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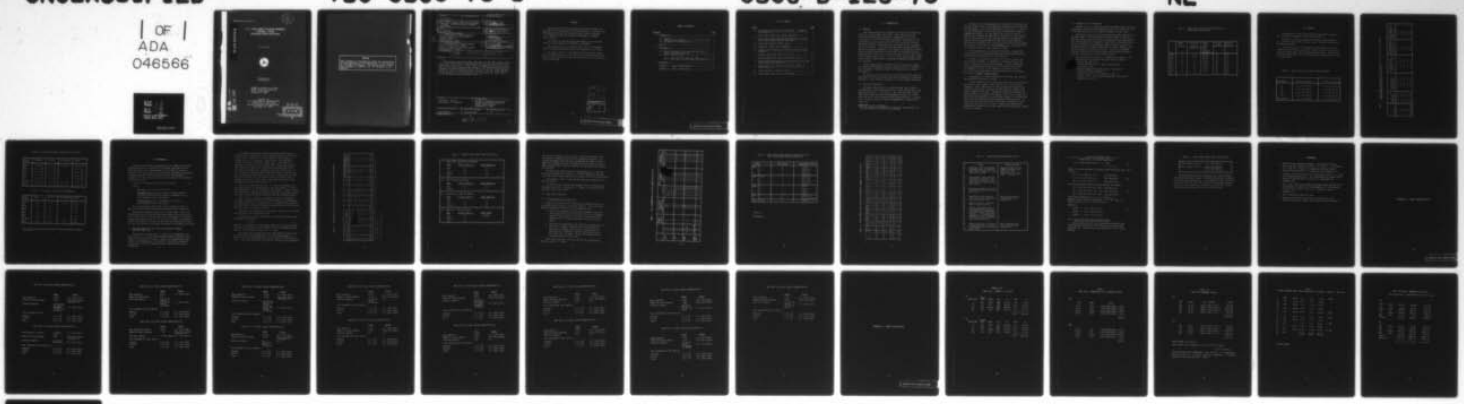

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U. S. COAST GUARD POLLUTION ABATEMENT PROGRAM: CUTTER ESTIMATED EXHAUST EMISSIONS

R.A. Walter

SEPTEMBER 1975
FINAL REPORT

Prepared for
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16. Abstract

The gaseous and particulate emissions of the Coast Guard cutter fleet are estimated by using measured emission factors and derived operational duty cycles. These data are compared to previous estimates by using emission factors found in the literature and the EPA estimates of total national vessel emissions and the total national emissions from all transportation sources. The U.S. Coast Guard fleet emissions for all categories of pollutants are less than 1% of the national transportation totals.

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PREFACE

The work described in this report was performed under the auspices of the United States Coast Guard, Office of Research and Development, Pollution Prevention Projects Branch, Commander D. B. Flanagan, Chief and Lieutenant Commander J. Sherrard, Project Officer.

The efforts of the engineering departments of the vessels involved in this study are gratefully acknowledged.

The contributions of D. Knapton and C. Wu of the Raytheon Service Company were invaluable in the completion of this work.

This work is part of a continuing effort by the U.S. Coast Guard to evaluate the emissions from Coast Guard power plants and minimize these emissions through the application of cost-effective control technology.

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1. INTRODUCTION

1.1 PURPOSE

This paper presents the findings of a study to estimate Coast Guard (CG) vessel exhaust emissions. Coast Guard vessel air-pollution emissions were previously estimated by TSC in 1971 (reference 1)*. These emissions calculations were based on fuel consumption records for each class of vessels and mass emission factors** based on average emission rates found in the literature for diesel engines. No distinctions were made between different designs of engines, condition of the engine, or differences between engine operating conditions or duty cycle of the engines used in determining the emission factors and the duty cycles of the various types of Coast Guard vessels. The 1971 report did provide a framework, however, within which a CG pollution-abatement program could be structured.

In the interim period, emissions tests of actual CG vessels were made establishing more accurate emission factors (reference 2), and, currently, a detailed study of CG operations is in process (reference 3).

The purpose of this analysis is to take the measured specific horsepower emission factors and additonal information on operations and obtain a more accurate estimate of CG vessel exhaust emissions.

1.2 SCOPE AND LIMITATIONS

Pollutants estimated are: carbon monoxide (CO), oxides of nitrogen (NO_x), total hydrocarbons (THC), sulfur oxides (SO_x), and particulates (Part.). In Section 2, emissions are given for the total Coast Guard fleet and as percentages of total U.S. vessel emissions and of total transportation related emissions. Information limitations restrict further disaggregation of emissions by vessel use.

*See Section 4 for references.
**Emission factors are quantities of emissions produced per unit of fuel consumed or unit of work performed.

Emission factors measurements were available for CO, NO_x, and THC for eleven vessels during underway operations of both main propulsion engines, ship-service generators, and boilers. In Section 3.1, the methodology is described for estimating main propulsion underway emissions of CO, NO_x, and THC for the five types of vessels which consume the most fuel. In Section 3.2, the methodology is shown whereby CO, NO_x, and THC emissions calculated in Section 3.1 are extrapolated to include total fleet emissions. Ship-service generation units and in-port emissions are calculated. In addition, in Section 3.2, the methodology for calculating fleet SO_x emissions based on sulfur content is shown.

Particulate-emissions estimation methodology is described based on the 1971 CG emission factors but with operational use reflecting recent operational data (reference 3).

A total of 15 classes of vessels were used as a basis for this emission estimate. In Appendix A, characteristics of the classes used in the calculation are given. Further information on the performance characteristics of CG vessels may be found in references 1 and 2, in the "Registry of Cutters of the U.S. Coast Guard" published by the Coast Guard, or in reference books such as Janes' Fighting Ships.

