Inhalation Health Risk Assessment of Air Toxic Emissions from Large Combustion Turbine Power Projects

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ABSTRACT

Power generation from combustion turbine projects continues to grow throughout the world. With natural gas as the most common primary fuel, and low-sulfur #2 oil as the backup fuel, combustion turbines are among the cleanest forms of fossil power generation. The combination of clean fuels and high thermal efficiency results in low emissions per megawatt of electrical power generated by these units. Yet, low emissions and high efficiency does not allow these units to escape the scrutiny of environmental regulators.

The Legislative and Regulatory Affairs committee of the American Society of Mechanical Engineers (ASME), International Gas Turbine Institute (IGTI), has followed the developments in the combustion turbine industry and the regulatory community. The advent of the Industrial Combustion Coordinated Rulemaking (ICCR) program and Maximum Achievable Control Technology (MACT) guidelines for combustion sources can have a significant impact on combustion turbine projects. Health risk assessments from air toxic emissions are one of the major issues requiring evaluation.

This paper discusses the results of a preliminary inhalation health risk assessment of air toxic emissions from four power plant configurations (nominal ratings): (1) a 184 MW simple cycle combustion turbine, (2) a 184 MW combustion turbine operating in a combined-cycle mode, (3) a 40 MW simple cycle combustion turbine, and (4) a 40 MW combustion turbine operating in a combined-cycle mode. Evaluations were performed for both natural gas and #2 oil fuels. Emissions were modeled for five (5) years to evaluate increased cancer risk, and both acute and chronic non-cancer health risks associated with these projects. The results of this study demonstrate that health risks from combustion turbines firing either natural gas or #2 oil are within acceptable limits.

INTRODUCTION

Power generation from combustion turbine projects continues to grow throughout the world. With natural gas as the most common primary fuel, and low-sulfur #2 oil as the backup fuel, combustion turbines are among the cleanest forms of fossil power generation. The combination of clean fuels and high thermal efficiency results in low emissions per megawatt of electrical power generated by these units. Yet, low emissions and high efficiency does not allow these units to escape the scrutiny of environmental regulators.

The Clean Air Act Amendments of 1990[1] require regulation of air emissions from several categories of industrial combustion sources, including boilers, process heaters, waste incinerators, combustion turbines, and internal combustion engines. The industrial combustion regulations affect thousands of sources nationwide, and have significant environmental and health impacts and cost considerations. The Environmental Protection Agency (EPA) has implemented the Industrial Combustion Coordinated Rulemaking (ICCR) to develop recommendations for Federal air emission regulations that address the various combustion source categories and pollutants. Regulations will be developed under sections 111, 112 and 129 of the Clean Air Act.

The overall goal of ICCR is to develop recommendations for a unified set of Federal air regulations that will maximize environmental and public health benefits in a flexible framework at a reasonable cost of compliance, staying within the constraints of the Clean Air Act.[2]

The Legislative and Regulatory Affairs Committee of the American Society of Mechanical Engineers (ASME), International Gas Turbine Institute (IGTI), has followed the developments in the combustion turbine industry and the regulatory community. The advent of the ICCR program and Maximum Achievable Control Technology (MACT) guidelines for power plant combustion sources can have a significant impact on combustion turbine projects. Health risk assessments from air toxic emissions are one of the major issues requiring evaluation.

A subcommittee of the ICCR Coordinating Committee is the Combustion Turbine Work Group (CTWG). One of the major roles of the CTWG is to provide recommendations focused toward combustion turbines, which includes air toxic emissions. The CTWG is evaluating available test data for air toxic emissions, and developing a coordinated emissions testing protocol for the collection of additional air toxic emissions, if needed. The testing program, if needed, will evaluate emissions before and after emissions control equipment to assist in the determination of the MACT Floor for new and existing sources.

In an effort to begin the evaluation, General Electric[3] engineers performed a survey of combustion turbine hazardous air pollutant emission factors in an attempt to establish true emissions for turbine engines, rather than using emission factors related to boilers, furnaces, and reciprocating engines.

This paper utilizes the General Electric median emission factors to calculate emissions rates for this study. These emissions were used to perform a preliminary inhalation health risk assessment of air toxic emissions from four power plant configurations: (1) a 184 MW simple cycle combustion turbine, (2) a 184 MW combustion turbine operating in a combined-cycle mode, (3) a 40 MW simple cycle combustion turbine, and (4) a 40 MW combustion turbine operating in a combined-cycle mode. Evaluations were performed for both natural gas and #2 oil fuels. Emissions were modeled for five (5) years to evaluate both acute and chronic health risks associated with these projects.

