Acurex Draft Final Report FR-82-104/EE

STUDY OF VISIBLE EMISSIONS FROM SHIPS WITH STEAM BOILERS: EXECUTIVE SUMMARY

January 1982

Acurex Project 6107

Contract A9-121-30

For

State of California
Air Resources Board
Research Division
P.O. Box 2815
Sacramento, California 95812

By

A. Walter Wyss, Henry J. Modetz
Acurex Corporation
Energy & Environmental Division
485 Clyde Avenue
Mountain View, California 94042

The statements and conclusions in this report are those of the contractor and not necessarily those of the California Air Resources Board. The mention of commercial products, their source or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products.

EXECUTIVE SUMMARY

Visible emissions from any source are restricted by California law from exceeding specified opacity standards as cited in the California Health and Safety Code, unless exempted. Vessels with steam boilers operating in coastal and inland waterways are granted specific exemptions in Section 41704 of the code. Unlimited exemptions are applicable to steam-boiler operations during emergency boiler shutdowns for safety reasons, safety and operational tests required by government agencies, and maneuvering to avoid hazards. In addition, operations necessary to light off a cold boiler and to dry wet or green refractory materials are given a conditional exemption until January 1, 1984.

Senate bill 2198 as adopted September 1978 amended the Health and Safety Code to allow for the above marine exemptions. In addition, section 2 of this bill mandated that a study be performed by the Air Resources Board to address this issue. The bill directed that the study be conducted in cooperation with local air pollution control districts and the maritime industry to determine if vessels using steam boilers could be brought into compliance with existing visible emission standards by January 1, 1984. The objectives of this study were to survey ship operations relevant to the exempted conditions, to investigate possible modifications to equipment and procedures which would reduce visible emissions, and to develop recommendations for a compliance schedule to reduce such emissions.

In order to meet the objectives of this study, the following tasks were performed:

- Normal and exempted operating modes were surveyed to identify the sources and periods of excess emissions
- The frequency, duration, causes and quantitative extent of emissions were characterized

- Modifications to equipment and operating procedures to reduce visible emissions were investigated
- Regulatory recommendations were suggested

Study efforts primarily focused upon vessels using steam boilers since these vessels are granted the exemptions, however, particulate emissions from both steam- and motor-powered vessels during normal modes of operation were quantified.

Normal and Exempted Mode Operating Procedures

The routine use of marine propulsion systems requires various operating modes with a subsequent wide range of boiler firing rates. For purposes of this study, normal modes were defined as those modes for which visible emission exemptions do not exist. Since exemptions currently exist for five modes of operation: 1) cold-boiler light offs, 2) drying of wet or green refractory, 3) government testing, 4) maneuvering to avoid hazards, and 5) emergency boiler shutdowns, normal modes encompass all other functions necessary for routine ship movement and operation. These include: cruise, transit, routine maneuvering, hoteling, cargo heating, and cargo unloading.

The exempted operating modes generally occur less frequently than the normal modes and for very short time periods. They can be scheduled as in the case of government tests and boiler light offs or can occur as a consequence of unplanned events such as equipment failure or unforeseen hazards.

Maneuvering to avoid hazards is required by the ship's legal obligation to take action when risk of collision exists. Risks are compounded by changing current conditions, reduced maneuverability at low power levels, and narrow traffic lanes caused by dredging limits, obstructions, or small craft. Power fluctuations required for maneuvering will cause rapid changes in demand for fuel, air, and water to the boilers. As a consequence, excessive emissions are likely to be generated until the boiler controls are adjusted to stabilize combustion. The engine load level may fluctuate between 10 and 100 percent of the design value. The duration of unplanned maneuvers and the subsequent period of excessive emissions are usually brief, lasting only several minutes.

Emergency boiler shutdowns are unusual events which occur when all preventive measures have not eliminated a casualty. Casualties requiring

immediate shutdown include failure of the boiler and/or boiler auxiliaries and fires in the machinery spaces. Any equipment failure eventually leading to an emergency boiler shutdown could produce improper combustion conditions and, consequently, excessive emissions. In automated boiler control systems, the shutdown will occur rapidly and the generation of excessive emissions would be of short duration. The emissions resulting from equipment failure in a manually operated system may be more intense and of longer duration since operator response time is likely to be longer than an automated system. In either case, the greatest amount of visible emissions would result from a failure of the air flow system and the subsequent brief period of air-starved combustion prior to the fuel being cut off. The duration of excessive emissions in either case is limited to several minutes.