In Appendix B, a sample calculation for the CO, NO_x, and THC main propulsion emissions is given.

As main propulsion units consume the most fuel, and the existing data was more complete, these sources are the most closely estimated. Where information was not available for detailed calculation, conservative estimates are used tending to make a high total estimate of emissions. Therefore, while the estimation of yearly emissions for some of the smaller vessels may be high, the emissions error estimation for the larger vessels (i.e., large fuel users) and the yearly total fleet emissions should be small. It should also be noted that a few of the vessels included in this study have been or will be retired. However, new vessels are scheduled for construction so that total fleet emissions will remain nearly as reported.

1.3 AVAILABILITY OF INFORMATION

Limited CG vessel operational data and engine-exhaust emission measurements necessitated the aggregation of vessel operations and of the emission analysis on vehicles consuming the most fuel.

Each vessel type or class has particular design characteristics and each type is associated with one or more types of missions. Missions include such activities as search and rescue, law enforcement, servicing aids to navigation, and others. Locational classification includes the geographical region to which the vessel is assigned, home port, whether operations are within harbors, and a general category of whether the vessel is in-port or underway. Sources of emissions on vessels include main propulsion engines, ship-service generators, and utilities boilers.

The information availability is summarized in Table 1. For the calculations, the following variables were considered:

- Cutter type and class
- Mission (a duty cycle is used to characterize each vessel type)
- Underway Hours (employment hours in reference 3)
- Location (in-port, underway)
- Emission factors (from references 1 and 2)
- Exhaust Source (main propulsion engines, ship-service generators, boilers).

TABLE 1. COAST GUARD CUTTER EMISSION ESTIMATION – INFORMATION AVAILABILITY

	Number of Vessels	Percentage of Total Fuel Consumption	Number of Employ-ment Hours per year (Reference 3)	Machinery Logs (Reference 4)	Emission Factors (Reference 2)
WHEC	33	52.0	83,339	Yes	Yes
WAGB	9	13.6	20,410	No	No
WMEC	22	8.2	48,977	Yes	Yes
WLB	36	7.0	53,806	Yes	Yes
WPB	79	4.1	58,450	Yes	Yes
WLM	17	2.1	16,679	No	Yes
WAGO	2	2.0	3,180	No	No
WYTL	15	0.4	17,717	Yes	Yes
WLV	7	0.3	--	No	Yes

2. RESULTS

Total annual CG cutter fleet emissions are shown in Table 2. This estimate is compared with the 1971 estimate.

In Table 3, CG vessel emissions are shown as percentages of: 1) national total vessel emissions, and 2) national total transportation emissions.

In Tables 4a and 4b, the amounts and percentage of fuel consumed by the most active classes of vessels are given for the two principal operational states (underway and in-port). The emissions for these operational states are approximately proportional to the total emissions.

TABLE 2. TOTAL COAST GUARD VESSEL ANNUAL EMISSIONS

Pollutants	Current Estimates	Previous Estimates
CO	3.67×10^6 lbs/yr.	5.5×10^6 lbs/yr.
HC	2.64×10^6 lbs/yr.	1.1×10^6 lbs/yr.
NO_x	8.92×10^6 lbs/yr.	1.5×10^7 lbs/yr.
SO_x	3.16×10^6 lbs/yr.	4.2×10^6 lbs/yr.
Particulates	5.60×10^6 lbs/yr.	4.6×10^6 lbs/yr.

TABLE 3. COAST GUARD VESSEL EMISSIONS PERCENTAGES OF NATIONAL TOTAL VESSEL/ TRANSPORTATION EMISSIONS (Reference 5)

Pollutants	CG Vessels Emissions (tons/yr.)	National Total Vessels Emissions (tons/yr.)	National Total Transportation Emissions (tons/yr.)	Percentage of National Total Vessels Emissions (%)	Percentage of Total Transportation Emissions (%)
CO	1.84×10^3	1.07×10^6	7.3×10^7	0.20	0.003
HC	1.32×10^3	3.60×10^6	1.4×10^7	0.40	0.010
NO_x	4.46×10^3	1.92×10^5	9.4×10^6	2.30	0.050
SO_x	1.58×10^3	1.02×10^5	6.4×10^5	1.54	0.250
Particulates	2.80×10^3	2.47×10^4	1.1×10^6	11.30	0.250

TABLE 4a. YEARLY FUEL USAGE BY VESSEL TYPE (Gal/Yr)

Vessel Type	Underway	In Port	On Station*	Total
WHEC	1.9×10^7	3.2×10^6	5.9×10^6	2.8×10^7
WAGB	6.6×10^6	7.5×10^5	-	7.4×10^6
WMEC	3.9×10^6	5.5×10^5	-	4.5×10^6
WLB	2.9×10^6	8.7×10^5	-	3.8×10^6
WPB	2.0×10^6	2.4×10^5	-	2.3×10^6
OTHERS	6.16×10^6	1.59×10^6	1.8×10^5	8.0×10^6
TOTAL	4.1×10^7	7.2×10^6	6.1×10^6	5.4×10^7

TABLE 4b. PERCENTAGE YEARLY FUEL CONSUMPTION

Vessel Type	Underway	In Port	On Station*	Total
WHEC	35.2	5.9	10.9	52.0
WAGB	12.2	1.4	-	13.6
WMEC	7.2	1.0	-	8.2
WLB	5.4	1.6	-	7.0
WPB	3.7	0.4	-	4.1
OTHERS	11.4	2.9	0.3	14.6
TOTAL	75.1	13.2	11.2	100.0

*The Ocean Station Keeping Program has been considerably reduced since 1973.