Health Risk Assessment Procedure

The state of California has been a leader in the development and implementation of cancer risk factors and non-cancer reference exposure levels (REL) for use in health risk assessments. The Air Toxics "Hot Spots" Act of 1987 (AB 2588)[4] began a long-term program to identify, assess, and control ambient levels of air toxic pollutants. A health risk assessment for air toxic emissions is a detailed and comprehensive analysis to evaluate and predict the dispersion of hazardous substances in the environment. As part of the evaluation, the health risk assessment studies the potential for exposure to human populations, and to assess and quantify both the individual and population wide health risks associated with those levels of exposure.[5]

Table 1 lists the published cancer unit risk factors[6], $(ug/m^3)^{-1}$, for those air toxic pollutants identified by General Electric[3] that may be found in combustion turbine exhausts. Risk was determined by multiplying the chemical's 5-year average concentration by the risk factor. Risks associated with different chemicals are additive.

Based on "Facility Prioritization Guidelines" for existing sources prepared by the AB2588 Risk Assessment Committee of the California Air Pollution Control Officers Association, facilities with both carcinogenic and non-carcinogenic unit risk factors of less than 1×10^{-5} are to be designated "low priority," facilities with unit risk factors of greater than 1×10^{-4} are to be designated "high priority," and facilities with unit risk factors between 1×10^{-5} and 1×10^{-4} are to be designated using additional factors. If a facility has a carcinogenic risk factor and non-carcinogenic unit risk factor that fall into different prioritization categories, the higher prioritization of the two categories is to be used. Facilities that are designated as "high priority" must prepare and submit a health risk assessment to the local air pollution control district.[7]

The California Air Resources Board's "Risk Management Guidelines for New and Modified Sources of Toxic Air Pollutants" provides risk assessment guidance for new and modified sources. In the document, all sources that have a potential cancer risk factor of greater than 1×10^{-6} must utilize Toxic Best Available Control Technology (T-BACT). T-BACT is defined as the most effective emissions limitation or control technique which has been achieved in practice for such permit unit category or class of source, or any other technique found to be technically and economically feasible by the local Air Pollution Control Officer. If T-BACT is used, districts are advised to approve new sources if the potential cancer risk is less than 1×10^{-5}, to deny new sources if the potential cancer risk is greater than 1×10^{-4}, and to approve sources with risks between 1×10^{-5} and 1×10^{-4} based on specific findings.[8]

Table 1 also lists the published chronic and acute non-cancer reference exposure limit (REL) hazard indexes, (ug/m^3). A chronic non-cancer hazard index is calculated by dividing the chemical's 5-year average concentration by the chronic REL. An acute non-cancer hazard index is calculated by dividing the chemical's maximum 1-hour average concentration by the acute REL. In general, a hazard index sum greater than 1.0 indicates a potential for adverse health effects.[7]

Non-carcinogenic adverse health effects for new and modified sources are evaluated by calculating the Total Hazard Index (THI) for each source. THI values are calculated by determining the chronic non-cancer hazard index for every air toxic chemical emitted from the source, and summing the chronic non-cancer hazard indexes that affect the same target organ. Sources that have a THI value greater than 0.2 must utilize T-BACT. If T-BACT is used, districts are advised to approve new sources if the THI is less than 1, to deny new sources if the THI is greater than 10, and to approve sources with THI values between 1 and 10 based on specific findings. THI values were not calculated in this study because, in all cases, the sum of all chronic non-cancer hazard indexes from the source is less than 1.0. Since THI values are a subset of chronic non-cancer hazard indexes, all THI values will be less than 1.0 as well.

MODELING STUDY

In order to obtain typical air quality impacts, a hypothetical site in Northern California was selected for the modeling study. The California site was selected to evaluate emission sources in a combination of simple, intermediate, and complex terrain. Five years of pre-processed meteorological data from Redding Airport (1987-1991) was used for input into the Industrial Source Complex Short-Term dispersion model (Bee-Line Software, Version 6.0 for Windows 95). Terrain features from the U. S. Geological Survey were obtained on CD-ROM for input into the model.

The receptor grid was: fenceline at 50 meter increments, 100 meter rectangular coordinates out to 2 km, 200 meters out to 5 km, and 500 meters out to 15000 km. A total of eight (8) cases were modeled at base (100%) load for the entire year:

Case 1	184 MW simple cycle combustion turbine firing natural gas with dry low NO_x (DLN) combustors, 70 ft stack height
Case 2	184 MW combustion turbine operating in a combined cycle mode, natural gas fuel, DLN, 175 ft stack height
Case 3	40 MW simple cycle, natural gas, DLN, 50 ft stack height
Case 4	40 MW combustion turbine operating in a combined cycle mode, natural gas fuel, DLN, 150 ft stack height
Case 5	184 MW simple cycle, #2 oil for 40 days (remainder of days gas fired), water injection for NO_x control on oil, 70 ft stack height
Case 6	184 MW combustion turbine operating in a combined cycle mode, #2 oil for 40 days (remainder gas fired), water injection for NO_x control on oil, 175 ft stack height
Case 7	40 MW simple cycle, #2 oil for 40 days (remainder gas fired), water injection for NO_x control on oil, 50 ft stack height
Case 8	40 MW combustion turbine operating in a combined cycle mode, #2 oil for 40 days (remainder gas fired), water injection for NO_x control on oil, 150 ft stack height

The complete set of exhaust parameters (excluding hypothetical X, Y coordinates) can be found in Table 2 for natural gas, and Table 3 for the #2 oil firing (for those days when oil was fired). Based on typical building dimensions and design criteria, the stack heights were considered to be Good Engineering Practice (GEP), and therefore, aerodynamic downwash effects were not evaluated. Modeling was run with a 1 lb/hr emission rate for all cases, and the corresponding maximum 1-hour and annual impacts (ug/m^3) for each pollutant were calculated by multiplying the actual emission rate (lb/hr) by the ground level impact corresponding to 1 lb/hr. To be conservative, the maximum 1-hour impact from all 5-years modeled was used for the acute impacts.