Testing as mandated by government agencies (primarily the U. S. Coast Guard) can directly or indirectly affect combustion conditions and hence produce excessive emissions. Specific tests that most often affect emissions are: 1) automation testing of boiler firing and safety controls, 2) safety valve setting, 3) sea, bay, or dock trials on new or repaired vessels, and 4) full-load or overspeed protection testing of equipment. The objective of each Coast Guard mandated test is to ensure proper operation, reliability, and safety to the crew and the vessel. The test procedures vary for different ships and are dictated by vessel design, safety considerations, and good marine practice. Boiler firing rates over the entire operating range are experienced, in some cases up to 110 percent of design load. These tests are normally conducted at least once each year on U. S. flag vessels, however more frequent testing can be required in some cases. The duration of each test procedure varies due to the vessel design, age, condition, degree of automation, and crew familiarity with the specific test being conducted; however, 1 to 2 hr is typical. Excessive emissions may total approximately 10 min if a complete evaluation of the ship's boiler, control, propulsion, and safety systems is performed.

Boiler light offs are the collective manually and automatically initiated operations required to bring a marine boiler online. Virtually all vessels, regardless of the type or sophistication of their boiler control system, conduct this procedure using manual controls. There are

essentially two types of boiler light offs: a cold-boiler light off and a normal boiler light off. The cold-boiler light off occurs on a vessel with no shipboard systems in operation. This light-off condition frequently exists on a ship which has been at a shipyard for repairs but can also occur at other locations, if all the boilers have been secured. The normal boiler light off occurs on ships with at least one boiler operating or when shore steam is available. This situation frequently occurs when a vessel has been dockside for a relatively short time but has secured any unneeded boiler(s).

Modern commercial marine boilers are fired with heavy residual fuel because of its availability and low cost. This fuel requires preheating prior to being atomized and combusted. During a normal boiler light off, steam from an online boiler or from shore utilities is used to preheat and atomize the residual fuel. When no atomizing steam or compressed air is available, distillate fuel is recommended for the initial boiler light off and warmup period. The period from the initial light off to when the boiler is producing steam at sufficient pressure to bring it online varies according to the specific system design and operating procedure but can require up to 4 hr. During this time, there are a number of specific actions which may cause transients in the combustion conditions and thus momentarily generate excessive particulate emissions. Such actions include burner light offs, air and fuel flow adjustments, burner cycling, burner sequencing, manual to automatic control switching, and system malfunctions.

Aside from the above cited actions, excessive emissions can also result from numerous operator-controllable factors. These include the following:

- Poor atomization of fuel oil caused by dirty atomizer tips, incorrect fuel oil temperture, low oil pressure, inadequate or wet atomizing steam or plugged fuel passages
- Unequal distribution of fuel or combustion air to the burners caused by individual burner root valves being throttled, air registers not opened in a uniform manner, carbonized diffusers, air leakage, or a blocked air register
- Faulty air register because of mechanical failures

During operation of a marine boiler, deposits of ash or slag may build up on the external heat transfer surfaces in the furnace. When these deposits seriously reduce the efficiency of the boiler, they must be removed through hand cleaning or high-pressure water washing. After such washing, exposed refractory surfaces must be dried. Similarly, during the useful life of a boiler, degradation of the refractory will occur to a point where repairs are necessary. The newly applied refractory, called "green" refractory, must be dried or cured to effect maximum strength and durability. Light offs of boilers following water washing or refractory repairs can produce periods of excessive emissions and it is during these times that vessel operators are currently exempted from meeting the standard visible emission regulation.

The procedures for drying wet or green refractory are similar to those used for a boiler light off. The boiler is fired at a low fuel rate in order to evaporate excessive moisture. It requires an estimated 6 to 8 hr to bring such a boiler online. Excessive visible emissions can be generated as a result of the initial burner light off and subsequent burner rotation. Causes of emissions are similar to those described for boiler light offs, however the effect of cold and wet furnace surfaces and the subsequent quenching of partially burned fuel particles is especially significant.