3. METHODOLOGY

Multiple source-emission inventories can be made by analytical techniques where it is impractical to measure individual sources. Total emissions can be approximated by the product of a source-activity level measure and an emission factor representing a measured or quantitative estimate of the rate at which the pollutant is released. For the calculation of CG vessel emissions the following expression is used.

Emissions = Horsepower Hours x Emission Factor (1)

where:

Emissions (lbs per year per vessel)

Horsepower Hours (hours per year at various throttle positions times delivered propeller horsepower at the corresponding throttle positions)

Emission Factor (lb of pollutant per HP hour at corresponding throttle positions)

As in all modeling, the accuracy of the results is only as good as the simplifying assumptions approximate actual operations.

The general procedure consists of two main steps. First, the emissions associated with main propulsion exhaust for those classes of CG vessels which consume the most fuel are measured or calculated. Second, the underway emissions for the total CG fleet are extrapolated and then emissions in-port and emissions from ship-service generators and ship boilers are estimated and added to the underway emissions.

3.1 MAIN PROPULSION CO, NO_x, AND THC EMISSIONS OF VESSELS CONSUMING MOST FUEL

The operation of each class of cutter can be represented by duty cycles (i.e., typical engine-operating hours at various engine speeds) for each type of mission. However, no information on duty cycles was available, and it was necessary, therefore, to generate typical duty cycles from engine-operating logs and overall fuel consumption.

By examining both fuel consumption records and missions performed by Coast Guard vessels, it is evident that most Coast Guard vessel fuel is consumed by a small number of cutter types performing few types of missions. Seven cutter types consume 89 percent of the fuel, with the largest cutters, the WHEC type, consuming 52 percent of all CG vessel fuel. The mission analysis shows that Coast Guard vessel operations consuming most of the fuel are concentrated in a relatively few types of missions. It is estimated that the WHEC type spends 86 percent of its underway time in performing three types of missions. Additionally the nine most active classes of vessel spend 57 percent of their time in performing five types of missions. These vessels and their most frequent missions are shown in Table 5.

The most frequent missions are: (1) aids to navigation, (2) search and rescue, (3) enforcement of laws and treaties, (4) military preparedness, and (5) port safety and security. These missions typically show a stop-and-go profile as compared to merchant marine or military operations which typically have long cruising periods.

Each class of CG vessel is assumed to be used in operations of either a single-type mission or missions that can be represented by a single duty cycle. The duty cycle is developed from machinery operating logs (reference 4) and from characteristics of the missions. The duty cycles are shown in Table 6.

Total hours of operations of each type of vessel are distributed proportional to the assumed duty cycle.

Horsepower (p) can be calculated as a function of engine speed according to the formula:

$$p = ks^e \qquad (2)$$

where k is a constant, s is the engine speed, and e is the propeller load function whose value lies between 2.5 and 3, depending on hull design. In this report, a value of 2.8 is used.

Horsepower load, assumed duty cycle, and number of hours underway yield estimated horsepower-hours at various percentages of throttle and total horsepower-hours of all vessels of the particular class. Total horsepower-hours are used to calculate fuel consumption

TABLE 5. DISTRIBUTION OF MISSIONS FOR MOST ACTIVE COAST GUARD VESSELS*

CUTTER TYPE	PERCENT OF TOTAL FUEL CONSUMPTION	NUMBER OF MISSIONS	NUMBER EMPLOYMENT HOURS	AN	SAR	ELT	MP	PSS	TOTAL OF 5 MISSIONS	MISSION PERFORMANCE DAYS	
										TOTAL OF ALL MISSIONS	PERCENTAGE OF ALL MISSION PERFORMANCE DAYS
WHEC	32.0	414	83,339	-	436	1,109	1,140	-	2,685	3,488	77.0
WAGB	13.6	[illegible]	20,410	-	-	20	-	-	20	1,187	1.7
WMEC	8.2	[illegible]	[illegible]	-	420	1,588	384	-	2,392	2,910	82.2
WLB	7.0	2,122	53,806	2,683	-	15	489	-	3,187	3,975	80.2
WPB	4.1	9,172	58,450	-	3,121	310	249	2,341	6,021	6,898	87.3
WLM	2.1	1,146	16,679	1,882	-	-	60	-	1,942	1,942	100.0
WAGO	2.0	40	4,759	-	-	-	9	-	9	99	9.1
WYTL	-	3,160	17,717	-	-	120	-	-	120	276	43.5
WLV	-	-	-	1,484	-	-	-	-	1,484	1,484	100.0
TOTAL	89.0	17,197	308.068	6,049	3,977	3,162	2,331	3,341	17,860	22,259	-

AN: Aids to Navigation, SAR: Search & Rescue, MP: Military Preparedness, ELT: Enforcement Law & Treaties, PSS: Port Safety & Securities

*This table is derived from Reference 3.

TABLE 6. ASSUMED COAST GUARD VESSEL DUTY CYCLES

I. WHEC, WMEC, WAGB TYPE OF VESSELS

MODE	TYPICAL TIME (%)	HORSE POWER (%)
Slow	5	15
2/3	25	25
Cruise	69	55
Full	1	79

II. WPB 95 TYPES OF VESSELS

MODE	TYPICAL TIME (%)	HORSE POWER (%)
Slow	30	32
Cruise	70	72

III. WLB, WPB 82 TYPES OF VESSELS

MODE	TYPICAL TIME (%)	HORSE POWER (%)
IDLE	5	3
2/3	25	22
Cruise	70	60

IV. WHEC 327, TYPE OF VESSELS

MODE	TYPICAL TIME (%)	HORSE POWER
IDLE	5	BOILER
Cruise	70	
Full	25	

for the class vessels; this serves as a check on the accuracy of the method by comparison with CG fuel consumption records. Calculated horsepower-hours and fuel consumption are shown in Table 7. Where fuel consumption values calculated did not agree with Coast Guard records within a factor of three, the duty cycle was examined and adjusted.