Table 4 lists the ground level impacts for the natural gas runs (1-4), and Table 5 lists the ground level impacts for the combination #2 oil/natural gas-fired runs (5-8).

Tables 6 and 7 list the cancer risk factors for the natural gas (1-4) and #2 oil/natural gas-fired runs (5-8), respectively. The total cancer risk factors ranged from 1.11E-6 to 4.48E-6 for natural gas. For the larger units with 40 days of oil firing (remainder of days on natural gas), the cancer risk factors ranged from 5.09E-6 to 9.48E-6. For the smaller units with 40 days of oil firing (remainder natural gas), the cancer risk factors ranged from 2.96E-6 to 4.591E-6. For all eight combinations, the cancer risk factors were in the acceptable ($<10^{-5}$) range.

Tables 8 and 9 list the chronic non-cancer hazard indices for natural gas and the combination #2 oil/natural gas-fired runs, respectively. The indices ranged from 0.0108 to 0.0436 for natural gas. For the larger units with 40 days of oil firing, the chronic non-cancer hazard indices ranged from 0.05 to 0.09. For the smaller units with 40 days of oil firing, the chronic non-cancer hazard indices ranged from 0.028 to 0.044. These levels are all considered to be acceptable risk in comparison to the guideline of 1.0, where values above 1.0 are considered unacceptable.

Tables 10 and 11 list the acute non-cancer hazard indices for natural gas and #2 oil/natural gas-fired runs, respectively. The indices ranged from 0.0004 to 0.0013 for natural gas. For the larger units with 40 days of oil firing, the acute non-cancer hazard indices ranged from 0.15 to 0.21. For the smaller units with 40 days of oil firing, the acute non-cancer hazard indices ranged from 0.08 to 0.09. These levels are all considered to be acceptable risk in comparison to the guideline of 1.0.

Need For Further Study

The CTWG of ICCR is pursuing the necessary study to complete the evaluation of air toxic emissions from combustion turbines. More accurate and thorough emissions data may be required to obtain representative emission factors for the various sizes and types of combustion turbines.

The impact of control equipment (e.g., oxidation catalysts for carbon monoxide control; DLN, catalytic combustors, or selective catalytic reduction (SCR) for NO_x control) on air toxic emissions need to be ascertained. In some cases, ammonia injection for SCR systems may contribute to non-cancer hazards.

The effect of background ambient air quality on combustion turbine emissions is critical given the high volume of air that passes through combustion turbines. As discussed in the General Electric[3] study, inorganic hazardous air pollutants may pass unchanged through the combustion zone. The large air flow rates through combustion turbines justifies consideration of an EPA-approved emissions adjustment for air toxic pollutants in the ambient air.

Gas turbine combustion equipment is manufactured using some advanced technology alloys and coatings to withstand high-temperature environments. As these parts slowly wear and erode, a process that may take many years, they may release small quantities of these coatings into the exhaust stream.[3] The expected contribution, if measurable, could be determined in further research.

Finally, variations in plant layouts, stack design (e.g., non-GEP stack heights), and operating loads (part load operation) may require evaluation due to the impact on dispersion characteristics. Short stacks (aerodynamic downwash) and part-load operation (less plume buoyancy) can have a significant effect on the dispersion of air pollutants and ground-level impacts.

CONCLUSION

The results of this preliminary health risk assessment for combustion turbines are as follows:

1. Based upon the use of natural gas emission factors, it appears that the ground level impacts will not pose significant cancer health risks to individuals living at the point of maximum ground-level impacts. Based upon the use of #2 oil emission factors with 40 days of oil-firing, it appears that the ground level impacts will also not pose significant cancer health risks to individuals living at the point of maximum ground-level impacts.
2. Non-cancer chronic and acute health risks were found to be acceptable for all eight (8) cases.
3. Even though the stack heights were higher, the ground-level impacts from combined-cycle plant operation were higher than those from simple cycle operation because of the added plume buoyancy and momentum rise (dispersion enhancement) associated with simple cycle operation.
4. Further study is needed to obtain more accurate emissions data, to evaluate impacts of ambient air quality on combustion turbine emissions, to evaluate the impacts of control equipment on air toxic emission rates, to evaluate various plant operating scenarios and designs, and to determine if there is measurable erosion of metal components during combustion (that may contribute to air toxic emissions).

