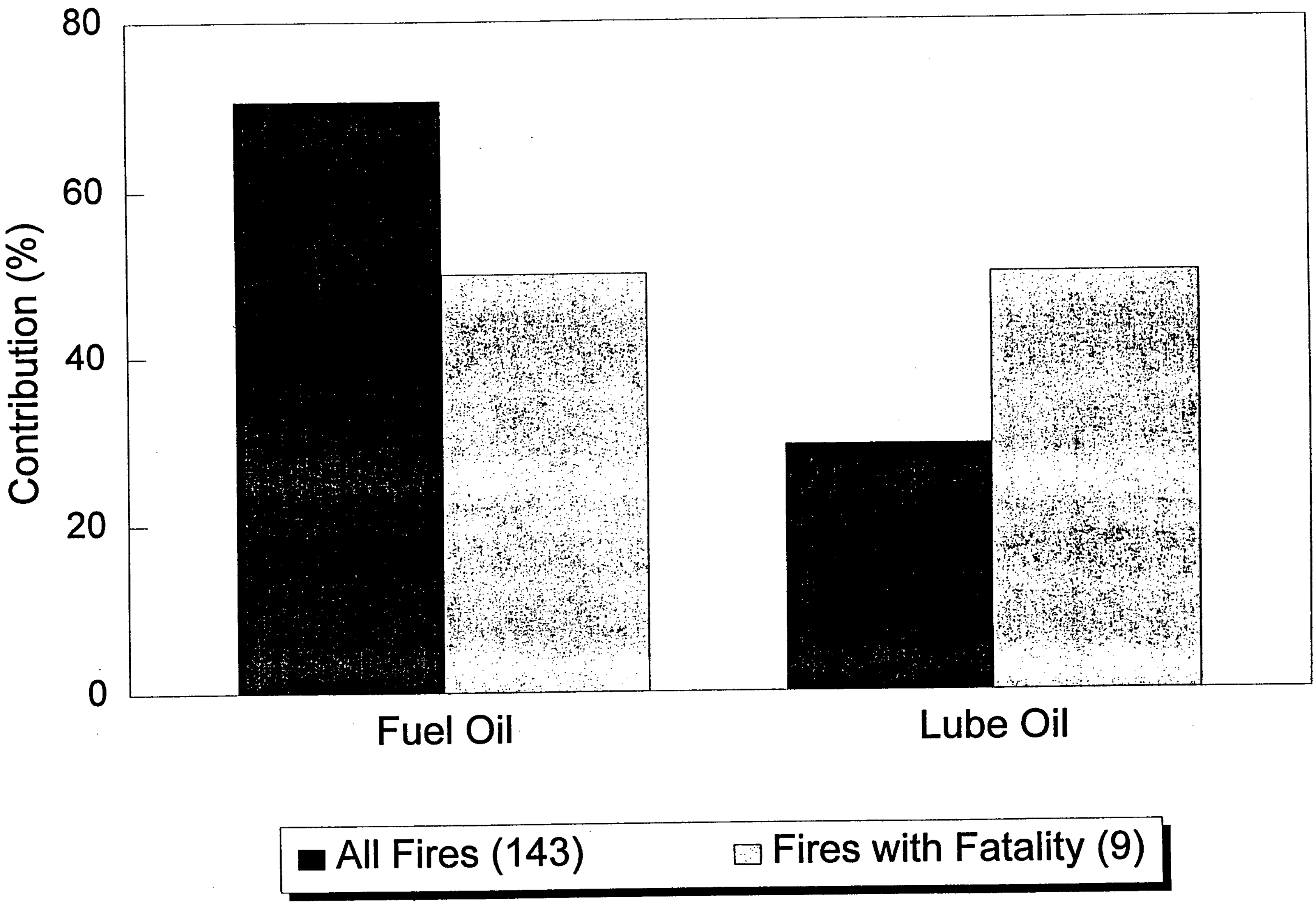
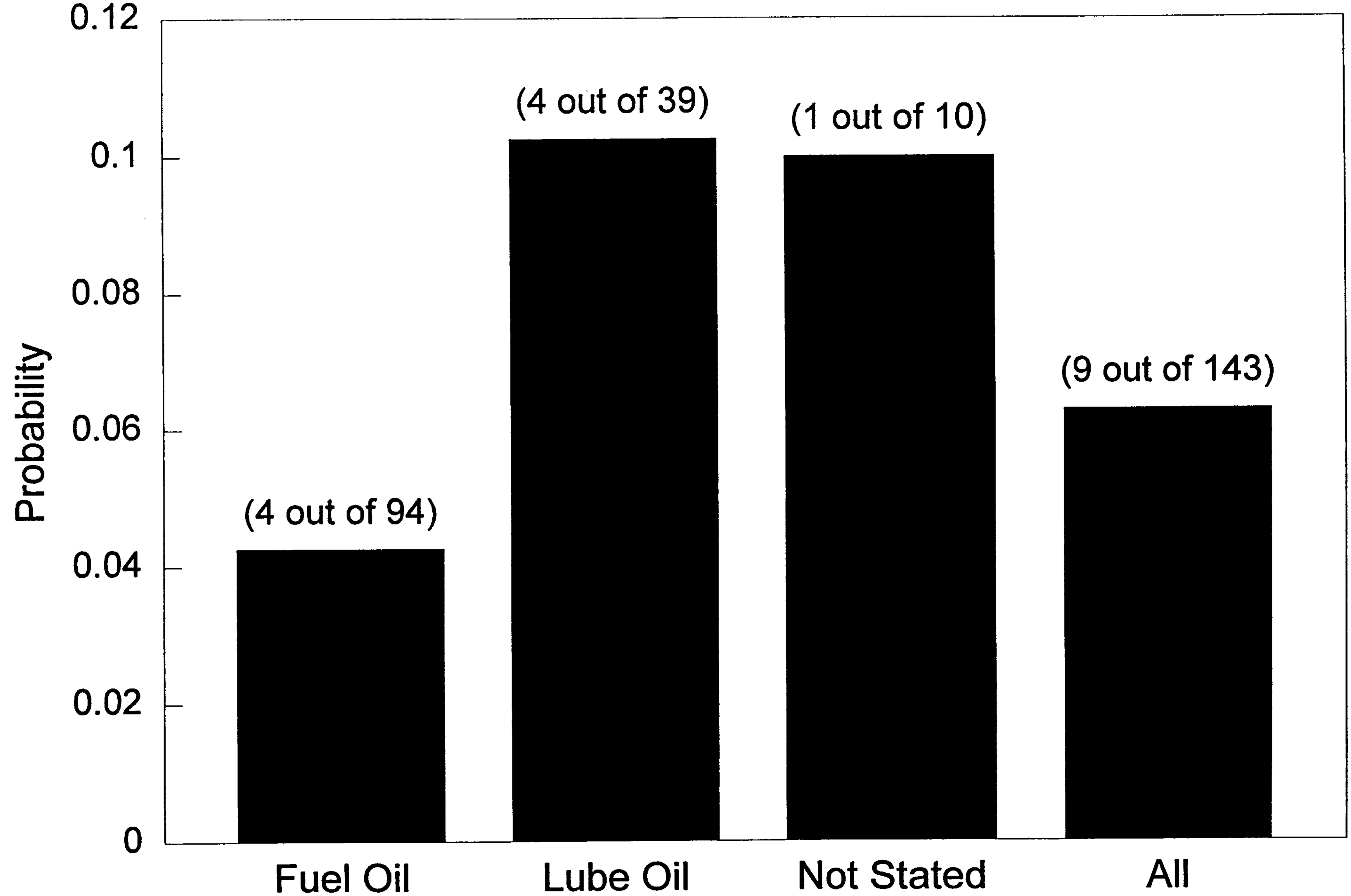


Figure 3.12 Probability of Fatality(ies) Given an Oil Fire



3.5 Damage Characterization — Figure 3.13 shows that the damage incurred in many spray fires (about 61%) was not stated in the incident reports. However, damage information was available in 57 incident reports, and Figure 3.13 shows that it is extensive.[h] The vessel sank in 6 of the incidents, incurred constructive total loss in 9 of the incidents, and incurred an average of about $293,000 in the remaining 42 incidents.

Figure 3.14 shows that vessels experienced loss of propulsion and/or steering in 70 incidents and were able to maintain these functions in 35 incidents. (These are important statistics because loss of propulsion and/or steering can lead to other incidents such as grounding and collision.) These numbers indicate that the probability of loss of propulsion and/or steering is about twice the probability of not losing these functions during spray fires.

3.6 Impact of Preliminary Recommendations — Figures 3.15, 3.16, and 3.17 show the expected factors of improvement for each preliminary recommendation (1 through 28) and for all preliminary recommendations combined (All) for all oil spray fires, all fires with injury or fatality, and all fires with fatality, respectively. In Figure 3.15, no single preliminary recommendation provides significant improvement (e.g., a factor of 2 improvement) by itself. (A factor of 2 improvement implies a 50% reduction of the frequency of incidents.) However, several preliminary recommendations (i.e., 1, 2, 3, 16, 20, 21, 26, and 27) do provide some improvements. The combined impact of all preliminary recommendations is a factor of 4 improvement (reduction of the frequency of incidents to 25% of its frequency without the benefits of these recommendations), primarily because of preliminary recommendations 1, 2, 3, 16, 20, 21, 26, and 27.

Figure 3.16 shows similar results for the impact of preliminary recommendations on fires with injury or fatality. However, the individual impact of several recommendations is higher in Figure 3.16. Also, some preliminary recommendations (i.e., 4 and 14) that had little or no impact in Figure 3.15 show some benefits in Figure 3.16. The combined impact of all preliminary recommendations is a factor of about 6 improvement (reduction of the frequency of incidents to 17% of its frequency without the benefits of these recommendations), primarily because of preliminary recommendations 1, 2, 3, 4, 14, 16, 19, 20, 21, 23, 26, and 27.

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[h]In addition to the 55 incident reports in Appendixes A through G that provided damage information, Figure 3.13 considers the damage from two other incidents: *Fire on Board the Bahamian Passenger Ship THE SCANDINAVIAN STAR in the Gulf of Mexico, March 15, 1988*, NTSB/MAR-89/04, National Transportation Safety Board, Washington, DC, July 1989, and *Engineroom Fire Aboard the U.S. Tankship CHARLESTON in the Atlantic Ocean About 35 Miles off the South Carolina Coast, March 7, 1989*, NTSB/MAR-90/06, National Transportation Safety Board, Washington, DC, October 1990. These two incidents were not included in the appendixes because these reports became available after the hazard evaluation described in Step 7 in Section 2. We considered them in Figure 3.13 because they were among the most expensive engine room fires for the shipping industry.