Emissions were then calculated using equation (1). Emission factors were taken from reference 2. Table 8 summarizes the duty cycle and vessels whose emission factors were used for the calculation.

The results of the CO, NO_x, and THC emission calculations are given in Table 9.

In Table 10, the step-by-step procedure used in the emission calculation is shown. In Appendix B, a sample calculation following these steps is presented.

3.2 TOTAL FLEET EMISSIONS

3.2.1 Fleet Emissions CO_x, NO_x, THC

Total fleet emissions were estimated from underway emissions of the most active types of CG vessels (Table 9). The total fleet emission calculation consisted of the following steps:

1. Total fleet underway emissions are estimated by multiplying the emissions of the five types of vessels consuming the most fuel (Section 3.1) by the ratio of total fleet underway fuel to the fuel consumed by the five classes above.

2. The emissions generated by the ship-service generators and boilers are assumed 10 percent of the main propulsion emissions. Although rated output of the generators is approximately 10 percent of the rated propulsion power the load levels are lower. Boilers are assumed to emit at approximately the same level.

Total fleet pollutants (CO, NO_x, and THC) are calculated as shown by equation (3) below.

TABLE 7. FUEL CONSUMPTION BY COAST GUARD CUTTER CLASS

		NUMBER OF VESSELS	EACH VESSEL AVERAGE UNDERWAY HOURS	HP-HRS	FUEL COMSUMPTION ESTIMATE (GAL./YR	PREVIOUS FUEL CONSUMPTION RECORD (GAL./YR.)
WHEC	378	12	4000	1.3×10^7	$7.4 \times$	7.4×10^5
	327	6	3921	Boiler	$7.9 \times$	5.6×10^5
	311	3	-	5.6×10^7	3.2×1	3.2×10^5
	255	12	930	Boiler	1.9×10^5	4.3×10^5
WAGB	310	1	3523	3.3×10^7	1.8×10^6	1.8×10^6
	290	1	1129	6.3×10^6	3.5×10^5	2.5×10^5
	269	6	2626	1.4×10^7	8.0×10^5	7.1×10^5
	230	1	2268	5.4×10^6	3.0×10^5	2.6×10^5
WMEC	213	1	1800	2.5×10^6	1.4×10^5	1.3×10^5
	210A/B	16	2305	4.7×10^6	2.6×10^5	2.1×10^5
	205	3	1626	5.4×10^6	3.0×10^5	1.2×10^5
	143	2	2709	2.2×10^6	1.2×10^5	9.0×10^4
WLB	180A/B/C	36	1495	1.2×10^6	6.6×10^4	8.2×10^4
WPB	82	53	839	7.5×10^5	4.2×10^4	2.2×10^4
	95	26	537	5.2×10^5	2.9×10^4	3.4×10^4

TABLE 8. COAST GUARD CUTTER EMISSION CALCULATION DUTY CYCLE AND EMISSION FACTOR ASSUMPTIONS

CLASS	DUTY CYCLE*	APPLICABLE VESSEL**
WHEC 378	I	"Chase"
327	IV	"Campbell"
311	I	"Chase"
255	IV	"Campbell"
WMEC 210 A/B	I	"Decisive"
213	I	"Decisive"
205	I	"Decisive"
143	I	"Decisive"
WAGB 310	I	"Chase"
290	I	"Chase"
269	I	"Chase"
230	I	"Chase"
WPB 95	II	"Cape Horn"
82	III	"Point Jackson"
WLB 180 A/B	II	"Cowslip"