Particulate Emissions From Marine Operations

In order to characterize the quantitative extent of emissions from marine operations, visible emissions from normal and the five exempted modes were inventoried. This was accomplished by estimating fuel consumption for the various vessel types during the different operating modes. Fuel consumption was then summed for all vessel types in each port. Emissions were estimated by multiplying fuel consumption by particulate matter emission factors. The inventory was limited to an estimate of particulate matter generated by the combustion of residual oil and distillate fuel while vessels were in the confines of a port area. The scope of the inventory was also limited to the port areas of the San Francisco Bay, Los Angeles, San Diego, Ventura County and San Luis Obispo County. Commercial and military vessel operations were compiled along with those of tugs used in the movement of cargo between ports. Emissions generated by intraport tug assistance activities, passenger

Table 2. Exempted Mode Emission Inventory Input Data and Assumptions

Parameter	Source	Exempted Modes of Operation				
		Maneuvering to Avoid Hazards	Emergency Shutdowns	Government Testing	Boiler Light offs	Refractory Drying
Power level, range (%)	Consultant	10 to 100	50 to 25	0 to 110	0 to 10	0 to 10
Inventory power level (%)	Assumption[a]	100/40	25/10[b]	110	5[c]	5[c]
Duration of procedure	Survey	4 min	10 min	~1 to 2 hr	2 to 3 hr/boiler	6 to 8 hr/boiler
Duration of excessive emissions	Assumption	4 min	5 min	10 min	10 min/boiler	30 min/boiler
Annual occurrences/ship	Survey	2	1	1	5[d]	0.5[e]
Total annual occurrences[f]	Calculation	800	400	400	2,000	200
Excessive emission opacity	Assumption					
Residual fuel (%)		80	80	60	60	80
Distillate fuel (%)		40	40	40	40	40
Exempted mode emission factors						
Residual fuel (lb/1,000 gal)	Calculated	352	352	200	200	352
Distillate fuel (lb/1,000 gal)	Calculated	150	150	150	150	150

[a]Upper end of power level range was selected for inventory purposes, second value is for military vessels
[b]Assumes emergency shutdown involves a single boiler on a vessel with two boilers operating at an average inport level of 50 percent typical of maneuvering (military values are lower)
[c]Based upon the assumption that each single boiler on a typical two-boiler vessel is operated at 5 percent of full-load during the light-off and warmup period
[d]Assumes that each occurrence involves the lighting off of a single boiler, thus on an annual basis, five boiler light offs occur per ship
[e]Assumes that each occurrence involves the drying of refractory on both boilers of a single ship and that this event occurs once every 2 yr
[f]Based upon the assumption that approximately 400 individual steamships call on California ports annually

Table 3. Exempted Mode Emissions Inventory (Tons/Year)

Port/Ship Type	Maneuvering	Emergency Shutdowns	Government Testing	Light Offs	Refractory Drying
San Francisco Bay					
Passenger	0.10	0.03	0.07	0.02	0.03
Dry Cargo	1.56	0.54	1.22	0.35	0.37
Tankers	0.91	0.32	0.71	0.19	0.20
Military	0.13	0.05	0.42	0.12	0.08
Subtotal	2.70	0.94	2.42	0.68	0.68
Los Angeles/Long Beach					
Passenger	0.13	0.04	0.10	0.03	0.03
Dry Cargo	1.22	0.42	0.95	0.28	0.30
Tankers	1.34	0.48	1.04	0.28	0.29
Military	0.35	0.12	1.00	0.33	0.21
Subtotal	3.04	1.06	3.09	0.92	0.83
San Diego					
Passenger	--	--	--	--	--
Dry Cargo	0.08	0.06	0.13	0.02	0.04
Tankers	--	--	--	--	--
Military	2.98	1.04	9.68	2.80	0.85
Subtotal	3.06	1.10	9.81	2.82	0.89
Ventura County					
Passenger	--	--	--	--	--
Dry Cargo	0.02	0.01	0.02	0.01	--
Tankers	--	--	--	--	--
Military	0.06	0.05	0.18	0.05	0.02
Subtotal	0.08	0.06	0.20	0.06	0.02
San Louis Obispo County					
Tankers	0.34	0.12	0.26	0.07	0.07
Total	9.2	3.3	15.8	4.6	2.5

government testing contribute approximately 45 percent of this total. This is primarily due to the brief period of high fuel consumption that is experienced during the test procedure. It is important to understand that the estimates have been based upon numerous assumptions that tend to reflect the worst case of emission generation. Operations necessary for refractory drying only contribute an estimated 2.5 tons/yr due to the low number of annual occurrences (200 or once per ship every 2 yr) and the low engine load level (5 percent per boiler) with its correspondingly low fuel firing rate.