Figure 3.13 Damage Characterization

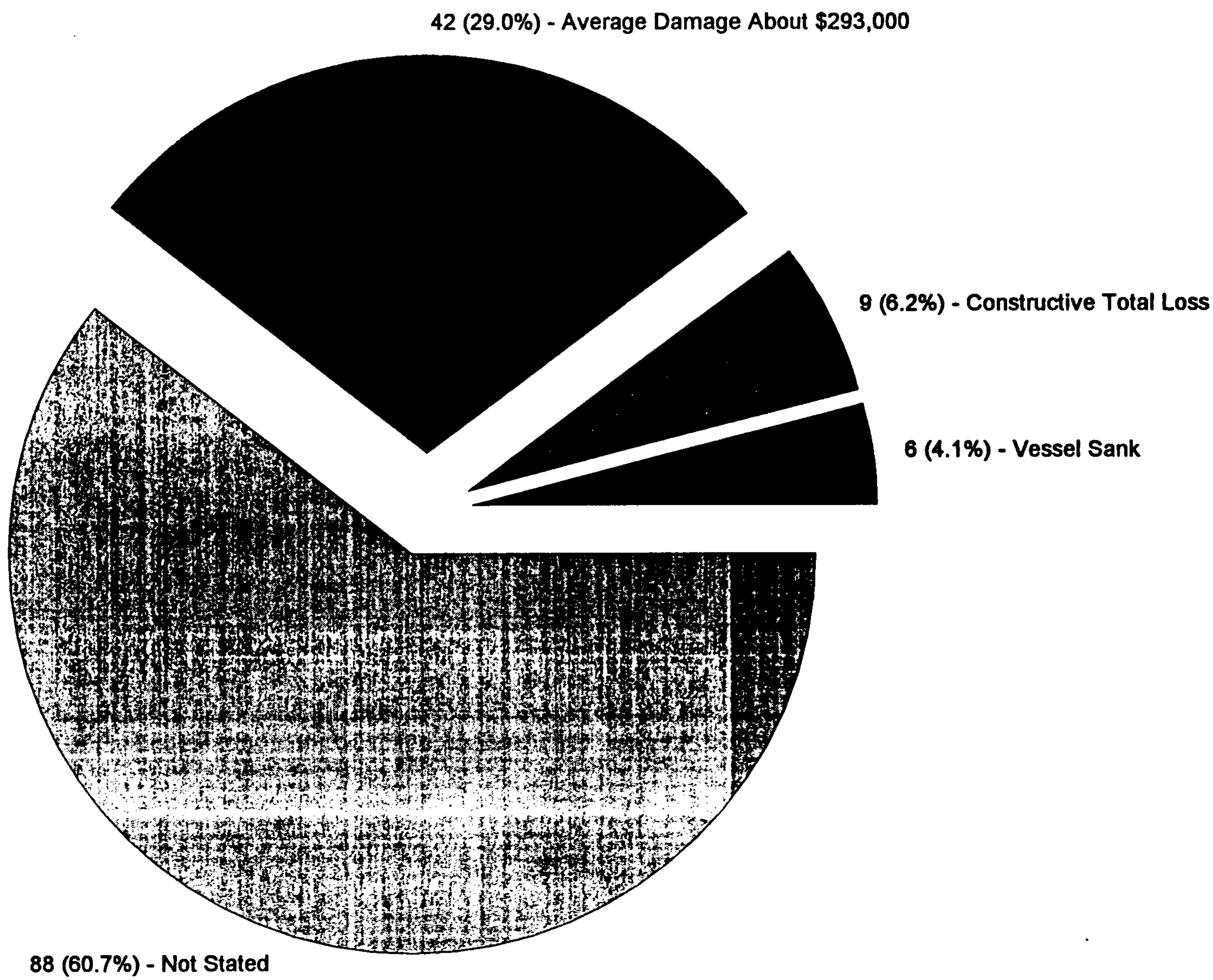

Figure 3.14 Impact on Propulsion/Steering: All Oil Fires

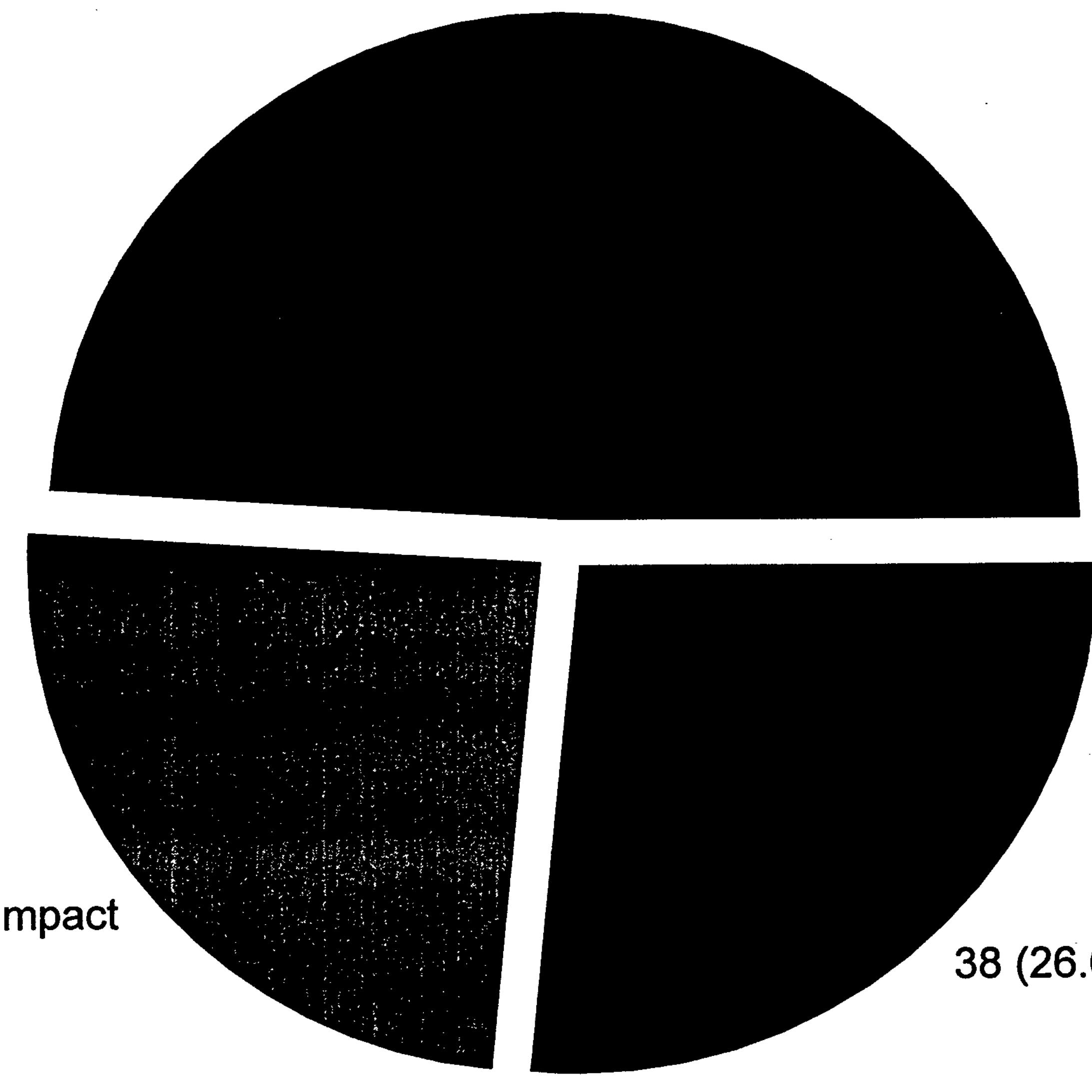

Figure 3.15 Expected Factors of Improvement for Preliminary Recommendations (All Oil Fires)

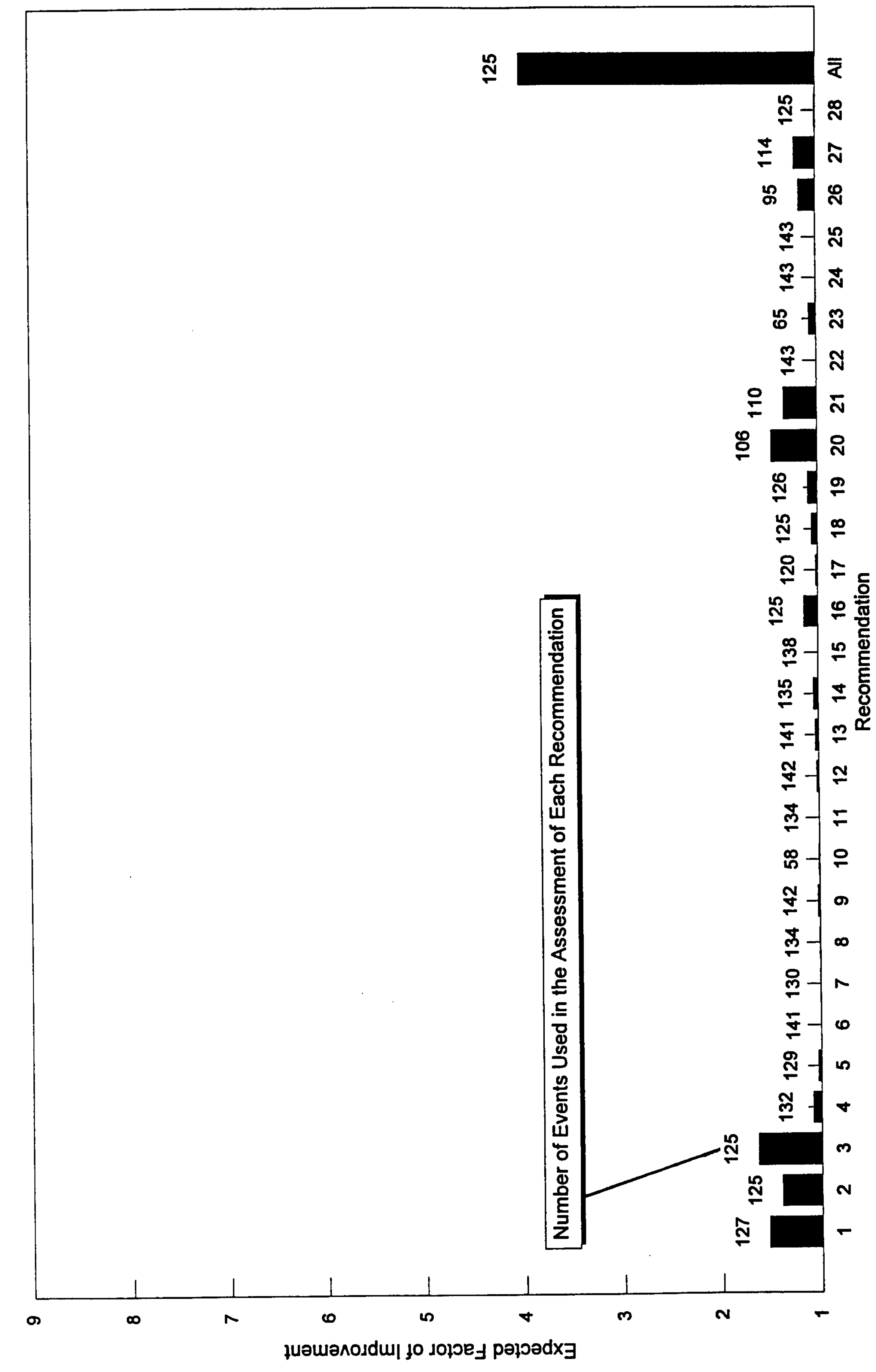

Figure 3.16 Expected Factors of Improvement for Preliminary Recommendations (All Fires with Injury or Fatality)