*Table 6

**Reference 2

TABLE 9. COAST GUARD VESSEL EMISSION ESTIMATION SUMMARY BY VESSEL CLASS

		Number of Vessels	Current Estimates (lbs./yr.)						Previous Estimates (lbs/yr.)					
			Average CO	Total CO	Average HC	Total HC	Average NOx	Total NOx	Average CO	Total CO	Average HC	Total HC	Average NOx	Total NOx
WHEC	378	12	$1.1x10^4$	$1.32x10^5$	$1.3x10^5$	$1.56x10^6$	$1.3x10^5$	$1.56x10^6$	$1.4x10^5$	$1.68x10^6$	$2.3x10^4$	$2.76x10^5$	$3.5x10^5$	$4.2x10^6$
	327	6	$3.9x10^3$	$2.34x10^4$	$7.2x10^2$	$4.32x10^3$	$3.0x10^4$	$1.8x10^5$	$1.5x10^4$	$9.0x10^4$	$1.4x10^4$	$8.4x10^5$	$8.6x10^4$	$5.16x10^5$
	311	3	$4.8x10^3$	$1.44x10^4$	$5.6x10^3$	$1.68x10^4$	$5.6x10^4$	$1.68x10^5$	$6.0x10^4$	$1.8x10^5$	$9.9x10^3$	$2.97x10^4$	$1.5x10^4$	$4.5x10^5$
	255	12	$9.3x10^2$	$1.12x10^4$	$1.7x10^2$	$2.04x10^3$	$7.0x10^3$	$8.4x10^4$	$8.4x10^3$	$1.0x10^5$	$7.5x10^3$	$9.0x10^4$	$4.6x10^4$	$5.52x10^5$
	Total 1	(33)		$(1.81x10^5)$		$(1.58x10^6)$		$(2.0x10^6)$		$(2.05x10^6)$		$(1.24x10^5)$		$(5.72x10^6)$
WAGB	310	1	$7.7x10^4$	$7.7x10^4$	$6.0x10^4$	$6.0x10^4$	$6.3x10^5$	$6.3x10^5$	$2.7x10^5$	$2.7x10^5$	$9.4x10^4$	$4.4x10^4$	$6.6x10^4$	$6.6x10^4$
	290	1	$1.5x10^4$	$1.5x10^4$	$1.1x10^4$	$1.1x10^4$	$1.2x10^5$	$1.2x10^5$	$5.8x10^4$	$5.8x10^4$	$9.6x10^3$	$9.6x10^3$	$1.5x10^5$	$1.5x10^5$
	269	6	$3.5x10^4$	$2.1x10^5$	$2.6x10^4$	$1.56x10^5$	$2.8x10^5$	$1.68x10^6$	$1.1x10^5$	$6.6x10^5$	$1.8x10^4$	$1.08x10^5$	$2.8x10^5$	$1.68x10^6$
	230	1	$1.3x10^4$	$1.3x10^4$	$9.7x10^3$	$9.7x10^3$	$1.0x10^5$	$1.0x10^5$	$4.1x10^4$	$4.1x10^4$	$6.7x10^3$	$6.7x10^3$	$1.0x10^5$	$1.0x10^5$
	Total 2	(9)		$(3.15x10^5)$		$(2.37x10^5)$		$(2.53x10^6)$		$(1.03x10^6)$		$(1.68.x10^5)$		$(2.0x10^6)$
WMEC	213	1	$1.0x10^4$	$1.0x10^4$	$1.2x10^3$	$1.2x10^3$	$3.1x10^4$	$3.1x10^4$	$2.4x10^4$	$2.4x10^4$	$4.0x10^3$	$4.0x10^3$	$6.0x10^4$	$6.0x10^4$
	210A/B	16	$1.3x10^4$	$2.1x10^5$	$1.6x10^4$	$2.5x10^4$	$4.0x10^4$	$6.4x10^5$	$3.0x10^4$	$4.9x10^5$	$5.1x10^3$	$8.1x10^4$	$8.0x10^4$	$1.2x10^6$
	205	3	$9.3x10^3$	$2.79x10^4$	$1.1x10^3$	$3.3x10^3$	$2.8x10^4$	$8.4x10^4$	$2.1x10^4$	$6.3x10^4$	$3.4x10^3$	$1.02x10^4$	$5.3x10^4$	$1.6x10^5$
	143	2	$1.6x10^4$	$3.2x10^4$	$1.9x10^3$	$3.8x10^3$	$4.7x10^4$	$9.4x10^4$	$1.5x10^4$	$3.0x10^4$	$2.4x10^3$	$4.8x10^3$	$3.7x10^4$	$7.4x10^4$
	Total 3	(22)		$(2.8x10^5)$		$(3.3x10^4)$		$(8.5x10^5)$		$(6.1x10^5)$		$(1.0x10^4)$		$(1.5x10^6)$
WLB	180'/a/c	36	$8.7x10^2$	$3.13x10^4$	$5.0x10^2$	$1.8c10^4$	$1.2x10^4$	$4.32x10^5$	$1.5x10^4$	$5.4x10^5$	$2.5x10^3$	$9.0x10^4$	$3.8x10^4$	$1.37x10^6$
	Total 4	(36)		$(3.13x10^4)$		$(1.8x10^4)$		$(4.3x10^5)$		$(5.4x10^5)$		$(9.0x10^4)$		$(1.37x10^6)$
WPB	82	53	$3.4x10^4$	$1.8x10^6$	$7.2x10^2$	$3.81x10^4$	$1.4x10^4$	$7.42x10^5$	$3.4x10^3$	$1.8x10^5$	$5.6x10^4$	$2.97x10^3$	$8.5x10^5$	$4.51x10^5$
	95	26	$3.3x10^3$	$8.58x10^4$	$7.3x10^2$	$1.90x10^4$	$6.2x10^3$	$1.61x10^5$	$4.9x10^3$	$1.27x10^5$	$8.1x10^3$	$2.11x10^4$	$1.2x10^4$	$3.12x10^5$
	Total 5	(79)		$(1.9x10^6)$		$(5.7x10^4)$		$(9.0x10^5)$		$(3.1x10^5)$		$(5.4x10^4)$		$(7.4x10^5)$
	TOTAL			$2.7x10^6$		$1.93x10^6$		$6.7x10^6$		$4.5x10^6$		$4.4x10^5$		$1.1x10^7$

TABLE 10. SAMPLE EMISSION CALCULATION STEPS

Steps	Sources of Data
1. Determine and plot underway operating hours at observed main diesel engines (M_1 & M_2) speed levels (RPM)	Machinery logs for one summer and one winter month of vessel operations (U.S. Coast Guard - reference 4).
2. From assumed power function (equation 2) calculate and plot each horsepower - propeller load at each observed speed level.	
3. Calculate percentage of time at various engine speed level duty cycle	
4. Distribute total underway hours to various speed level according to duty cycle.	Total underway hours (Tetra Tech., Inc. - reference 3)
5. From (1) and (2) calculate total horsepower-hours.	
6. Convert horsepower-hours to fuel consumption and check calculated fuel consumption with Coast Guard fuel usage records. If calculated fuel consumption is in agreement with fuel records proceed to emission calculations.	
7. Obtain emissions by multiplying emission rate (#lbs/hrs.) by operating hours at various speed level.	Mass. Emission Rate (Scott Research Lab. - reference 2).