REFERENCES

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2. Introductory Statement from ICCR Committee document, http://134.67.104.12/G-DRIVE/ICCR/DIRSM/INTRO1.TXT
3. Feitelberg, A., Chalfin, J., Torosian, J., Schorr, M., Sumner, J., and Sabla, P. *Survey of Gas Turbine Hazardous Air Pollutant Emission Factors*, Air & Waste Management Association 90th Annual Meeting & Exhibition, Paper 97-RP144.03, June, 1997.
4. California Health and Safety Code, Sections 44300-44394.
5. California Statutes, *Air Toxics "Hot Spots" Information and Assessment*, Chapter 1, Section 44306 (1988).
6. California Air Pollution Control Officers Association (CAPCOA), Air Toxicology Unit of the Office of Environmental Health Hazard Assessment, and the Special Project Section of the Toxic Air Contaminant Research Identification Branch, California Air Resources Board. *Air Toxics "Hot Spots" Program, Revised 1992, Risk Assessment Guidelines*, October, 1993.
7. California Air Pollution Control Officers Association (CAPCOA), Air Toxicology Unit of the Office of Environmental Health Hazard Assessment, and the Special Project Section of the Toxic Air Contaminant Research Identification Brach, California Air Resources Board. *Air Toxics "Hot Spots" Program: Facility Prioritization Guidelines*, July, 1990.
8. California Environmental Protection Agency Air Resources Board, *Proposed Risk Management Guidelines for New and Modified Sources of Toxic Air Pollutants*, June, 1993.

Table 1. Gas and Oil Median Emission Factors, Cancer Unit Risk Factors $(ug/m^3)^{-1}$, and Reference Exposure Limits (ug/m^3) for Select Hazardous Air Pollutants.

Pollutant	Gas ($lb/10^6$ lb fuel)	Oil ($lb/10^6$ lb fuel)	Unit Risk Factor $(ug/m^3)^{-1}$	Chronic Non-Cancer REL (ug/m^3)	Acute Non-Cancer REL (ug/m^3)
1,3 Butadiene	ND	0.4	1.70E-04	--	--
Acetaldehyde	BDL	2.9	2.70E-06	9	--
Acrolein	ND	0.2	--	2.00E-02	2.5
Arsenic	0.003	0.003	3.30E-03	0.5	--
Benzene	<Ambient	0.8	2.90E-05	71	--
Beryllium	BDL	0.003	2.40E-03	4.80E-03	--
Cadmium	BDL	0.02	4.20E-03	3.5	--
Chromium	0.03	0.4	1.50E-01	2.00E-03	--
Cyanide Cmpds	ND	3.4	--	70	--
Formaldehyde	BDL	2.8	6.00E-06	3.6	370
Lead	0.01	0.2	8.00E-05	1.5	--
Manganese	0.06	0.3	--	0.4	--
Mercury	0.01	0.02	--	0.3	30
Nickel	0.02	3	2.60E-04	0.24	1
Phosphorus	0.2	2.5	--	0.007	--
Polycyclic Organics	0.004	0.2	1.70E-07	--	--
Selenium	BDL	0.06	1.40E-04	0.5	2
Styrene	BDL	0.2	5.70E-07	700	--
Toluene	0.5	<Ambient	--	200	--
Xylenes	ND	<Ambient		300	4400

ND = No data available BDL = Below detectable limit

Note: for the purposes of this study, emission rates for air toxics with emission factors containing ND, BDL, and <Ambient were not considered in the calculation of potential health risks.

Table 2. Modeling Parameters for Health Risk Assessment, Natural Gas-Fired Runs.

		Natural Gas Runs			
Parameter	**Units**	**Case 1**	**Case 2**	**Case 3**	**Case 4**
Type of Operation		SC	CC	SC	CC
Combustion turbine Load	MW	184	184	40	40
Fuel		Gas	Gas	Gas	Gas
NOx Control		DLN	DLN	DLN	DLN
Stack Height	ft	75	175	50	150
Stack Diameter	ft	19	18	10	9.5
Fuel Flow Rate	lb/hr	80,650	80,650	20,000	20,000
Fuel Heating Value, LHV	Btu/lb	20,979	20,979	20,979	20,979
Fuel Heating Value, HHV	Btu/lb	23,287	23,287	23,287	23,287
Heat Input, LHV	10^6 Btu/hr	1,692	1,692	420	420
Heat Input, HHV	10^6 Btu/hr	1,878	1,878	466	466
Exhaust Flow Rate	lb/hr	3,808,170	3,808,170	1,122,000	1,122,000
Stack Exit Temperature	deg F	1050	180	1000	200
Stack Exit Flow Rate	acfm	2,530,624	1,072,582	720,908	325,890
Stack Exit Velocity	ft/sec	148.8	70.2	153.0	76.6

Table 3. Modeling Parameters for Oil-fired Operation.