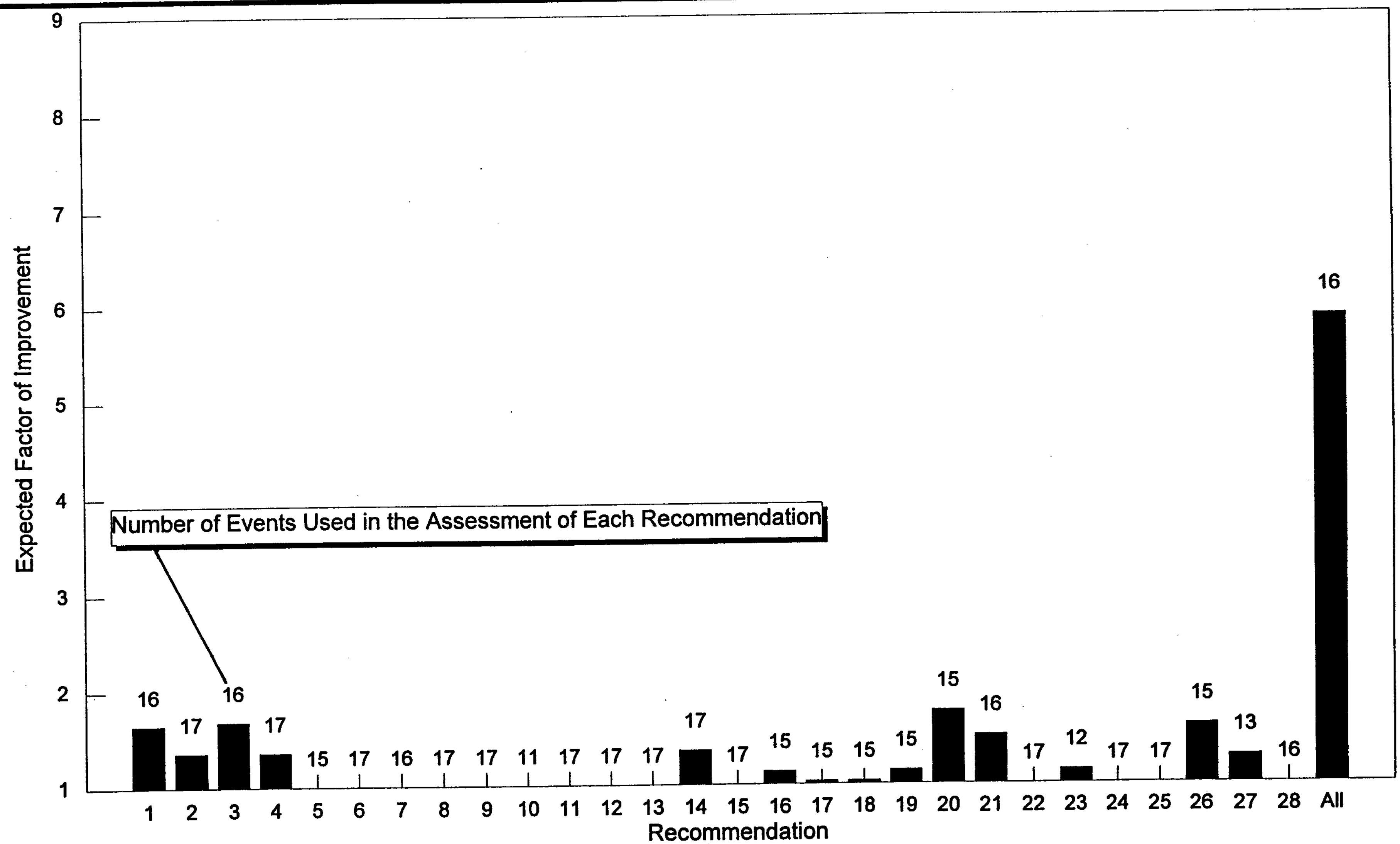

Figure 3.17 Expected Factors of Improvement for Preliminary Recommendations
(All Fires with Fatality)

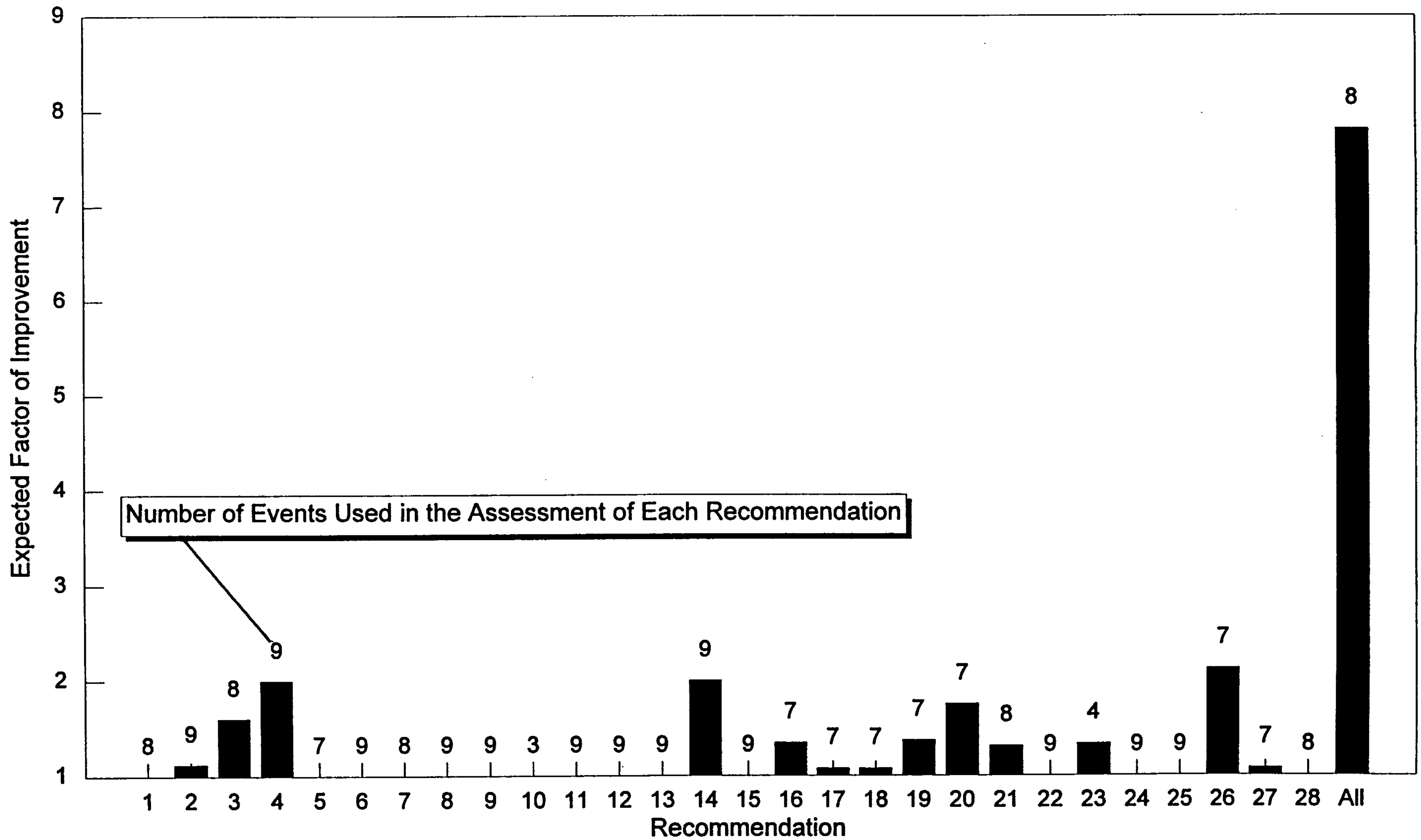

Figure 3.17 shows similar results for the impact of preliminary recommendations on fires with fatality. In this case, the individual impact of some of the preliminary recommendations (i.e., 4, 14, and 26) is about 50% reduction in the frequency of fatal fires (factor of 2 improvement). Also, the combined impact of all preliminary recommendations is a factor of about 8 improvement (reduction of the frequency of incidents to 13% of its frequency without the benefits of these recommendations), primarily because of preliminary recommendations 3, 4, 14, 16, 19, 20, 21, 23, and 26.

3.7 Miscellaneous Results and Observations — The NK Report (Reference 19) investigated actual conditions and causes of more than 70 engine room fires in NK-classed ships during 13 years from 1980 to 1992, and it provided several insights that were substantiated by our investigation. This subsection presents these useful insights.

First, the NK report indicated that there is no correlation between the number of fires and the ***age*** of ships. While we have not obtained sufficient data to statistically verify this claim, our analysis of the causes of fuel oil/lube oil spray fires (Subsection 3.1) does indicate that these fires are not directly associated with age. For example, Figure 3.1 shows that almost 25% of all releases resulted from personnel error during inspection or maintenance. Another 10% resulted from personnel error and/or equipment failure during (1) preparation for inspection or maintenance or (2) restoration to service after inspection or maintenance. Many of these incidents were caused by a lack of understanding of the design and operation of vessel systems and components, and they can certainly happen any time in the life of a ship. This helps explain the lack of correlation between the number of spray fires and the ship's age.

In addition, Figure 3.1 shows that 20% of the releases were attributed to incorrect design, deficiencies in manufacturing, and/or errors during installation. One might expect that these types of causes of fires would affect newer ships more than older ships. Thus, it would appear that the frequency of these fires should decrease with the ship's age. However, several spray fires were attributed to incorrect design, deficiencies in manufacturing, and/or errors during installation deficiencies *following ship modifications* (not following initial design and commissioning). That is, ship modifications allow these types of deficiencies to be introduced throughout the life of a ship, thereby helping explain the lack of correlation between the number of spray fires and the ship's age.