Options to Control Visible Emissions

This study evaluated potential options to reduce visible emissions from vessels operating in the five exempted modes. It was discovered that in three of the modes the operator has little control to vary operating procedures or implement additional measures to reduce emissions while operating in these modes.

For example, when maneuvering to avoid hazards, the vessel operator is required by law to ensure safety. Boiler operations necessitated by maneuvering may cause brief periods (typically 4 min/occurrence) of excessive emissions. Although increased operator awareness of navigational hazards and improved boiler response capability might reduce the need for operating in this mode, it was concluded that required safety practices are being employed to the fullest extent possible when these situations do occur. In addition, an increasing number of vessels are using automated boiler control systems. Consequently, additional measures were not judged feasible for this operating mode.

Similarly, an emergency boiler shutdown can cause periods of excessive emissions (typically 5 min/occurrence) due to the inability of the operator and/or the boiler control system to respond to rapid system changes caused by component failure. In theory, emissions could be reduced by implementing maintenance measures to reduce system failures and by improving boiler response capability. However, it is believed that procedures which minimize the frequency of equipment failure are already being practiced to the maximum degree possible to ensure safety and reduce costs.

During government tests, the operator is required to simulate events which produce improper combustion conditions for brief periods

(typically 10 min per ship, annually). The objectives of these tests are to verify the proper operation, reliability, and safety of the vessel. In certain tests the need to demonstrate safe operation under various conditions outweighs environmental concerns.

By contrast, a review of the boiler light off and refractory drying operations indicated that operators are able to control the timing and procedures used during these modes. In spite of equipment operating requirements and economic constraints, the boiler operator can greatly influence the generation of excess emissions during these modes. These modes are of much longer duration than maneuvering to avoid hazards, emergency shutdowns, or government testing. For these reasons, the examination of emission abatement options was limited to these two modes. The procedures employed for boiler light off and refractory drying are essentially the same, therefore no distinction is made between the two in the following discussion of available control strategies.

Table 4 summarizes the options available to reduce emissions during boiler light off. Options that increase operator awareness or increase the use of distillate fuel are the most feasible and applicable. Pollutant generation is directly related to the operator's skill in conducting a light off. Therefore, effective abatement strategies involve increasing the operator's awareness of: 1) visible emission regulatory requirements, 2) "correct" light-off procedure, and 3) combustion conditions during light-off. This can be accomplished through education (information dissemination and training) and instrumentation (opacity monitors and oxygen analyzers).

Table 5 presents an evaluation of these measures to increase operator awareness. Minimal concerns of any type (economic, operational, legal, safety, energy) are associated with the education-oriented options. In addition, these measures have a high degree of applicability in the two exempted modes under consideration.

Although the abatement effectiveness of these measures is difficult to quantify, observations of actual boiler light offs with residual fuel indicated that observant and trained operators using proper procedures could conduct the light off in compliance with the standard visible emission law (i.e., section 41701 of the California Health and Safety Code). The observations also indicated that limiting the emissions to an