		#2 Oil and Gas-Fired Runs			
Parameter	**Units**	**Case 5**	**Case 6**	**Case 7**	**Case 8**
Type of Operation		SC	CC	SC	CC
Combustion turbine Load	MW	184	184	40	40
Fuel Type		Oil (40 days)			
NO_x Control		Water Injection, WI (oil)			
Stack Height	ft	75	175	50	150
Stack Diameter	ft	19	18	10	9.5
Fuel Flow Rate	lb/hr	99,120	99,120	24,290	24,290
Fuel Heating Value, LHV	Btu/lb	18,759	18,759	18,759	18,759
Fuel Heating Value, HHV	Btu/lb	19,885	19,885	19,885	19,885
Heat Input, LHV	10^6 Btu/hr	1,859	1,859	456	456
Heat Input, HHV	10^6 Btu/hr	1,971	1,971	483	483
Exhaust Flow Rate	lb/hr	3,855,640	3,855,640	1,148,000	1,148,000
Stack Exit Temperature	deg F	1050	286	1000	290
Stack Exit Flow Rate	acfm	2,564,490	1,266,960	738,433	379,332
Stack Exit Velocity	ft/sec	150.7	83.0	156.7	89.2

Table 4. Ground Level Impacts (ug/m^3) for Natural Gas Runs 1-4.

		Natural Gas Runs			
Parameter		**Case 1**	**Case 2**	**Case 3**	**Case 4**
Fuel Type		Gas	Gas	Gas	Gas
1-Hour Average for 1 lb/hr Emission Rate	1987	0.479	0.800	1.052	1.299
	1988	0.490	0.790	1.053	1.237
	1989	0.479	0.783	1.054	1.278
	1990	0.479	0.797	1.045	1.248
	1991	0.478	0.786	1.055	1.251
	Maximum	**0.490**	**0.800**	**1.055**	**1.299**
Annual Average for 1 lb/hr Emission Rate	1987	0.006	0.014	0.013	0.027
	1988	0.005	0.011	0.010	0.023
	1989	0.005	0.012	0.013	0.022
	1990	0.005	0.012	0.013	0.021
	1991	0.006	0.013	0.013	0.025
	5-year avg.	**0.005**	**0.012**	**0.012**	**0.024**
Pollutant		**Maximum 1-Hour Impact (ug/m^3)**			
1,3 Butadiene		--	--	--	--
Acetaldehyde		--	--	--	--
Acrolein		--	--	--	--
Arsenic		1.187E-04	1.936E-04	6.331E-05	7.794E-05
Benzene		--	--	--	--
Beryllium		--	--	--	--
Cadmium		--	--	--	--
Chromium		1.187E-03	1.936E-03	6.331E-04	7.794E-04
Cyanide Compounds		--	--	--	--
Formaldehyde		--	--	--	--
Lead		3.956E-04	6.455E-04	2.110E-04	2.598E-04
Manganese		2.373E-03	3.873E-03	1.266E-03	1.559E-03
Mercury		3.956E-04	6.455E-04	2.110E-04	2.598E-04
Nickel		7.911E-04	1.291E-03	4.221E-04	5.196E-04
Phosphorus		7.911E-03	1.291E-02	4.221E-03	5.196E-03
Polycyclic Organics		1.582E-04	2.582E-04	8.442E-05	1.039E-04
Selenium		--	--	--	--
Styrene		--	--	--	--
Toluene		1.978E-02	3.227E-02	1.055E-02	1.299E-02
Xylenes		--	--	--	--
		Maximum 5-Year Average Impact (ug/m^3)			
1,3 Butadiene		--	--	--	--
Acetaldehyde		--	--	--	--

Table 4. Ground Level Impacts (ug/m^3) for Natural Gas Runs 1-4 (continued).

		Natural Gas Runs			
Parameter		**Case 1**	**Case 2**	**Case 3**	**Case 4**
Fuel Type		Gas	Gas	Gas	Gas
		Maximum 5-Year Average Impact (ug/m^3)			
Acrolein		--	--	--	--
Arsenic		1.254E-06	2.979E-06	7.402E-07	1.410E-06
Benzene		--	--	--	--
Beryllium		--	--	--	--
Cadmium		--	--	--	--
Chromium		1.254E-05	2.979E-05	7.402E-06	1.410E-05
Cyanide Compounds		--	--	--	--
Formaldehyde		--	--	--	--
Lead		4.179E-06	9.931E-06	2.467E-06	4.701E-06
Manganese		2.508E-05	5.959E-05	1.480E-05	2.820E-05
Mercury		4.179E-06	9.931E-06	2.467E-06	4.701E-06
Nickel		8.359E-06	1.986E-05	4.934E-06	9.402E-06
Phosphorus		8.359E-05	1.986E-04	4.934E-05	9.402E-05
Polycyclic Organics		1.672E-06	3.972E-06	9.869E-07	1.880E-06
Selenium		--	--	--	--
Styrene		--	--	--	--
Toluene		2.090E-04	4.966E-04	1.234E-04	2.350E-04
Xylenes		--	--	--	--

Table 5. Ground Level Impacts (ug/m^3) for #2 Oil and Gas-Fired Runs 5-8.