Second, the NK report indicated that there is no correlation between the number of fires and the ***size*** of ships. Specifically, the NK report presented a figure (Reference 19, page 8) that shows similar probabilities of fires on board ships with gross tonnage from 500 tons to 50,000 tons. Again, while we have not obtained sufficient data to statistically verify this claim, our investigation revealed similar fuel oil/lube oil fires on board ships of many sizes. For example, Appendix A presents 55 releases involving Coast Guard vessels, which are relatively small compared to the vessels considered in most of the other appendixes.

Third, the NK report indicated that there is little correlation between the number of fires and the ***kind*** of ship (cargo, oil tanker, LPG tanker, chemical tanker, reefer carrier, car carrier, bulk carrier, etc.), except for a slightly higher probability of fire on board reefer carriers and car carriers. (According to the NK report, fires often occurred on these carriers with small engine room spaces.) Our investigation revealed very similar fuel oil/lube oil fires on board many kinds of ships, including fishing (e.g., both incidents documented by TSB of Canada, Appendix E), tanker (e.g., the first incident documented by MIIU of Australia, Appendix F), Coast Guard vessels (all incidents documented by the Coast Guard, Appendix A), and tug/tow (many of the incidents documented by MSIS of the U.S., Appendix B).

Fourth, the NK report indicated that there is no correlation between the number of fires and ship ***nationality***. Specifically, the NK report presented a figure (Reference 19, page 21) that shows similar probabilities of fires on board ships from Japan, Panama, Liberia, Cyprus, Philippine, etc. Our investigation revealed very similar fuel oil/lube oil fires on board ships of many nationalities, including Australia (e.g., the third incident documented by MIIU of Australia, Appendix F, page F-17), Canada (e.g., both incidents documented by TSB of Canada, Appendix E, pages E-5 and E-11), Liberia (e.g., the first incident documented by NTSB of the U.S., Appendix G, page G-5), New Zealand (e.g., the second incident documented by MIIU of Australia, Appendix F, page F-11), Norway (e.g., the first incident documented by MIIU of Australia, Appendix F-5), and the U.S. (e.g., all incidents documented by the Coast Guard, Appendix A, and most incidents documented by MSIS of the U.S., Appendix B).

Fifth, the NK report did not mention the potential benefits of installing mist detectors in the engine room to help alert the crew to the presence of an oil spray. (It has been postulated by others that mist detectors can be strategically located in the engine room to indicate these hazardous conditions [Reference 6].) Our investigation revealed a different conclusion in this regard, at least for safety-related spray fires (i.e., fires that can result in personnel injury/fatality). Specifically, we observed that most safety-related oil spray fires in engine rooms occur during maintenance activities while the crew is in the engine room. These fires tend to ignite very quickly (in a matter of seconds in many cases). There is often insufficient time for crew evacuation, thereby resulting in personnel injury/fatality. Crews need no device or alarm to alert them to the presence of an oil spray in these cases. On the other hand, oil sprays that do not ignite quickly have a tendency to not ignite at all. *Thus, mist detectors would not have helped prevent or mitigate safety-related fuel oil/lube oil fires in the engine room.* The same conclusion also appears correct for non-safety-related spray fires (i.e., fires that cause equipment/vessel damage but do not result in personnel injury/fatality).

4. *RECOMMENDATIONS*

This section presents feasible, practical control measures to reduce risks associated with fuel oil/lube oil spray fires in engine rooms. Specifically, based primarily on the information provided in Appendix H and the results presented in Subsection 3.6, we developed a total of 18 recommendations for reducing the risks. They are presented in four separate subsections:

- ***4.1 — Specific recommendations for existing ships***
- ***4.2 — Specific recommendations for new ships***
- ***4.3 — Specific recommendations for additional research***
- ***4.4 — General recommendations for improved management practices***

Subsection 4.1 presents 12 recommendations that address specific changes to existing fuel oil/lube oil equipment and systems and specific changes to management issues, including improvements to inspections and maintenance, safe work practices, training, and emergency response. Subsection 4.2 presents three recommendations that address more significant changes to fuel oil/lube oil equipment in engine rooms. Because they may be too difficult to retrofit to existing ships, they are presented for new (or significantly modified) ships.

We also identified two areas that require additional research and development efforts; Subsection 4.3 presents the two recommendations addressing these areas. Finally, our investigation of the causes of previous incidents revealed that much of the risk associated with fuel oil/lube oil spray fires stems from deficiencies in (or lack of) safety and reliability management systems. That is, the root cause of these incidents is generally the absence of, neglect of, or deficiencies in the management systems. Subsection 4.4 presents a general recommendation for ship operators to ensure that their management practices address all elements suggested in industry standards and guidelines.

For each of the following recommendations, an estimated potential reduction in the frequency of spray fires is presented. This estimate represents the reduction for that particular recommendation. Cumulative estimates were not calculated for multiples of these recommendations.

4.1 Specific Recommendations for Existing Ships — This section presents 12 recommendations that address specific changes to existing fuel oil/lube oil equipment and systems and specific changes to management issues.

Recommendation 1: Sheath, cover, or provide deflector shielding for fuel oil/lube oil piping, tubing, and hoses (particularly fittings, flanges, and flexible joints) in high pressure service and/or that are attached to diesel engines, pumps, turbochargers, boilers, or oil tanks. Deflector shields should also be provided for equipment flanges such as the cover flanges on strainers, filters, coalescers, and purifiers used in fuel oil/lube oil systems. In the case of fuel oil injection tubing for diesel engines, tubing should be fastened on both ends to prevent movement in case of catastrophic failure, and a deflector shield should be provided on each side to help divert sprays away from hot surfaces (e.g., exhaust manifold and pipe).

Discussion: Specific ways of implementing this recommendation include providing secondary pipe or hose (e.g., for fuel oil lines on large diesel engines), spray-preventing tape, insulation/lagging, and a flange deflector shield. These control measures may prevent leaks in fuel oil/lube oil systems from spraying into the surrounding areas. This recommendation is consistent with recent changes to international regulations (References 3 and 4):

> Paragraph 2.6.9: *All external high pressure fuel delivery lines between the high pressure fuel pumps and fuel injectors shall be protected with a jacketed piping system capable of containing fuel from a high pressure line failure. A jacketed pipe incorporates an outer pipe into which the high pressure fuel pipe is placed forming a permanent assembly. The jacketed piping system shall include a means for collection of leakages and arrangements shall be provided for an alarm to be given of a fuel line failure.*

> Paragraph 2.6.11: *Oil fuel lines shall be screened or otherwise suitably protected to avoid as far as practicable oil spray or oil leakages onto hot surfaces, into machinery air intakes, or other sources of ignition...*

(Paragraph 3 of Reference 3 extends the second item above to lube oil systems. However, Paragraph 2.6.9 does not apply to lube oil piping.) This recommendation is also consistent with recently developed international guidelines (Reference 5):

> Appendix 1, Section 4.3: *Any fuel, lubricating or hydraulic oil leakages should be dealt with promptly. The screening arrangements and pipe securing devices should be kept in good order.*

> Appendix 3, Item 2: *Spray shields are intended for use around flanged joints, flanged bonnets and any other flanged connection in oil pressure systems which are located above the floor plates and which have no insulation in way of the joints. The purpose of spray shields is to prevent the impingement of leaked or sprayed flammable liquid onto a hot surface or other source of ignition.*

However, there are potential limitations associated with this recommendation. First, sheathing often needs to be removed before performing equipment maintenance, which makes it ineffective during maintenance (several fires occurred when the crew was performing maintenance on the equipment). Second, it may not be possible to sheath all fuel oil/lube oil piping, tubing, and fittings. For example, it may be difficult to sheath the lube oil piping to turbochargers. Also, at least for some engine types and sizes, it may be difficult to sheath the nozzles and fittings on either side of the engine injection tubing. Finally, maintenance personnel may fail to reinstall sheathing after maintenance or may reinstall it incorrectly. (Sheathing can be useful in helping prevent fires, but it requires strict control to be effective.)

The expected impact of implementing this recommendation is about 30% reduction in the frequency of spray fires and 25% reduction in the frequency of fires involving injury or fatality.

Recommendation 2: Sheath hot surfaces (e.g., engine exhaust manifold or pipe, turbine casing, turbocharger casing, steam line) in the vicinity of fuel oil/lube oil systems.

Discussion: Hot surface is by far the most common source of ignition of sprays of fuel oil/lube oil in engine rooms. Sheathing these surfaces should help prevent contact of fuel/lube oil with hot surfaces, thereby reducing the probability of ignition. This recommendation is consistent with recent changes to international regulations (References 3 and 4):

> Paragraph 2.6.10: *All surfaces with temperatures above 220 °C which may be impinged as a result of a fuel system failure shall be properly insulated.*

(Paragraph 3 of Reference 3 extends the item above to lube oil systems.) This recommendation is also consistent with recently developed international guidelines (Reference 5):

> Appendix 1, Item 4.2: *When maintenance or repair to the main or auxiliary engines has been carried out, checks should be made to ensure that the insulation covering the heated surfaces has been properly replaced. A regular check of the engines should be made to confirm that the insulation is in place*

> Appendix 7, Item 3: *Manufacturers' instructions [for insulation installation] should be followed if available. Permanent insulation should be used to the greatest extent possible. Insulation should be provided with readily removable sections to allow access for normal maintenance. Where the insulation used is oil absorbent or may permit the penetration of oil, the insulation should be encased in steel sheathing or equivalent material.*

> Appendix 7, Item 4: *A regular check of equipment should be made to confirm that the insulation is in place. When maintenance or repair to equipment has been carried out, checks should be made to ensure that the insulation covering the heated surfaces has been properly replaced.*

To achieve maximum benefits, all hot surfaces near potential sources of oil sprays (e.g., strainers) in the engine room should be insulated. It may be necessary to measure the temperature on potential hot surfaces (e.g., steam pipe hangers) to determine whether sheathing is necessary.

However, there are potential limitations associated with this recommendation. Specifically, maintenance personnel sometimes fail to reinstall sheathing after maintenance. (Sheathing can be useful in helping prevent fires, but it requires strict control to be effective.) Recommendation 17 discusses another potential limitations associated with this recommendation.

The expected impact of implementing this recommendation (along with Recommendation 17) is about 38% reduction in the frequency of fatal incidents from spray fires.