Table 4. Summary of Boiler Light-Off Control Options

Options	Comments
• Feasible options with high degree of applicability	
-- Increased operator awareness of visible emission regulations through posting of notices	-- Difficult to assess possible impact on visible emissions
-- Increased operator awareness of "correct" light-off procedure through operator training	-- Difficult to assess possible impact on visible emissions
-- Installation of smoke meters, oxygen analyzers, and/or alarms to increase operator awareness of flue gas and combustion conditions	-- Already required for automated plants on newer ships, could assist in identifying problems to nonobservant operators
-- Increased use of distillate fuel for boiler light offs	-- Already in use on some ships but could be extended to other vessels
• Feasible options with low degree of applicability	
-- Increased use of steam from the operating boiler to preheat and atomize residual fuel	-- Current practice utilizes steam from the operating boiler whenever available. Optimizing current practice appears to have limited applicability since most operators are currently using this procedure.
-- Increased use of shore steam for preheating and atomizing residual fuel thereby improving the combustion conditions	-- Current practice utilizes shore services when required and available to initiate light-off, optimizing current practice could reduce visible emissions but overall impact is felt to be slight.
-- Preheat furnace and/or combustion air with steam from operating boiler or shore steam	-- Possible if soot blowers or heat exchangers are in appropriate locations, direct heating by burning distillate fuel represents more efficient use of fuel
-- Installation and use of steam-atomized burners	-- The majority of currently operating vessels already use these burners therefore this option is not available to many operators
-- Blending of distillate fuel with residual fuel to reduce viscosity	-- Specialized expertise and equipment needed to effect successful blending, possible incompatibility exists with some fuels

Table 4. Concluded

Options	Comments
• Options which are ineffective or not feasible	
-- Installation of new or additional combustion controls including viscosimeter, flame scanners, electronic igniters (does not include opacity monitors and oxygen analyzers)	-- Modern control systems are not designed for light-off conditions, light offs are manually initiated and controlled, thus, installation of more sophisticated controls would result in minimal emission reduction
-- Separate burner designed specifically for boiler light off	-- No such burner currently exist, currently available steam-atomizing wide-range burner generally performs adequately at low load
-- Burning of gaseous fuels for boiler light off	-- U. S. Coast Guard regulations prohibit use of machinery fuel with flashpoint less than 140°F
-- Modification of residual fuel by additives designed to reduce combustion-generated particulate matter	-- No experimental data exists which demonstrates that such an additive is effective in reducing light-off emissions, expertise and specialized equipment needed to implement option, would not be widely available
-- Keep boilers operating while in port thereby reducing the number of light offs needed	-- Inefficient use of fuel since boilers would be operating at extremely low load, multiple boilers operating at low load also are likely to generate more emissions per unit of fuel burned than a single boiler at higher load. Presently most ships in port less than 12 to 24 hr maintain both boilers operating.

Table 5. Evaluation of Increased Operator Awareness Options

Control Options	Effect on Safety	Applicability to Vessels of Different Types, Size, and Function	Abatement Effectiveness	Institutional and Legal Barriers to Implementation	Capital and Operating Costs	Operational Concerns	Energy Impact
• Notices in boiler rooms	None	All	Difficult to quantify[a]	None	Minimal	None	None
• Notification through pilots, agents, unions	None	All	Difficult to quantify[a]	Requires voluntary cooperation of pilots, agents, and unions	Minimal	None	None
• Operator training	None -- possibly increases safety	All, as needed	Difficult to quantify[a]	Must be performed in compliance with union regulations, should be similar to safety training	Minimal	None	Minimal -- may enhance optimal use of fuel
• Observer	None	All	Difficult to quantify[a]	May require additional personnel	Labor costs if additional personnel are required	None	None
• Opacity monitor	None -- possibly increases safety	Ships built prior to 1960 or those not already having them	Difficult to quantify[a]	None	$5,000 to $7,000 for capital costs, negligible operating cost	Minimal -- existing personnel should be able to operate	None, can be used along with oxygen analyzer to optimize fuel use
• Oxygen analyzer	None -- possibly increases safety	Ships built prior to 1970 to 1975 or those not already having them	Difficult to quantify[a]	None	Same as for opacity monitor	Minimal -- existing personnel should be able to operate	None, can be used to optimize fuel use

[a]The abatement effectiveness of each of these options is difficult to quantify, however, implementation of these options should allow most operators to conduct a normal boiler light off in compliance with the standard visible emission law. Additional control measures may be necessary to keep cold-boiler light offs and other light offs under specific circumstances within the 3-min allowance of the standard regulation.

opacity level less than 40 percent except for 3 min/hr would be difficult in some cases, unless the light-off procedure were altered or distillate fuel used.

Those options requiring instrumentation would involve a capital cost for retrofitting opacity monitors and oxygen analyzers but minimal operating costs. Overall, the impacts of all measures to increase operator awareness are beneficial and barriers to their implementation are minimal.