		#2 Oil and Gas-Fired Runs			
Parameter	**Year**	**Case 5**	**Case 6**	**Case 7**	**Case 8**
Fuel Type		Oil (40 days); Gas (325 days)			
1-Hour Average for 1 lb/hr Emission Rate	1987	0.47558	0.6794	1.03786	1.18474
	1988	0.48613	0.67961	1.03369	1.07434
	1989	0.47558	0.66938	1.03968	1.06802
	1990	0.47493	0.67747	1.03079	1.07602
	1991	0.47462	0.67165	1.04152	1.14087
	Maximum	**0.48613**	**0.67961**	**1.04152**	**1.18474**
Annual Average for 1 lb/hr Emission Rate	1987	0.00615	0.00958	0.01263	0.01877
	1988	0.00460	0.00775	0.01002	0.01530
	1989	0.00496	0.00775	0.01281	0.01652
	1990	0.00452	0.00753	0.01280	0.01612
	1991	0.00551	0.00874	0.01232	0.01641
	5-year avg.	**0.00515**	**0.00827**	**0.01212**	**0.01662**

Table 5. Ground Level Impacts (ug/m^3) for #2 Oil and Gas-Fired Runs 5-8 (continued).

		#2 Oil and Gas-Fired Runs			
Parameter	**Year**	**Case 5**	**Case 6**	**Case 7**	**Case 8**
Fuel Type		Oil (40 days); Gas (325 days)			
Pollutant		**Maximum 1-Hour Impact (ug/m^3)**			
1,3 Butadiene		1.927E-02	2.695E-02	1.012E-02	1.151E-02
Acetaldehyde		1.397E-01	1.954E-01	7.337E-02	8.345E-02
Acrolein		9.637E-03	1.347E-02	5.060E-03	5.755E-03
Arsenic		1.446E-04	2.021E-04	7.590E-05	8.633E-05
Benzene		3.855E-02	5.389E-02	2.024E-02	2.302E-02
Beryllium		1.446E-04	2.021E-04	7.590E-05	8.633E-05
Cadmium		9.637E-04	1.347E-03	5.060E-04	5.755E-04
Chromium		1.927E-02	2.695E-02	1.012E-02	1.151E-02
Cyanide Compounds		1.638E-01	2.290E-01	8.601E-02	9.784E-02
Formaldehyde		1.349E-01	1.886E-01	7.084E-02	8.058E-02
Lead		9.637E-03	1.347E-02	5.060E-03	5.755E-03
Manganese		1.446E-02	2.021E-02	7.590E-03	8.633E-03
Mercury		9.637E-04	1.347E-03	5.060E-04	5.755E-04
Nickel		1.446E-01	2.021E-01	7.590E-02	8.633E-02
Phosphorus		1.205E-01	1.684E-01	6.325E-02	7.194E-02
Polycyclic Organics		9.637E-03	1.347E-02	5.060E-03	5.755E-03
Selenium		2.891E-03	4.042E-03	1.518E-03	1.727E-03
Styrene		9.637E-03	1.347E-02	5.060E-03	5.755E-03
Toluene		--	--	--	--
Xylenes		--	--	--	--
		Maximum 5-Year Average Impact (ug/m^3)			
1,3 Butadiene		2.237E-05	3.593E-05	1.290E-05	1.770E-05
Acetaldehyde		1.622E-04	2.605E-04	9.353E-05	1.283E-04
Acrolein		1.118E-05	1.797E-05	6.450E-06	8.850E-06
Arsenic		1.284E-06	2.922E-06	7.558E-07	1.388E-06
Benzene		4.474E-05	7.187E-05	2.580E-05	3.540E-05
Beryllium		1.678E-07	2.695E-07	9.676E-08	1.328E-07
Cadmium		1.118E-06	1.797E-06	6.450E-07	8.850E-07
Chromium		3.353E-05	6.246E-05	1.949E-05	3.026E-05
Cyanide Compounds		1.901E-04	3.054E-04	1.097E-04	1.505E-04
Formaldehyde		1.566E-04	2.515E-04	9.031E-05	1.239E-04
Lead		1.491E-05	2.681E-05	8.647E-06	1.304E-05
Manganese		3.910E-05	8.001E-05	2.286E-05	3.839E-05
Mercury		4.840E-06	1.064E-05	2.842E-06	5.071E-06

Table 5. Ground Level Impacts (ug/m^3) for #2 Oil and Gas-Fired Runs 5-8 (continued).