Recommendation 3: Provide deflector shielding (e.g., metal plate) between the fuel oil/lube oil strainer, filter, coalescer, or purifier (which can be sources of fuel oil/lube oil sprays) and potential sources of ignition (e.g., engine exhaust manifold or pipe, turbine casing, turbocharger casing, steam line). Shielding should be installed in a way that it does not have to be removed for performing equipment maintenance, which would make shielding ineffective during maintenance (several fires occurred when the crew was performing maintenance on the equipment). Alternatively, provide physical separation and/or partitions between these devices and potential sources of ignition. (For example, purifiers are often located in a separate room.)

Discussion: Hot surfaces are by far the most common source of ignition of sprays of combustible liquids in engine rooms. Providing deflector shielding between the potential sources of sprays and the potential sources of ignition should help prevent direct contact of sprays with the most common source of ignition. This should help reduce the probability of ignition. However, there are potential limitations associated with this recommendation. Specifically, maintenance personnel sometimes fail to reinstall shielding after maintenance. (Shielding can be useful in helping prevent fires, but it requires strict control to be effective.)

The expected impact of implementing this recommendation is about 50% reduction in the frequency of fatal incidents from spray fires.

Recommendation 4: Duplex devices such as strainers, filters, or coalescers should not be opened when the fuel oil/lube oil system is in operation and pressurized. This can be accomplished administratively (i.e., never allow opening the devices when the oil system is pressurized).

Discussion: Among the oil fires documented in Attachments A through G, duplex strainers, filters, or coalescers have been involved in about 13% of all fires, 30% of the fires with injury or fatality, *and 55% of fires with fatality.* Most of these incidents involved a crew member opening one of these devices (usually a duplex strainer) when the fuel oil/lube oil system was under operation and pressurized.

The expected impact of implementing this recommendation (and/or Recommendation 15) is about 50% reduction in the frequency of fatal incidents from spray fires.

Recommendation 5: Provide fine-water mist systems for local application on selected equipment areas in engine rooms, including diesel engine, turbocharger, and duplex strainer/filter/coalescer areas. Both remote and local actuation capability should be provided, and the local actuator should be easy to operate (e.g., similar to the actuators for safety showers and eyewashes). (Other Coast Guard research has shown that local application of fine water mist can be effective in extinguishing spray fires. [Reference 21])

Discussion: Most fatal incidents described in Attachments A through G happened very fast (typically within seconds), and crew members had little or no time to react. It is clear in several of these cases that a readily accessible mist system could have helped the crew to evacuate the engine room. Also, there are many other fires (with no fatalities) in which the crew detected the fire at a relatively early stage but were unable to control it with portable extinguishers. These fires expanded and caused significant damage. Again, it appears that a mist system could have prevented these fires from turning into larger, more costly fires.

The expected impact of implementing this recommendation is about 53% reduction in the frequency of fatal incidents from spray fires.

Recommendation 6: Ensure that all alterations (i.e., modifications that are not replacements in kind [RIK])[i] to fuel oil/lube oil systems are unambiguously posted/logged for the other chief engineers and for the company records. These alterations should be reviewed by the company (e.g., at arrival in the next port) and during inspections by administrations (e.g., Coast Guard) and classifications societies.

Discussion: Ships sometimes undergo changes (e.g., to increase efficiency and accommodate technical innovation). Also, on occasion, temporary repairs, connections, bypasses, or other modifications may be made out of necessity. Any of these changes can introduce new hazards or compromise the safeguards built into the original design. For example, a fire on board the SEAL ISLAND (Event NTSB01 in Attachment G) resulted in the death of three crew members and serious injury to six other crew members. The NTSB determined that the probable cause of the fire on board the SEAL ISLAND was the chief engineer's failure to recognize the risks introduced by a *temporary repair* to the engine room oil strainer.

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[i]RIK is an item (equipment, procedure, etc.) that meets the design specification of the item it is replacing. This can be an identical replacement or any other design alternative specifically provided for in the design specification, as long as the alternative does not in any way adversely affect the use of the item or associated items.

As another fatal example, the NK report documents an incident (Event NK04 in Attachment D) that involved a crew member replacing a steel portion of a fuel oil mixing column pipe work with a pipe made of plastic. The plastic pipe ruptured during operation, resulting in a fire that killed one crew member. Preventing the use of nonapproved parts in fuel oil and lube oil systems should reduce the frequency of these types of accidents.

However, there are potential limitations associated with this recommendation. Specifically, many repairs of fuel oil and lube oil systems result from failures that occur while the ship is underway. Crew members often have to improvise if spare parts and equipment are not available. Documentation of alterations should improve the chances that unsafe conditions introduced by the alteration will be detected and corrected. However, detection and correction may take some time (e.g., when the ship reaches the next port). Unfortunately, in some cases, the unsafe conditions cause failures shortly after the repair is performed. (Incident NK04 is a good example of an incorrect repair causing a fatal incident shortly after the repair was completed.) The effectiveness of this recommendation is reduced in this case.

The expected impact of implementing this recommendation is about 7% reduction in the frequency of fatal incidents from spray fires.

Recommendation 7: Ensure that standard operating procedures (SOPs) are developed and implemented to (1) operate duplex strainers/filters/coalescers in fuel oil/lube oil systems (SOPs should be posted at the device location), (2) operate (startup, shutdown, etc.) propulsion and auxiliary boilers, and (3) fill fuel oil/lube oil tanks in machinery spaces. SOPs should include all phases of operation, the hazards associated with the procedure, and the personal protective equipment (PPE) that should be used.

Discussion: It is widely recognized that a set of SOPs can help reduce the likelihood of human errors (Reference 22). Providing these SOPs on board ships is crucial because personnel errors are significant contributors to the risk associated with pressurized oil systems. In fact, several engine room fires resulted from personnel errors during operation of fuel oil/lube oil equipment (e.g., replacing strainer elements). To reduce the frequency of these types of incidents, the NK report recommended written, step-by-step procedures for operating strainers and purifiers (Reference 19). (The procedures should be available at the location of the equipment.)

The NK report also documents several engine room fires (NK17 through NK21 in Attachment D) that were initiated by malfunction of the boiler burner. These malfunctions resulted in explosion, damage to expansion joints in the fuel oil system, and subsequent fire. The NK report suggested that the frequency of occurrence of these explosions can be reduced by providing adequate purging of the furnace before startup. One way to help ensure adequate purging is to write (and enforce) the steps, including purging, required for safe startup of the furnace.

Another fire (NK27 in Attachment D) occurred during replenishment of fuel in a double bottom fuel tank. After replenishment, the oil remaining in the piping system was purged with air, but the air space in the tank was insufficient for the purging operation because the tank was overfilled. (Also, there is a high probability of fuel oil overflowing due to changes in trim and heel, sea conditions, and changes in temperature.) To prevent this type of incident, the NK report suggests procedural controls (i.e., fuel oil tanks should not be filled above 90% to 95% of the tank's capacity). Again, one way to help ensure adherence to procedural steps is to write the steps required for safe operation, including safe operating limits (e.g., maximum tank level).

As a last example of the importance of adequate procedures, the Australian Marine Incident Investigation Unit (MIIU) investigated the fire on board the fishing vessel NORTHERN L (MIIU03). MIIU concluded that the "quality of the operational procedures and standards practiced (or not practiced) aboard the NORTHERN L created the conditions in which accidents were more likely to occur, and where emergencies were more likely to get out of hand."

The different types or procedures that should be documented include inspection, test (e.g., for standby systems), and maintenance. They should consider: (1) all phases of operation (e.g., startup, normal, shutdown, temporary, emergency), (2) the hazards associated with the procedure, (3) the safe operating limits (e.g., maximum oil tank inventory), (4) PPE required, (5) the consequences of deviating from the procedural steps (skipping or performing incorrectly), and (6) actions required to correct or avoid deviations. However, there are potential limitations associated with this recommendation, such as difficulties with language. For example, an engine room crew may be composed of Italian nationals and Philippine nationals. Crew members would use their native language to communicate among themselves and English as the common language for communication between the different nationalities. Also, some of the manuals on board could be in German if the equipment was made in Germany.

The expected impact of implementing this recommendation is about 7% reduction in the frequency of fatal incidents from spray fires.

Recommendation 8: Establish and implement safe work practices for fuel oil/lube oil systems (particularly duplex devices such as strainers, filters, and coalescers), including safety policies for (1) wearing personal protective equipment and ensuring availability of breathing apparatuses and fire protection equipment, (2) isolating equipment for inspection and maintenance (e.g., replacing elements in duplex strainers), (3) verifying that the equipment is depressurized, including labels and warning signs posted at the equipment location, (4) providing means (e.g., vents, bleeders, gauges) to verify depressurization of equipment that is isolated for inspection/maintenance, (5) ensuring that all vent/bleeder valves for fuel oil/lube oil equipment are self-closing valves and that these valves are plugged or capped when not in use, and (6) ensuring that the discharge of all vent and bleed valves are routed to a safe location.

Discussion: MSIS22 in Attachment B describes a fatal incident that resulted from following unsafe practices in preparation of a vessel for the winter (crew member was using a handheld torch to warm up and unplug an oil transfer line). Other fires resulted from inadequate preparation of the equipment for maintenance (i.e., release of pressurized liquid when the equipment is opened for maintenance). In some instances, no means (pressure gauge, vent/bleed valve, etc.) were available to allow the crew to verify that the equipment was depressurized and properly isolated for maintenance. In fact, the NK report recommends that means should be provided to verify that high pressure equipment, particularly fuel oil and lube oil strainers, are depressurized before opening the equipment for maintenance.

However, there are potential limitations associated with this recommendation. Specifically, regarding verification that equipment (e.g., strainer) is depressurized, some instruments may not work properly in some services. For example, a pressure gauge can plug in dirty-oil service. Also, providing the means to verify that the equipment is depressurized does not ensure that the crew will perform this verification. This recommendation requires adequate training of personnel and strict controls to ensure that personnel follow established procedures.

The expected impact of implementing this recommendation is about 27% reduction in the frequency of fatal incidents from spray fires.

Recommendation 9: Supplement periodic training of engine room personnel with a short video on the hazards of fuel oil/lube oil systems, including (1) synopses of some of the most catastrophic incidents (e.g., SEAL ISLAND), (2) typical causes, equipment involved, ignition sources, and consequences of spray fires, and (3) the relatively high risk of lube oil compared to fuel oil.

Discussion: Several fires in the engine room resulted from human errors during operation and/or maintenance of equipment (e.g., strainer). It is clear in many cases that the crew did not know how to safely perform the activity. Also, it is clear that they did not fully understand the hazards associated with operating/maintaining the equipment. This is particularly true for the operation of fuel oil and/or lube oil strainers (i.e., replacement of the strainer element). In fact, the NK report recommended providing training for operating and maintaining strainers and purifiers. In addition, improved training is the most common "corrective action" listed for the incidents in Attachment A. (Attachment A contains the MISREP reports, which are usually more complete [compared to the reports in the other attachments] regarding corrective actions to prevent recurrence.) This indicates that there may be significant deficiencies in training programs for many ships.