$$Pt = \left[Pi \times \frac{\text{Total Fleet Underway Fuel}}{\text{Underway Fuel of Vessels Calculated}}\right] \times 1.1$$

$$+ Ei \times \text{Fleet In-Port Fuel} \times 7.2 \div 1000 \qquad (3)$$

$$(i = 1, 2, 3)$$

where Pi are the pollutants calculated from five major types of CG vessels,

$$P_1 = 2.7 \times 10^6 \text{ (lbs. yr.)} \qquad \text{(CO emissions)}$$

$$P_2 = 1.93 \times 10^6 \text{ (lbs./yr.)} \qquad \text{(THC emissions)} \qquad (4)$$

$$P_3 = 6.7 \times 10^6 \text{ (lbs./yr.)} \qquad (NO_x \text{ emissions})$$

Ei are the average of Scott Emission Factors for Boilers

$$E_1 = 2.44 \text{ (lbs./1000 lbs. Fuel)} \quad \text{(CO emissions)}$$

$$E_2 = 2.034 \text{ (lbs./1000 lbs. Fuel)} \quad \text{(THC emissions)} \qquad (5)$$

$$E_3 = 2/667 \text{ (lbs./100 lbs. Fuel)} \quad (NO_x \text{ emissions})$$

Total Fleet Underway Fuel = 4.1×10^7 (Gal./Yr.)
Underway Fuel of Vessels calculated = 3.44×10^7 (Gal./Yr.)
Fleet In Port Fuel = 7.2×10^6 (Gal./Yr.).

Therefore:

$$P_t(CO) = 3.67 \times 10^6 \text{ (lbs./yr.)} \qquad (6)$$

$$P_t(THC) = 2.64 \times 10^6 \text{ (lbs./yr.)}$$

$$P_t(NO_x) = 8.92 \times 10^6 \text{ (lbs./yr.)}$$

3.2.2 Total Fleet Emissions SO_x Particulates

Sulfur oxides emissions are calculated using fleet fuel sulfur average contents for diesel fuel and for boiler fuel (reference 2). SO_x emissions are assumed to be all of sulfur dioxide.

TABLE 11. COAST GUARD VESSEL TOTAL SO_x EMISSIONS

Diesel powered vessels =	1.15×10^6 (lbs/yr)
Boiler powered vessels =	2.02×10^6 (lbs/yr)
	3.17×10^6 (lbs/yr)

Particulate emissions are calculated in a similar manner, the emission factors, however, come from the earlier TSC report on CG emissions (reference 1). Diesel-powered vessels emissions factor was 15.8 lbs. per 1000 lbs. of fuel and boiler powered vessels emission factor was 0.0158 lbs. per 1000 lbs. of fuel. Total particulate emissions are 2.8×10^3 tons/year.

11. REFERENCES

1. "USCG Pollution Abatement Program: A Preliminary Study of Vessel and Boat Exhaust Emissions," R.A. Walter, A.J. Broderick, J.C. Sturm, E.C. Klaubert, Transportation Systems Center, Report No. DOT-TSC-USCG-72-3, Cambridge, MA, November 1971.

2. "A Study of Stack Emissions from Coast Guard Cutters" A.F. Souza, Scott Research Laboratories, Inc., Transportation Systems Center, Report No. DOT-TSC-USCG-73-1/CG-D-13-73, Cambridge, MA, September 1973.

3. "U.S. Coast Guard Energy Research and Development Program Plan," Interim Report prepared for the Commandant, U.S. Coast Guard, TT-A-436-74-126, Tetra Tech., Inc., Arlington, Virginia, December 1974.

4. Coast Guard Engine Machinery Logs.

5. National Emission Data, Emissions as of March 12, 1975, National Air Quality Branch, Environmental Protection Agency.

APPENDIX A - VESSEL CHARACTERISTICS

WHEC TYPE 378 CLASS, ENGINE CHARACTERISTICS

	Value	Source
Main engine HP	7,200	U.S. Coast Guard
Number of hours underway	4,000	Tetra Tech Report (reference 3)
Auxiliary engines	(2) 700 HP (1) 1000 HP Emergency (2) 3000 lb/hr boiler	U.S. Coast Guard
Fuel consumed per year		
Underway	7.4×10^5	U.S. Coast Guard
In-Port	6.6×10^4	U.S. Coast Guard
Total	8.0×10^5	U.S. Coast Guard

WHEC TYPE, 327 CLASS, ENGINE CHARACTERISTICS

Main engine HP (boiler)	(2) Boiler 3,100	U.S. Coast Guard
Number of hours underway	3,921	Tetra Tech Report (reference 3)
Auxiliary engines	(1) 300 HP Diesel Aux.	U.S. Coast Guard
Fuel consumed per year (gal./yr.)		
Underway	5.6×10^5	U.S. Coast Guard
In-Port	1.8×10^5	U.S. Coast Guard
Total	7.4×10^5	U.S. Coast Guard

WHEC TYPE, 311 CLASS, ENGINE CHARACTERISTICS

	Value	Source
Main engine HP	6,400	U.S. Coast Guard
Number of hours under	N.A.	
Auxiliary engines	(2) 480 HP Diesel (2) 292 HP Diesel (2) Boiler	U.S. Coast Guard
Fuel consumed per year (gal/yr)		
Underway	3.2×10^5	U.S. Coast Guard
In-Port	7.3×10^4	U.S. Coast Guard
Total	3.9×10^5	U.S. Coast Guard

WHEC TYPE, 255 CLASS, ENGINE CHARACTERISTICS

	Value	Source
Main engine HP (Boiler)	6,400	U.S. Coast Guard
Number of hours underway	930	Tetra Tech. Report (reference 3)
Auxiliary engines	(1) 143 Diesel	U.S. Coast Guard
Fuel consumed per year (gal/yr)		
Underway	4.3×10^5	U.S. Coast Guard
In-Port	9.4×10^4	U.S. Coast Guard
Total	5.2×10^5	U.S. Coast Guard