		#2 Oil and Gas-Fired Runs			
Parameter	**Year**	**Case 5**	**Case 6**	**Case 7**	**Case 8**
Fuel Type		Oil (40 days); Gas (325 days)			
		Maximum 5-Year Average Impact (ug/m^3)			
Nickel		1.752E-04	2.872E-04	1.011E-04	1.411E-04
Phosphorus		2.142E-04	4.014E-04	1.246E-04	1.943E-04
Polycyclic Organics		1.267E-05	2.150E-05	7.329E-06	1.052E-05
Selenium		3.355E-06	5.390E-06	1.935E-06	2.655E-06
Styrene		1.118E-05	1.797E-05	6.450E-06	8.850E-06
Toluene		1.861E-04	4.421E-04	1.098E-04	2.093E-04
Xylenes		--	--	--	--

Table 6. Summary of Cancer Risk Factors for Natural Gas Runs 1-4.

	Natural Gas Runs			
	Case 1	**Case 2**	**Case 3**	**Case 4**
Pollutant	**Cancer Risk Factor**			
1,3 Butadiene	--	--	--	--
Acetaldehyde	--	--	--	--
Acrolein	--	--	--	--
Arsenic	4.138E-09	9.832E-09	2.443E-09	4.654E-09
Benzene	--	--	--	--
Beryllium	--	--	--	--
Cadmium	--	--	--	--
Chromium	1.881E-06	4.469E-06	1.110E-06	2.115E-06
Cyanide Compounds	--	--	--	--
Formaldehyde	--	--	--	--
Lead	3.343E-10	7.945E-10	1.974E-10	3.761E-10
Manganese	--	--	--	--
Mercury	--	--	--	--
Nickel	2.173E-09	5.164E-09	1.283E-09	2.444E-09
Phosphorus	--	--	--	--
Polycyclic Organics	2.842E-13	6.753E-13	1.678E-13	3.197E-13
Selenium	--	--	--	--
Styrene	--	--	--	--
Toluene	--	--	--	--
Xylenes	--	--	--	--
SUM	**1.888E-06**	**4.485E-06**	**1.114E-06**	**2.123E-06**

Table 7. Summary of Cancer Risk Factors for #2 Oil and Gas Runs 5-8.

	Oil and Natural Gas Runs			
	Case 5	Case 6	Case 7	Case 8
Pollutant	**Cancer Risk Factor**			
1,3 Butadiene	3.803E-09	6.109E-09	2.193E-09	3.009E-09
Acetaldehyde	4.379E-10	7.034E-10	2.525E-10	3.465E-10
Acrolein	--	--	--	--
Arsenic	4.238E-09	9.644E-09	2.494E-09	4.582E-09
Benzene	1.297E-09	2.084E-09	7.482E-10	1.027E-09
Beryllium	4.026E-10	6.468E-10	2.322E-10	3.186E-10
Cadmium	4.697E-09	7.546E-09	2.709E-09	3.717E-09
Chromium	5.030E-06	9.369E-06	2.924E-06	4.539E-06
Cyanide Compounds	--	--	--	--
Formaldehyde	9.395E-10	1.509E-09	5.418E-10	7.434E-10
Lead	1.192E-09	2.145E-09	6.918E-10	1.043E-09
Manganese	--	--	--	--
Mercury	--	--	--	--
Nickel	4.555E-08	7.467E-08	2.630E-08	3.669E-08
Phosphorus	--	--	--	--
Polycyclic Organics	2.154E-12	3.656E-12	1.246E-12	1.789E-12
Selenium	4.697E-10	7.546E-10	2.709E-10	3.717E-10
Styrene	6.375E-12	1.024E-11	3.679E-12	5.045E-12
Toluene	--	--	--	--
Xylenes	--	--	--	--
SUM	**5.093E-06**	**9.475E-06**	**2.960E-06**	**4.591E-06**

Table 8. Summary of Chronic Hazard Indices for Natural Gas Runs 1-4.

	Natural Gas Runs			
	Case 1	Case 2	Case 3	Case 4
Pollutant	**Chronic Hazard Index**			
1,3 Butadiene	--	--	--	--
Acetaldehyde	--	--	--	--
Acrolein	--	--	--	--
Arsenic	2.508E-06	5.959E-06	1.480E-06	2.821E-06
Benzene	--	--	--	--
Beryllium	--	--	--	--
Cadmium	--	--	--	--
Chromium	6.269E-3	1.490E-2	3.701E-3	7.051E-3

Table 8. Summary of Chronic Hazard Indices for Natural Gas Runs 1-4 (continued).

	Natural Gas Runs			
	Case 1	Case 2	Case 3	Case 4
Pollutant	**Chronic Hazard Index**			
Cyanide Compounds	--	--	--	--
Formaldehyde	--	--	--	--
Lead	2.786E-06	6.621E-06	1.645E-06	3.134E-06
Manganese	6.269E-05	1.490E-04	3.701E-05	7.051E-05
Mercury	1.393E-05	3.310E-05	8.224E-06	1.567E-05
Nickel	3.483E-05	8.276E-05	2.056E-05	3.917E-05
Phosphorus	1.194E-02	2.837E-02	7.049E-03	1.343E-02
Polycyclic Organics	--	--	--	--
Selenium	--	--	--	--
Styrene	--	--	--	--
Toluene	1.045E-06	2.483E-06	6.168E-07	1.175E-06
Xylenes	--	--	--	--
SUM	**0.0183**	**0.0436**	**0.0108**	**0.0206**

A sum less than 1.0 indicates acceptable risk.