The crew must be trained to work safely, including specific training in the written procedures, safe work practices, and emergency response and control measures. Industry regulations and standards generally request initial training, periodic (refresher) training, and training certification programs. In addition, industry regulations and standards request that whenever a change is made, all affected personnel should be trained or otherwise informed of the change before implementing the change.

The expected impact of implementing this recommendation is about 43% reduction in the frequency of fatal incidents from spray fires.

Recommendation 10: Ensure that the inspection and maintenance programs for fuel oil/lube oil equipment includes (1) demonstration of the operation of three-way transfer valves in duplex strainers/filters/coalescers (these valves must move easily for one person without the need for impact [as from a hammer or a foot] or leveraging [as with a length of pipe or other temporary extension of the valve handle]), (2) periodic inspection and replacement of hoses, tubings and fittings on diesel engines and turbochargers, and (3) provisions for periodic inspection of devices that prevent sprays of oil (covers, deflector shields, tapes, plugs/caps for vent and drain valves, etc.) and devices that prevent oil sprays from contacting hot surfaces (insulation, lagging, etc.), including ensuring that these protections are reinstalled whenever they need to be removed for maintenance.

Discussion: This recommendation was originally a recommendation for developing and implementing a program for ensuring quality and mechanical integrity of fuel oil/lube oil systems and related safety systems and equipment (see Management Practice 7 in Table 4.1). However, many elements of quality and mechanical integrity programs are already in place in the shipping industry. Thus, we adapted the original recommendation to emphasize deficiencies that exist (as indicated by the incidents in Attachments A through G) in the shipping industry. This recommendation is consistent with recently developed international guidelines (Reference 5):

> Appendix 1, Item 4.1: *Many fires have been caused by pipe connections and fittings working loose. The fuel, lubricating and hydraulic oil pipes, their fittings, connections and securing arrangements should be routinely checked. Care should be taken not to overtighten fittings during these checks.*

> Appendix 2, Item 4: *Hoses should be installed in accordance with the manufacturers instruction, having regard to: minimum bend radius, twist angle and orientation, also support where necessary. In locations where hoses are likely to suffer external damage, adequate*

protection should be provided. After installation, the system should be operated at maximum pressure and checked for possible malfunctions and freedom from leaks.

Appendix 5, Item 4: *Bellows expansion joints should be inspected regularly and be replaced whenever there is doubt as to their suitability to continue in service.*

Appendix 8, Item 3: *Copper gauge piping is particularly sensitive to work-hardening. All gauge pipes and fittings should be regularly inspected and maintained in good working order.*

The expected impact of implementing this recommendation is about 24% reduction in the frequency of fatal incidents from spray fires.

Recommendation 11: All ships should (1) provide readily accessible emergency breathing apparatus to facilitate escape from engine rooms and (2) conduct periodic engine room fire and evacuation drills. The International Maritime Organization (IMO) should develop a standard for engine room fire and escape drills.

Discussion: This recommendation was originally a recommendation to ensure that an emergency response and control program is developed and implemented, including addressing emergencies involving systems containing pressurized fuel oil/lube oil. However, regulations and practices in the shipping industry require emergency action plans with assigned authority to the appropriate persons, evacuation procedures, and training/drills. Therefore, we modified this recommendation to focus on selected issues that may not be completely addressed in current practices and regulations. Specifically, based on the incidents documented in Attachments A through G, it is evident that emergency action plans have been inadequate for emergencies initiated by or involving fuel oil/lube oil systems in the engine room. In fact, many incident investigation teams have identified deficiencies during fires on board vessels. For example, an NTSB incident investigation team proposed the following specific recommendations regarding the fire on board the SEAL ISLAND (some of these recommendations were also made regarding the fires on board the STONEWALL JACKSON and BAY STATE) (Reference 20):

1. All ships should maintain readily accessible emergency breathing apparatus to facilitate escape from the engine room
2. Conduct periodic engine room fire and escape drills
3. IMO should develop a standard for engine room fire and escape drills that will include, at a minimum, how to locate and don breathing apparatus and how to find and use emergency exits in simulated fire conditions

4. Test all modes of fire pump starting systems, including electric, hydraulic, and pneumatic, during fire and boat drills

The expected impact of implementing this recommendation is about 25% reduction in the frequency of fatal incidents from spray fires.

Recommendation 12: Ensure that hazard analyses are performed for systems containing pressurized fuel oil or lube oil. The hazard analyses should consider human factors, previous incidents, and equipment location issues. These should also address all phases of operation (startup, shutdown, maintenance, temporary operations, etc.).

Discussion: The objective of these hazard analyses should be to minimize the likelihood of the occurrence of spray incidents, and this is accomplished by systematically identifying and evaluating all equipment/systems that contain pressurized fuel oil/lube oil (Reference 23). Special consideration should be given to human factors, previous incidents, and equipment location issues, and hazard analyses should consider all phases of operation (startup, shutdown, maintenance, temporary operations, etc.).

Regulations for other industries (e.g., petrochemical industry) and industry standards generally request initial hazard analyses and periodic reviews and updates. Also, these regulations and standards request that:

1. the hazard analysis be performed by a team knowledgeable in engineering, operations, design, safety, environmental, and other specialties (e.g., fire protection), as appropriate, and
2. at least one member of the hazard analysis team should be proficient in the hazard analysis methodologies used.

The hazard analysis team considers this recommendation one of the most useful in reducing spray-related risks. This is primarily because many of the causes and contributing factors to spray fires are typical of hazards considered in a hazard analysis. Thus, several of these incidents might have been avoided if periodic hazard analyses had been performed on these ships.

The expected impact of implementing this recommendation is about 26% reduction in the frequency of fatal incidents from spray fires.

4.2 Specific Recommendations for New Ships — This section presents three recommendations that address significant changes to equipment in engine rooms. They are presented for consideration in new designs or for ships that are undergoing significant modifications.

Recommendation 13: Use diesel engines, fuel oil pumps, and lube oil pumps with integrated channels for fuel oil and/or lube oil (i.e., monolithic equipment housing that integrates fuel oil/lube oil piping, particularly the discharging piping).

Discussion: Failure of tie-in piping has caused several fires in engine rooms. Eliminating/reducing tie-in piping, including associated flanges, valves, etc., should help reduce the frequency of these fires. However, there are limitations associated with this recommendation. Specifically, this recommendation would reduce the piping that is under the control of the manufacturer (i.e., the piping that comes with the engine skid or pump skid). However, it does not affect piping outside the engine skid (e.g., piping from the oil tanks to strainers and filters, and piping from strainers and filters to the engine). Also, this type of engine may still require gauges (e.g., temperature, pressure) and associated lines to the engine's passage ways. These instruments and instrument lines are still susceptible to failure caused by equipment failure or human error. That is, tie-in piping can be reduced but not necessarily eliminated. Finally, these types of engines and pumps (1) may not be available for all applications (e.g., for all engine and pump sizes), (2) may not operate efficiently and reliably for all types of fuel oil or lube oil, and (3) may require excessive maintenance in some applications.

The expected impact of implementing this recommendation is about 35% reduction in the frequency of spray fires.

Recommendation 14: When instrument signals (e.g., pressure indication) from fuel oil/lube oil systems are sent to gauge boards (either a local board by the engine or a central board), pneumatic/electronic transducers should be used near the instrument tap to avoid lengthy runs of tubing or piping containing oil.

Discussion: The MSIS database describes an engine room fire (see MSIS24 in Attachment B) that resulted from an instrument line failure. (The line that failed had been replaced 2 days before the incident, and it failed because the crew used a plastic line instead of the original plastic-coated steel line.) While other databases (i.e., other than MSIS) have not reported similar incidents, most of the databases have several incidents involving "line cracked" or "line failed." It is possible that some of these incidents were in fact lengthy instrument lines.

Recommendation 15: Duplex devices such as strainers, filters, or coalescers should not be opened when the fuel oil/lube oil system is in operation and pressurized. On new installations, parallel simplex devices (with double-blocking shutoff and bleed valve arrangements) or, when commercially available, self-cleaning (e.g., backwash type) devices can be used.

Discussion: Among the oil fires documented in Attachments A through G, duplex strainers, filters, or coalescers have been involved in about 13% of all fires, 30% of the fires with injury or fatality, *and 55% of fires with fatality.* Most of these incidents involved a crew member opening one of these devices (usually a duplex strainer) when the fuel oil/lube oil system was under operation and pressurized. These incidents are much more unlikely to happen with parallel simplex devices (with double-blocking shutoff and bleed valve arrangements) or, when commercially available, self-cleaning (e.g., backwash type) devices. This recommendation is consistent with recently developed international guidelines (Reference 5):

Appendix 6, Item 2: *Filters and strainers should be designed such that they cannot be opened when under pressure.*

The expected impact of implementing this recommendation (and/or Recommendation 4) is about 50% reduction in the frequency of fatal incidents from spray fires.

*4.3 **Specific Recommendations for Additional Research*** — Our analysis has identified two areas that require additional research and development efforts. This section presents the two recommendations for this additional research.

Recommendation 16: Develop guidelines for fuel oil/lube oil fittings and nipples used in high-pressure marine applications. The guidelines should address fittings/nipples on engine-mounted equipment as well as on piping, strainers, and other equipment used in high-pressure fuel oil/lube oil systems.

Discussion: Among the oil fires documented in Attachments A through G, skid piping, tubing, and hoses mounted on engine/pump skids have been involved in about 38% of all fires and 44% of the fires with injury or fatality. Many of these events were the result of failures of fittings (e.g., a flare fitting) and nipples. It is often clear in the incident description that more robust fittings and nipples would have helped prevent the incident.

The expected impact of implementing this recommendation is about 18% reduction in the frequency of spray fires and 22% reduction in the frequency of fires involving injury or fatality.

Recommendation 17: Review existing design specifications and installation guidelines for insulation/lagging to ensure that these specifications and guidelines include provisions for preventing ignition (e.g., oil-repellant paint, positioning of seams away from potential sources of spray, covering of any openings in the insulation/lagging for instrument and valve line).

Discussion: Hot surface is by far the most common source of ignition of sprays of fuel oil/lube oil in engine rooms. Sheathing these surfaces should help prevent contact of fuel oil/lube oil with hot surfaces, thereby reducing the probability of ignition. To achieve maximum benefits, all hot surfaces near potential sources of oil sprays (e.g., strainers) in the engine room should be insulated. It may be necessary to measure the temperature on potential hot surfaces (e.g., steam pipe hangers) to determine whether sheathing is necessary. However, there are potential limitations associated with this recommendation. First, sheathing is typically provided to help (1) protect personnel from burn hazards and (2) reduce the heat load on ventilation systems. Therefore, sheathing will not necessarily cover all hot surfaces that could be sources of ignition. For example, there may be openings in the insulation/lagging for instrumentation and vent/drain valves. An oil spray could infiltrate through these openings and ignite.