WAGB TYPE, 269 CLASS, ENGINE CHARACTERISTICS

	Value	Source
Main engine HP	12,000	U.S. Coast Guard
Number of hours underway	2,626	Tetra Tech Report (reference 3)
Auxiliary engines	(3) 900 HP Diesel Generator (1) 45 HP Diesel Generator (2) Boiler	U.S. Coast Guard
Fuel consumed per year (gal/yr)		
Underway	7.1×10^5	U.S. Coast Guard
In-Port	7.1×10^4	U.S. Coast Guard
Total	7.8×10^5	U.S. Coast Guard

WAGB TYPE, 310 CLASS, ENGINE CHARACTERISTICS

	Value	Source
Main engine HP	20,000	U.S. Coast Guard
Number of hours underway	3,523	Tetra Tech Report (reference 3)
Auxiliary engines	N.A. (4) 500 HP Diesel (2) Boiler	N.A.
Fuel consumed per year (gal/yr)		
Underway	1.8×10^6	U.S. Coast Guard
In-Port	9.6×10^4	U.S. Coast Guard
Total	1.9×10^6	U.S. Coast Guard

WAGB TYPE, 290 CLASS, ENGINE CHARACTERISTICS

	Value	Source
Main engine HP	12,000	U.S. Coast Guard
Number of hours underway	1,129	Tetra Tech Report
Auxiliary engines	(4) 500 HP Diesel (2) Boilers	N.A.
Fuel consumed per year (gal/yr)		
Underway	2.5×10^5	U.S. Coast Guard
In-Port	1.8×10^5	U.S. Coast Guard
Total	4.3×10^5	U.S. Coast Guard

WAGB TYPE, 230 CLASS, ENGINE CHARACTERISTICS

	Value	Source
Main engine HP	5,100	U.S. Coast Guard
Number of hours underway	2,268	Tetra Tech Report
Auxiliary engines	N.A.	N.A.
Fuel consumed per year (gal/yr)		
Underway	2.6×10^5	U.S. Coast Guard
In-Port	3.9×10^4	U.S. Coast Guard
Total	2.9×10^5	U.S. Coast Guard

WMEC TYPE, 210 A/B CLASS, ENGINE CHARACTERISTICS

	Value	Source
Main engine HP	4,425	U.S. Coast Guard
Number of hours underway	2,305	Tetra Tech Report
Auxiliary engines	(2) 350 HP Generator (1) 195 HP Emergency (2) Boiler	U.S. Coast Guard
Fuel consumed per year (gal/yr)		
Underway	2.1×10^5	U.S. Coast Guard
In-Port	2.5×10^4	U.S. Coast Guard
Total	2.4×10^5	U.S. Coast Guard

WMEC TYPE 213 CLASS, ENGINE CHARACTERISTICS

	Value	Source
Main engine HP	3,000	U.S. Coast Guard
Number of hours underway	1,800	Tetra Tech Report
Auxiliary engines	N.A.	N.A.
Fuel consumed per year (gal/yr)		
Underway	1.3×10^5	U.S. Coast Guard
In-Port	3.7×10^4	U.S. Coast Guard
Total	1.7×10^5	U.S. Coast Guard

WMEC TYPE, 205 CLASS, ENGINE CHARACTERISTICS

	Value	Source
Main engine HP	7,400	U.S. Coast Guard
Number of hours underway	1,626	Tetra Tech Report
Auxiliary engines	N.A.	N.A.
Fuel consumed per year (gal/yr)		
Underway	1.2×10^5	U.S. Coast Guard
In-Port	3.0×10^4	U.S. Coast Guard
Total	1.5×10^5	U.S. Coast Guard

WMEC TYPE, 143 CLASS, ENGINE CHARACTERISTICS

	Value	Source
Main engine HP	1,800	U.S. Coast Guard
Number of hours underway	2,709	Tetra Tech Report
Auxiliary engines	N.A.	N.A.
Fuel consumed per year (gal/yr)		
Underway	9.0×10^4	U.S. Coast Guard
In-Port	1.8×10^4	U.S. Coast Guard
Total	1.1×10^5	U.S. Coast Guard

WPB TYPE, 82 CLASS, ENGINE CHARACTERISTICS

	Value	Source
Main engine HP	1,800	U.S. Coast Guard
Number of hours underway	839	Tetra Tech Report
Auxiliary engines	(2) 80 HP Diesel (1) 21.6 HP Boiler	U.S. Coast Guard
Fuel consumed per year (gal/yr)		
Underway	2.2×10^4	U.S. Coast Guard
In-Port	2.2×10^3	U.S. Coast Guard
Total	2.4×10^4	U.S. Coast Guard

WPB TYPE, 95 CLASS, ENGINE CHARACTERISTICS

	Value	Source
Main engine HP	2,400	U.S. Coast Guard
Number of hours underway	537	Tetra Tech Report
Auxiliary engines	(2) 68 HP Diesel (1) Boiler (1) Burner	U.S. Coast Guard
Fuel consumed per year (gal/yr)		
Underway	3.4×10^4	U.S. Coast Guard
In-Port	4.8×10^3	U.S. Coast Guard
Total	3.9×10^4	U.S. Coast Guard

WLB TYPE, 180 CLASS, ENGINE CHARACTERISTICS

	Value	Source
Main engine HP	1,367	U.S. Coast Guard
Number of hours underway	1,495	Tetra Tech Report
Auxiliary engines	(1) 222 HP Diesel (1) 150 HP Diesel	U.S. Coast Guard
Fuel consumed per year (gal/yr)		
Underway	8.2×10^4	U.S. Coast Guard
In-Port	2.4×10^4	U.S. Coast Guard
Total	1.1×10^5	U.S. Coast Guard