Table 9. Summary of Chronic Hazard Indices for #2 Oil and Gas-Fired Runs 5-8.

	#2 Oil and Gas-Fired Runs			
	Case 5	Case 6	Case 7	Case 8
Pollutant	**Chronic Hazard Index**			
1,3 Butadiene	--	--	--	--
Acetaldehyde	1.802E-05	2.895E-05	1.039E-05	1.426E-05
Acrolein	5.592E-04	8.983E-04	3.222E-04	4.443E-04
Arsenic	2.568E-06	5.845E-06	1.512E-06	2.777E-06
Benzene	6.301E-07	1.012E-06	3.634E-07	4.986E-07
Beryllium	3.495E-05	5.615E-05	2.016E-05	2.766E-05
Cadmium	3.195E-07	5.133E-07	1.843E-07	2.529E-07
Chromium	1.677E-02	3.123E-02	9.740E-03	1.510E-02
Cyanide Compounds	2.716E-06	4.363E-06	1.567E-06	2.149E-06
Formaldehyde	4.349E-05	6.987E-05	2.508E-05	3.442E-05
Lead	9.937E-06	1.787E-05	5.765E-06	8.691E-06
Manganese	9.776E-05	2.000E-04	5.714E-06	9.597E-05
Mercury	1.613E-05	3.547E-05	9.473E-06	1.690E-05
Nickel	7.300E-04	1.196E-03	4.220E-04	5.880E-04
Phosphorus	3.060E-02	5.735E-02	1.780E-02	2.780E-02
Polycyclic Organics	--	--	--	--

Table 9. Summary of Chronic Hazard Indices for #2 Oil and Gas-Fired Runs 5-8 (continued).

	#2 Oil and Gas-Fired Runs			
	Case 5	**Case 6**	**Case 7**	**Case 8**
Pollutant	**Chronic Hazard Index**			
Selenium	6.710E-06	1.078E-05	3.870E-06	5.310E-06
Styrene	1.598E-08	2.567E-08	9.215E-09	1.264E-08
Toluene	9.303E-07	2.211E-06	5.492E-07	1.046E-06
Xylenes	--	--	--	--
SUM	**0.0489**	**0.0911**	**0.0284**	**0.0441**

A sum less than 1.0 indicates acceptable risk.

Table 10. Summary of Acute Hazard Indices for Natural Gas Runs 1-4.

	Natural Gas Runs			
	Case 1	**Case 2**	**Case 3**	**Case 4**
Pollutant	**Acute Hazard Index**			
1,3 Butadiene	--	--	--	--
Acetaldehyde	--	--	--	--
Acrolein	--	--	--	--
Arsenic	--	--	--	--
Benzene	--	--	--	--
Beryllium	--	--	--	--
Cadmium	--	--	--	--
Chromium	--	--	--	--
Cyanide Compounds	--	--	--	--
Formaldehyde	--	--	--	--
Lead	--	--	--	--
Manganese	--	--	--	--
Mercury	1.319E-05	2.152E-05	7.035E-06	8.660E-06
Nickel	7.911E-04	1.291E-03	4.221E-04	5.196E-04
Phosphorus	--	--	--	--
Polycyclic Organics	--	--	--	--
Selenium	--	--	--	--
Styrene	--	--	--	--
Toluene	--	--	--	--
Xylenes	--	--	--	--
SUM	**0.0008**	**0.0013**	**0.0004**	**0.0005**

A sum less than 1.0 indicates acceptable risk.

Table 11. Summary of Acute Hazard Indices for #2 Oil and Gas-Fired Runs 5-8.

	#2 Oil and Gas-Fired Runs			
	Case 5	**Case 6**	**Case 7**	**Case 8**
Pollutant	**Acute Hazard Index**			
1,3 Butadiene	--	--	--	--
Acetaldehyde	--	--	--	--
Acrolein	3.855E-03	5.389E-03	2.024E-03	2.302E-03
Arsenic	--	--	--	--
Benzene	--	--	--	--
Beryllium	--	--	--	--
Cadmium	--	--	--	--
Chromium	--	--	--	--
Cyanide Compounds	--	--	--	--
Formaldehyde	3.646E-04	5.098E-04	1.914E-04	2.178E-04
Lead	--	--	--	--
Manganese	--	--	--	--
Mercury	3.212E-05	4.491E-05	1.687E-05	1.918E-05
Nickel	1.446E-01	2.021E-01	7.590E-02	8.633E-02
Phosphorus	--	--	--	--
Polycyclic Organics	--	--	--	--
Selenium	1.446E-03	2.021E-03	7.590E-04	8.633E-04
Styrene	--	--	--	--
Toluene	--	--	--	--
Xylenes	--	--	--	--
SUM	**0.1503**	**0.2101**	**0.0789**	**0.0897**

A sum less than 1.0 indicates acceptable risk.