As another example, sheathing is not required for personnel protection if the hot surface is out of reach for personnel; insulation is typically provided for steam piping and steam turbine casing, but it may not be provided for the pipe hangers. Second, current design specifications and installation guidelines for insulation/lagging have been developed for personnel protection and control of heat load. Therefore, they may not address issues related to preventing ignition of oil sprays. For example, while some types of lagging paint are not oil repellant and may allow soaking of insulation from oil sprays, there appear to be no specifications/guidelines for selecting paint that is oil repellant. Recommendation 2 discusses another potential limitations associated with sheathing.

The expected impact of implementing this recommendation (along with Recommendation 2) is about 38% reduction in the frequency of fatal incidents from spray fires.

4.4 General Recommendations for Improved Management Practices — It is clear from the review of the causes of previous incidents that much of the risk associated with fuel oil/lube oil spray fires stems from deficiencies in (or lack of) safety and reliability management systems. That is, the root cause of these incidents is generally the absence of, neglect of, or deficiencies in the management system. Thus, several of the 17 recommendations presented in the previous subsections suggest specific changes to management issues, including improvements to inspections and maintenance, safe work practices, training, and emergency response.

However, the previous recommendations are specific to selected issues identified during the review of incident investigation reports. While they should help prevent incidents similar to incidents that have already happened, they may not address all types of incidents that can happen in the future. Experience from other industries indicates that the best way to prevent future incidents is to implement several management systems to monitor and control hazards (References 7 through 10). Examples of management systems include a system to control changes, a system to investigate incidents, and a system to perform periodic hazard analysis. These systems are generally documented in written policies and procedures, and all affected personnel are trained to ensure that they understand and follow these policies and procedures. Recommendation 18 addresses these management issues.

Recommendation 18: Ship operators should ensure that their management practices are consistent with management practices suggested in industry standards and guidelines. Specifically, ship operators should review their management practices and ensure that they address the management practices issues presented in Table 4.1.

Discussion: This recommendation is very consistent with the position of major classification societies and the IMO. For example, DNV established the *Safety Management and Environmental Protection* rules for the certification of marine safety management in 1990 (Reference 12), and IMO adopted the ISM code in 1995 (effective July 1, 1998, for about 40,000 ships and July 1, 2002, for other types of ships) (Reference 11). Both of these efforts are aimed at reducing accidents in the shipping industry through better safety management systems. The emphasis on management systems is based on the widely accepted belief that some 80% of all accidents in the shipping industry are caused by human error, negligence, or lack of training (Reference 12). This point was perhaps best expressed by Captain Vanagt, RMT-Oostende Lines Safety Officer (Reference 13):

> *For a vessel to become substandard, one condition alone suffices; she must be under a "substandard management" ... Only by tackling substandard management itself will we get to the root of the problem, and consequently eliminate substandard vessels.*

Based on these findings, we have prepared Table 4.1, which contains 11 management practices for reducing risks associated with spray fires. These management practices are very similar to the safety and environmental management practices used in other industries that use, produce, process, or store flammable substances (oil exploration and production, oil refining, petrochemical, and chemical). We know that many ships have already implemented some of the practices suggested in Table 4.1. However, our review of the incidents in Appendixes A through G indicates that these practices are often incomplete, poorly implemented, or even nonexistent.

Table 4.1 Management Practices that Help Reduce Risks

Management Practice 1 ***Ensure that safety and reliability information is developed and maintained for all systems containing fuel oil/lube oil***
This information provides the basis for implementing several of the other management practices (e.g., Management Practices 2 and 3) suggested in this table. It should include information about the hazards (e.g., fire) posed by these systems and system/mechanical design information, including materials of construction, design basis of relief systems, design of ventilation systems, equipment and piping specifications (including diagrams), and descriptions of emergency shutdown systems
Management Practice 2 ***Ensure that hazard analyses are performed for all systems containing fuel oil/lube oil***
The objective of the hazard analysis should be to minimize the likelihood of the occurrence of spray incidents and/or mitigate the consequences of such incidents, and this is accomplished by systematically identifying and evaluating all equipment/systems that contain fuel oil/lube oil.[j] Special consideration should be given to human factors, previous incidents, and equipment location issues. Also, a hazard analysis should consider all phases of operation (startup, shutdown, maintenance, temporary operations, etc.). Regulations for other industries (e.g., petrochemical industry) and industry standards generally request an initial hazard analysis and periodic reviews and updates. Also, these regulations and standards request that (1) the hazard analysis be performed by a team knowledgeable in engineering, operations, design, safety, environmental, and other specialties (e.g., fire protection), as appropriate, and (2) at least one member of the hazard analysis team should be proficient in the hazard analysis methodologies used

[j] *Guidelines for Hazard Evaluation Procedures, Second Edition with Worked Examples*, Center for Chemical Process Safety, American Institute of Chemical Engineers, New York, NY, 1992.

Table 4.1 Management Practices that Help Reduce Risks (cont'd)

Management Practice 3 ***Ensure that a management of change (MOC) system is developed and implemented for all systems containing fuel oil/lube oil***
Ships are subject to continual changes (e.g., to increase efficiency and accommodate technical innovation). Also, on occasion, temporary repairs, connections, bypasses, or other modifications may be made out of necessity. Any of these changes can introduce new hazards or compromise the safeguards built into the original design. An MOC system identifies and controls hazards associated with changes and maintains the accuracy of safety and reliability information.[k] Examples of changes that should be considered for inclusion in the scope of MOC systems include changes to (1) system/equipment (e.g., using a different type of gasket in a fuel oil system), (2) operating, inspection, or maintenance procedures, (3) safe work practices, (4) safety-related systems (e.g., fire protection), (5) personnel (e.g., reducing the number of crew members), and (6) organization (e.g., switching from separate maintenance organizations that support selected types of ships for one company to a centralized maintenance organization that supports all ships for the company) Note: Recommendation 6 addresses specific improvements to controlling modifications that are not replacement in kind, and these improvements are expected to result in significant risk reduction. Addressing these specific improvements should be the priority while implementing this management practice

[k]M. L. Casada et al., *A Manager's Guide to Implementing and Improving Management of Change Systems*, Chemical Manufacturers Association, Washington, DC, September 1993.

Table 4.1 Management Practices that Help Reduce Risks (cont'd)

Management Practice 4 ***Ensure that written procedures are developed and implemented to operate, inspect, and maintain all systems containing fuel oil/lube oil***
Historical experience indicates that personnel errors during inspection or maintenance are significant contributors to the risk associated with fuel oil/lube oil releases and spray fires. Personnel errors while performing other activities (e.g., operating a winch in the vicinity of an oil line) on board ships have also caused releases of oil. Obviously, improved training is one way to reduce the probability of personnel error (see Management Practice 6). However, it is also widely recognized that a set of written procedures can help reduce the likelihood of human errors.[1] The different types or procedures that should be documented for systems containing fuel oil/lube oil include inspection, test (e.g., for standby systems), and maintenance procedures, and they should consider all phases of operation (e.g., startup, normal, shutdown, temporary, emergency). All written procedures should document the hazards associated with the procedure, PPE required, the consequences of deviating (skipping or performing incorrectly) from the procedural steps, and actions required to correct or avoid deviations Note: Recommendation 7 addresses specific improvements to written procedures, and these improvements are expected to result in significant risk reduction. Addressing these specific improvements should be the priority while implementing this management practice

[1]D. K. Lorenzo, *A Manager's Guide to Reducing Human Errors Improving Human Performance in the Chemical Industry*, Chemical Manufacturers Association, Washington, DC, July 1990.

Table 4.1 Management Practices that Help Reduce Risks (cont'd)

Management Practice 5 ***Ensure that safe work practices are established and implemented for all (1) systems containing fuel oil/lube oil and (2) onboard activities that could affect systems containing fuel oil/lube oil***
Safe work practices for all personnel, including contractors, should help ensure the safe conduct of hazardous activities on board ships. As a minimum, safe work practices for systems containing fuel oil/lube oil should include (1) opening of equipment or piping, (2) lockout and tagout of electrical and mechanical energy sources, and (3) crane operations in the vicinity of the system piping and equipment Note: Recommendation 8 addresses specific improvements to safe work practices, and these improvements are expected to result in significant risk reduction. Addressing these specific improvements should be the priority while implementing this management practice
Management Practice 6 ***Ensure that a training program is developed and implemented for all personnel involved in the operation, inspection, and maintenance of systems containing fuel oil/lube oil***
Improved training is the most common "corrective action" listed for the incidents in Appendix A, which indicates that there may be significant deficiencies in training programs for many ships. The crew must be trained to work safely, including specific training in the written procedures (Management Practice 4), safe work practices (Management Practice 5), and emergency response and control measures (Management Practice 9). Industry-recommended practices and standards generally request initial training, periodic (refresher) training, and training certification programs. In addition, industry recommended practices and standards request that whenever a change is made (see Management Practice 3), all affected personnel should be trained or otherwise informed of the change before implementing the change Note: Recommendation 9 addresses specific improvements to training programs, and these improvements are expected to result in significant risk reduction. Addressing these specific improvements should be the priority while implementing this management practice

Table 4.1 Management Practices that Help Reduce Risks (cont'd)

Management Practice 7 ***Ensure that a program is developed and implemented for assuring the quality and mechanical integrity of all systems containing fuel oil/lube oil***
All systems containing fuel oil/lube oil must be designed, fabricated, installed, inspected, monitored, tested, and maintained in a manner consistent with appropriate service requirements, manufacturer's recommendations, industry standards, and applicable regulations. This is accomplished through a number of activities that occur throughout the life of the systems: • *Procurement* — Written procedures for procurement of critical equipment should be developed to verify compliance with applicable design and material specifications • *Fabrication* — Written procedures should be developed to confirm that materials and construction, during the fabrication stage, are in accordance with the design specification • *Installation* — Appropriate checks and inspection procedures should be established and implemented before startup to verify that the installation of critical equipment is consistent with design specifications and manufacturer's instructions • *Maintenance* — Maintenance programs that include appropriate inspection and testing should be established and implemented for critical equipment to sustain ongoing mechanical integrity. Elements of the maintenance program include written procedures and work practices, training, quality control for materials and spare parts, and personnel qualification • *Inspection* — Inspection, testing (e.g., for standby systems), and equipment monitoring should be established for critical equipment, including listing of critical equipment and systems that are within the scope of the program, written procedures, documentation of inspection/testing/monitoring results, and procedures for correcting deficiencies Note: Recommendation 10 addresses specific improvements to mechanical integrity (inspection and maintenance) programs that are expected to result in significant risk reduction. Addressing these specific improvements should be the priority while implementing this management practice
Management Practice 8 ***Ensure that a pre-startup safety review program is developed and implemented for all systems containing fuel oil/lube oil***
This program covers new or significantly modified systems to confirm that (1) construction and equipment are in accordance with specifications, (2) all written procedures (operating, maintenance, emergency, etc.) are in place, (3) safety and reliability information is current, (4) a hazard analysis has been performed and all recommendations from the hazard analysis have been addressed, (5) training has been completed, and (6) safe work practices are in place