APPENDIX B - SAMPLE CALCULATIONS

STEPS 1,2,3

(WHEC 378) - 3600H P @ 900 RPM

M_1:

Shaft RPM	Engine RPM	Mode	H.P.	(%)	HRS	(%)
75	460	Slow	548	(15.22)	5.6	(5.46)
95	560	2/3	951	(26.39)	29.0	(28.27)
125	742	Cruise	2091	(58.08)	67.0	(65.30)
145	840	Full	2917	(81.03)	1.0	(0.97)
					102.6	(100.00)

M_2:

Shaft RPM	Engine RPM	Mode	H.P.	(%)	HRS	(%)
75	450	Slow	516	(14.33)	5.6	(5.86)
95	550	2/3	904	(25.11)	20.0	(20.92)
125	720	Cruise	1922	(53.39)	69.0	(72.18)
145	820	Full	2767	(76.86)	1.0	(1.04)
					95.6	(100.00)

STEP 4

WHEC TYPE - HORSEPOWER (%) VS. UNDERWAY HOURS

M_1:

HP%	Mode	Hours
15.22	Slow	1/2(0.0546)(4000) = 109.2
26.39	2/3	1/2(0.2827)(4000) = 565.4
58.08	Cruise	1/2(0.6530)(4000) =1306.0
81.03	Full	1/2(0.0097)(4000) = 19.4
		2000.0

M_2:

14.33	Slow	1/2(0.0586)(4000) = 117.2
25.11	2/3	1/2(0.2092)(4000) = 418.4
53.39	Cruise	1/2(0.7218)(4000) =1443.6
76.86	Full	1/2(0.0104)(4000) = 20.8
		2000.0

STEPS 5,6

WHEC TYPE (UNDERWAY HP-HRS)

M_1=

RPM	HP(%)	HP x TOT HRS	HP-HRS
460	15.22	.1522 x 7200 x 109.2 =	119,665
560	26.39	.2639 x 7200 x 565.4 =	1,074,305
742	58.08	.5808 x 7200 x1306.0 =	5,461,378
840	81.03	.8103 x 7200 x 19.4 =	113,182
			6,768,530

M_2=

450	14.33	.1433 x 7200 x 117.2 =	120,922
550	25.11	.2511 x 7200 x 418.4 =	756,433
720	53.39	.5339 x 7200 x1443.6 =	5,549,313
840	76.86	.7686 x 7200 x 20.8 =	115,105
			6,541,722

TOTAL HP-HRS = 13,310,252

Total yearly fuel consumption = $(13.3 \times 10^6)(0.4)(\frac{1}{7.2})$ =

7.39×10^5 gal/yr

(The calculated fuel consumption, 7.39×10^5 gal., is in agreement with the value of 7.4×10^5 gal. reported in reference 1. Therefore, proceed to calculate emissions - STEP 7).

STEP 7

"CHASE" EMISSION RATE (SCOTT RESEARCH LAB. REPORT) - 3600 H.P. @900 RPM

	RPM	%H.P.	CO	HC	NO_x	PART
M_1	460	15.22	4.20	1.77	10.86	-
M_1	560	26.39	2.19	1.69	22.06	-
M_1	742	58.08	3.87	2.75	33.31	-
M_1	840	81.03	10.20	4.10	42.69	5.832
M_2	450	14.33	3.82	1.50	8.95	1.921
M_2	550	25.11	1.20	1.37	20.78	-
M_2	600	-	7.96	3.47	42.26	3.288
M_2	720	53.39	2.28	5.28	38.80	-
M_2	800	76.86	11.29*	5.59*	57.8*	11.244
M_2	840	-	(7.58 15.00)	(5.58 5.59)	(52.28 63.32)	-

*Average Number

WHEC 378 CLASS - EMISSION CALCULATION:

Yearly Emissions = Emission Rate (lbs/hr) x hours

M_1

RPM	Mode	CO(lbs)	HC(lbs)	NO_x(lbs)
460	Slow	458.60	193.30	1185.90
560	2/3	1238.20	955.50	12472.70
742	Cruise	5054.20	3591.50	43502.90
840	Full	197.90	79.50	828.20
Total 1		6948.90	4819.80	57989.70

M_2

450	Slow	447.70	175.80	1048.90
550	2/3	502.10	573.20	8694.40
720	Cruise	3291.40	7622.20	56011.70
820	Full	234.80	116.30	1202.20
Total 2		4476.00	8487.50	66957.20
Total 1+2		11424.90	13307.30	124946.90
		$=1.1 \times 10^4$	$=1.3 \times 10^4$	$=1.3 \times 10^5$

WMEC 210 CLASS - EMISSION CALCULATION:

Yearly Emission = Emission Rate (lbs/hr) x hours

M_1

RPM	CO	HC	NO_x
460	0	0	0
560	10,061.07	1,115.58	30,162.36
742	72,247.92	12,884.21	389,983.50
840	1,466.73	332.16	5,813.28
$\Sigma 1$	83,775.72	14,331.95	275,959.14

M_2

450	0	151.28	0
550	14,041.85	1,103.29	28,380.73
720	111,803.91	9,503.33	327,984.77
820	1,726.02	247.40	8,342.43
$\Sigma 2$	127,571.78	11,005.30	364,707.93

$\Sigma 2+\Sigma 1$:

211,347.50	25,337.25	640,667.07
$=2.1 \times 10^5$ lbs	$=2.5 \times 10^4$ lbs	$=6.4 \times 10^5$ lbs

Previous estimates:

4.1×10^5 lbs	8.1×10^4 lbs	1.23×10^6 lbs