The increased use of distillate fuel could reduce emissions in situations when the alternate strategy of increased operator awareness is unsuccessful or impractical. For example, during light offs on a "dead" ship when steam for oil preheating and atomization is unavailable. The use of distillate fuel could also be extended to light offs on vessels which have one boiler operating and steam available. Currently, nearly all commercial marine boilers use heavy residual fuel because of its availability and low cost. Distillate fuel (i.e., distillate fuel marine, DFM) is routinely used for all operating modes on U.S. Naval vessels. Most, if not all, steam-propelled vessels are already equipped to use distillate fuel for boiler light offs. Boiler manufacturers recommend that distillate fuel be used when steam is unavailable. For operational reasons, those vessels not equipped to burn distillate fuel would need to be retrofitted with a completely separate fuel delivery system.

The exact degree of particulate and visible emission reduction which would occur by using distillate fuel for boiler light offs cannot be quantified; however, by comparison of fuel properties, it is evident that distillate fuel will burn cleaner and more easily. As mentioned earlier, pollutant emissions are in large part governed by operator-controllable variables such as fuel atomization and air input. Because of its lower viscosity, distillate fuel does not require preheating and is easier to atomize than residual fuel. The ease by which distillate fuel can be atomized and combusted is especially important during the light-off period when steam for preheating and atomization may not be available. Operating expenses for using distillate fuel for light offs will primarily consist of the cost differential between residual fuel and the higher priced distillate fuel (approximately $55 to $163 for each 2 to 3 hr light off). The increased use of distillate fuel for cold and normal boiler

light offs could present safety concerns if precautions are not taken. These concerns can be minimized if operating personnel are familiar with the proper procedures for using distillate fuel and proper safeguards are built into the fuel delivery system.

It was determined that if an operator uses distillate fuel along with good marine practices, he should be capable of easily complying with the standard visible emission regulation in nearly all situations (i.e., less than 20 percent opacity except for 3 min/hr).

Regulatory Recommendations

The California Health and Safety Code as amended in 1978 allows for unlimited exemptions to the visible emission standard for vessels using steam boilers during emergency boiler shutdowns, safety and operational tests, and maneuvering to avoid hazards. This exemption should remain in effect indefinitely. These operating modes occur as a result of efforts to promote and ensure crew and vessel safety. The paramount need to operate vessels in a safe manner outweighs environmental concerns which may stem from the infrequent and brief periods of excessive emissions.

The conditional visible emission exemption due to expire on January 1, 1984 for cold-boiler light offs and refractory drying should not be extended beyond that date. Vessels with steam boilers should be required to comply with section 41701 of the code and thereby limit emissions from boiler light off and refractory drying operations to the Ringelmann 2 level except for 3 min in any 1 hr. The findings of this study indicate that vessel operators can, by 1984, confine visible emissions to this standard limitation. There is no significant technical, economic, institutional, safety, or operational justification for the special exemption to be continued. Ship owners using informed and observant operators aided by the use of exhaust gas opacity or oxygen analyzers can conduct most boiler light offs with residual fuel in compliance with the standard regulation (i.e., section 41701). This is especially true for normal boiler light offs where steam for residual feul preheating and atomization is available. In those cases where light offs with residual fuel cannot be performed in compliance with the 3-min limitation, the use of distillate fuel is suggested.

Prior to the expiration of the boiler light off and refractory drying exemption in 1984, vessel operators should be notified so that the

necessary procedures can be implemented. A period of 6 months is suggested as being sufficient for operators to be notified and trained in conducting light offs that minimize visible emissions and to retrofit exhaust gas analyzers if necessary.

Additionally, it is recommended that vessel operators be required to meet the Ringelmann 2 limitation of the Health and Safety Code rather than the more restrictive visible emission regulations (i.e., Ringelmann 1) established by four of the five local districts in the port areas studied. Vessel operators lighting off their boilers with residual fuel would have difficulty meeting the Ringelmann 1 limitation even with observant operators using good marine practice and exhaust gas analyzers. Compliance with the Ringelmann 2 limitation can be achieved in most cases with increased operator awareness and in an infrequent number of special situations (e. g., cold light offs on a "dead" ship or after some refractory repairs) by using distillate fuel. In order to comply with a Ringelmann 1 standard, distillate fuel would likely be required for all light offs. The increased disruption to the normal operating scheme caused by this requirement is not justified by the minimal incremental emission reduction produced by the more restrictive standard.