Table 4.1 Management Practices that Help Reduce Risks (cont'd)

Management Practice 9 ***Ensure that an emergency response and control program is developed and implemented, including addressing emergencies involving systems containing fuel oil/lube oil***
Regulations and industry practices require emergency action plans with assigned authority to the appropriate persons, evacuation procedures, and training/drills. The emergency action plan for the ship should include emergencies initiated by or involving fuel oil/lube oil Note: Recommendation 11 addresses specific improvements to emergency response and control programs, and these improvements are expected to result in significant risk reduction. Addressing these specific improvements should be the priority while implementing this management practice
Management Practice 10 ***Ensure that an incident investigation program (with emphasis on learning from the incident and preventing recurrence) is developed and implemented for all systems containing fuel oil/lube oil***
Incidents that result or could result in serious safety or environmental consequences should be investigated. However, our review of the incident reports in Appendix A indicated that in approximately 30% of all incident reports, the incident investigation team did not find (or did not document) the cause of the incident in sufficient detail to help prevent recurrence. In these reports, the listed "cause" of the incident is the ***proximate cause***,[m] which only characterizes the condition that is readily identifiable as leading to the incident. For example, each of the event characterizations on pages A-81, A-85, A-153, A-161, A-165, and A-173 in Appendix A lists the failure of a line, joint, fitting, or gasket as the cause of the incident, and the event on page A-93 lists "crankcase explosion" as the cause of an oil spray. That is, a component (e.g., engine) or piece-part (e.g., gasket) is listed as the cause of the occurrence, and the reason(s) for the component or piece-part failure is not provided in these incident descriptions It is important to know why these components failed to be able to develop corrective actions. For example, if it is also determined that a gasket failed because the wrong type of gasket was purchased for the application, then it is possible to propose improvements to prevent recurrence. The reason, or "root cause," of these events must be determined during the investigation. The ***root cause*** of the incident is defined as the most basic reason(s) why the equipment/piping failed, any of which would, if corrected, prevent recurrence.[m, n] Because some improvement(s) in management systems could have helped prevent most (or all) of the incidents of interest, the root cause of these incidents is generally the absence, neglect, or deficiencies of management system features

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[m] H. M. Paula and G. W. Parry, *A Cause-Defense Approach to the Understanding and Analysis of Common Cause Failures*, NUREG/CR-5460 (SAND89-2368), U.S. Nuclear Regulatory Commission, Washington, DC, March 1990.

[n] D. L. Gano, "Root Cause and How to Find It," *Nuclear News*, pages 39-43, Vol. 30, No. 10, August 1987.

Table 4.1 Management Practices that Help Reduce Risks (cont'd)

Management Practice 10 (cont'd)
Incident investigation programs generally include (1) prompt initiation of the investigation (considering the necessity of securing the incident scene and protecting personnel), (2) an investigation team with personnel knowledgeable of the hazards and systems involved, investigation techniques, and other specialties (e.g., fire protection), as required, (3) identifying the nature of the incident, the contributing factors, and recommendations to prevent recurrence, and (4) a follow-up system to ensure that all recommendations are addressed An important point highlighted in regulations and industry standards is that the intent of the investigation should be to learn from the incident and help prevent similar incidents
Management Practice 11 ***Ensure that an audit program is developed and implemented for the safety and reliability management programs applicable to systems containing flammable or combustible liquids***
The areas of hazard management and management programs presented in the previous 10 management practices should be audited periodically to ensure effective performance. The objective of the audit includes determining that all management programs (1) are in place, (2) incorporate all requirements, and (3) are effective. Audits should include review of documentation, interviews of personnel at various levels (ship and onshore facilities), and ship inspections. The findings of the audit should be provided to the management personnel responsible for the program, and management should establish a system to determine and document the appropriate response to the findings and ensure satisfactory resolution

5. CONCLUSIONS

Our investigation approach consisted of eight research steps, including assessment of current practices for controlling risks of spray fires and extensive review of spray fires that have occurred worldwide on board vessels. Our research findings substantiated several (and refuted a few) previous findings/beliefs regarding spray fires. In addition, our research evaluated the reduction in risk that can be expected from the implementation of each proposed control measure to prevent/mitigate the impacts of spray fires.

One of the principal activities of this project was to identify a large number of incident investigation reports that could be used to provide insights into the causes of fires and potential options for frequency reduction and/or consequence mitigation. For this purpose, we identified many sources of relevant incident investigation reports: the Coast Guard; the U.S. Marine Safety Information System; Lloyd's Maritime Information Services Limited; the Japanese classification society Nippon Kaiji Kyokai; the Transportation Safety Board of Canada; the Marine Incident Investigation Unit, Inspector of Marine Accidents, Australia; and the U.S. National Transportation Safety Board.

Overall, these sources provided a total of 182 incident records. Of these, 175 involved releases of fuel oil/lube oil in the engine room on board ships (the other 7 were determined to be outside the scope of this project), and 143 releases ignited and resulted in fires. Of the 143 fires caused by releases of fuel oil/lube oil, 9 fires are known to have resulted in fatalities and another 8 are known to have resulted in personnel injury.

Our investigation provided the following insights:

- Oil releases on board ships have occurred because of a variety of human-related and/or equipment-related causes. Although each incident is unique regarding the specific cause of failure, we identified six general categories of causes of failure: (1) lack of adequate inspection or maintenance (10% of all releases), (2) personnel error during inspection or maintenance (25%), (3) personnel error and/or equipment failure during preparation for inspection/maintenance or restoration to service after inspection/maintenance (10%), (4) design, manufacturing, or installation deficiencies (20%), (5) unknown root cause (30%), and (6) external impact (5%). Obviously, improvements in human factors and management systems are essential for reducing the frequency of releases.

- Hot surface (particularly engine exhaust manifold/pipe, turbocharger casing, and steam line) was responsible for the ignition of about 93% of all fires, 93% of all fires with injury or fatality, and

86% of the fires with fatalities. Obviously, control measures to prevent oil sprays from reaching hot surfaces are essential for reducing the frequency of oil spray fires in engine rooms.

- The skid piping, tubing, or hose for diesel engines, turbochargers, or boilers are the most common sources of spray (almost 40% of all fires). These results are interesting because skid piping/tubing/hose is usually under the control of the manufacturer (i.e., the piping/tubing/hose that comes with an engine skid or pump skid), and it is generally not subject to regulations and standards that are in place for piping outside the engine/pump skid. Obviously, control measures to prevent oil sprays from skid piping/tubing/hose are essential for reducing the frequency of oil spray fires in engine rooms.

- Duplex strainers, filters, or coalescers are the most common sources of fatal spray fires (55%). In one case, a crew member damaged the O-ring of a strainer cover, resulting in a leak. In another case, a temporary change to a duplex strainer defeated an original safeguard (safety pin) provided by the manufacturer. This eventually led to an oil spray that ignited. In two other cases, the crew was having difficulties moving the three-way transfer valve to divert flow from one strainer chamber to the other chamber so that the strainer element could be cleaned or changed. In one instance, the crew member decided to loosen the mounting bolts of the packing retaining cover to facilitate movement of the valve. This was done excessively, resulting in an oil spray through the packing retaining cover. In the other instance, the crew member decided to kick the lever on the duplex strainer. He inadvertently hit a vent valve, which ruptured and released an oil spray. In both cases, while attempting to overcome an equipment malfunction (stuck transfer valve), crew members undertook unsafe actions that caused oil sprays and fires. Obviously, control measures to prevent oil sprays from duplex strainers/filters/coalescers are essential for reducing the frequency of fatal fires in engine rooms.

- Fuel oil systems account for about 70% of all oil fires while lube oil systems account for about 30%. However, when fires with fatality are considered, these contributions are 50% for fuel oil systems and 50% for lube oil systems. This indicates that while fuel oil fires occur more often (about twice as much) than lube oil fires, the fewer lube oil fires have caused as many fatal incidents as fuel oil. This suggests that the probability of a fatality given a lube oil fire is more than twice the probability of a fatality given a fuel oil fire. *Lube oil fires are less frequent than fuel oil fires, but they tend to be more fatal when they do occur.*

- Of all 57 incidents that documented the damage incurred by a spray fire, the vessel sank in 6 of the incidents, suffered constructive total loss in 9 of the incidents, and experienced an average damage of about $293,000 in the remaining 42 incidents.

- Of all 105 incidents that documented the impact of the spray fire on the propulsion and/or steering systems, vessels experienced loss of propulsion and/or steering in 70 incidents and were able to maintain these functions in 35 incidents. These are important statistics because loss of propulsion and/or steering can lead to other incidents such as grounding and collision. These numbers indicate that the probability of loss of propulsion and/or steering is about twice the probability of not losing these functions during spray fires in the engine room.

- It has been proposed that mist detectors can be strategically located in the engine room to indicate hazardous oil spray conditions (Reference 6). Our investigation revealed a different conclusion in this regard, at least for safety-related spray fires (i.e., fires that can result in personnel injury/fatality). Specifically, we observed that most safety-related oil spray fires in engine rooms occur during maintenance activities while the crew is in the engine room. These fires tend to ignite very quickly (in a matter of seconds in many cases). There is often insufficient time for crew evacuation, thereby resulting in personnel injury/fatality. Crews need no device or alarm to alert them to the presence of an oil spray in these cases. On the other hand, oil sprays that do not ignite quickly have a tendency to not ignite at all. *Thus, mist detectors would not have helped prevent or mitigate safety-related fuel oil/lube oil fires in the engine room.* The same conclusion also appears correct for non-safety-related spray fires (i.e., fires that cause equipment/vessel damage but do not result in personnel injury/fatality).

- There is no correlation between the number of spray fires and the ship's age, size, kind (oil tanker, fishing vessel, tug/tow, etc.) and nationality.

Our investigation resulted in several feasible, practical control measures (presented in Section 4) to reduce risks associated with fuel oil/lube oil spray fires in engine rooms.

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