

Chromium Emissions from Comfort Cooling Towers — Background Information for Proposed Standards

Emissions Standards Division

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air And Radiation
Office Of Air Quality Planning And Standards
Research Triangle Park, North Carolina 27711

March 1988

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ENVIRONMENTAL PROTECTION AGENCY

Background Information
and Draft
Environmental Impact Statement
for Chromium Emissions From Comfort Cooling Towers

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3/28/88
(Date)

1. The proposed standards of performance would eliminate hexavalent chromium emissions from existing and new comfort cooling towers by prohibiting the use of hexavalent chromium in these towers. Under Section 6 of the Toxic Substances Control Act, EPA is authorized to impose regulatory controls if the Agency finds that there is a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance presents or will present an unreasonable risk of injury to human health or the environment.
2. Copies of this document have been sent to the following Federal Departments: Labor, Health and Human Services, Defense, Transportation, Agriculture, Commerce, Interior, and Energy; the National Science Foundation; the Council on Environmental Quality; members of the State and Territorial Air Pollution Program Administrators; the Association of Local Air Pollution Control Officials; EPA Regional Administrators; and other interested parties.
3. The comment period for review of this document is 60 days from the date of publication of the proposed standard in the Federal Register. Mr. Doug Bell or Ms. Debbie Stackhouse may be contacted at (919) 541-5258 regarding the date of the comment period.
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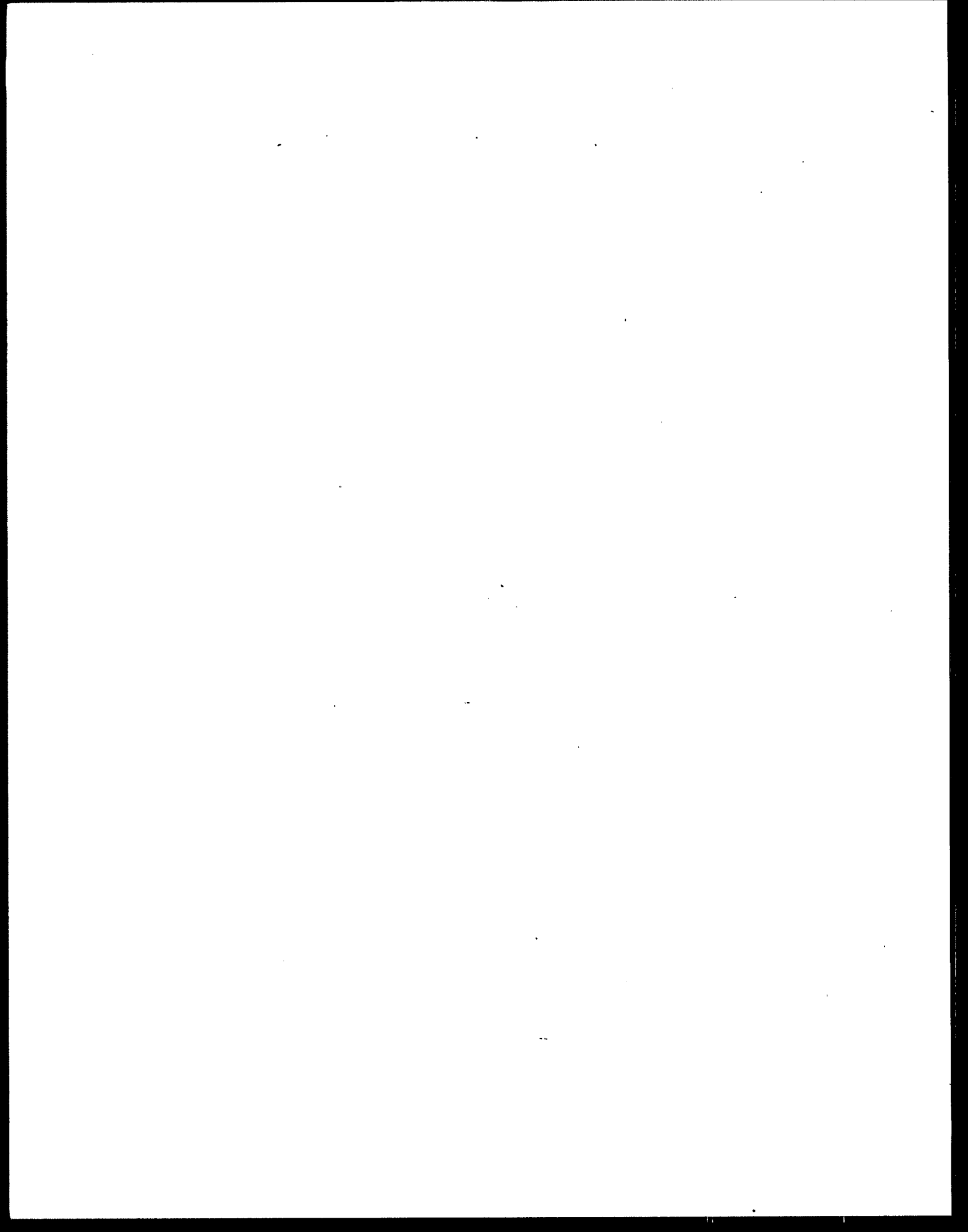


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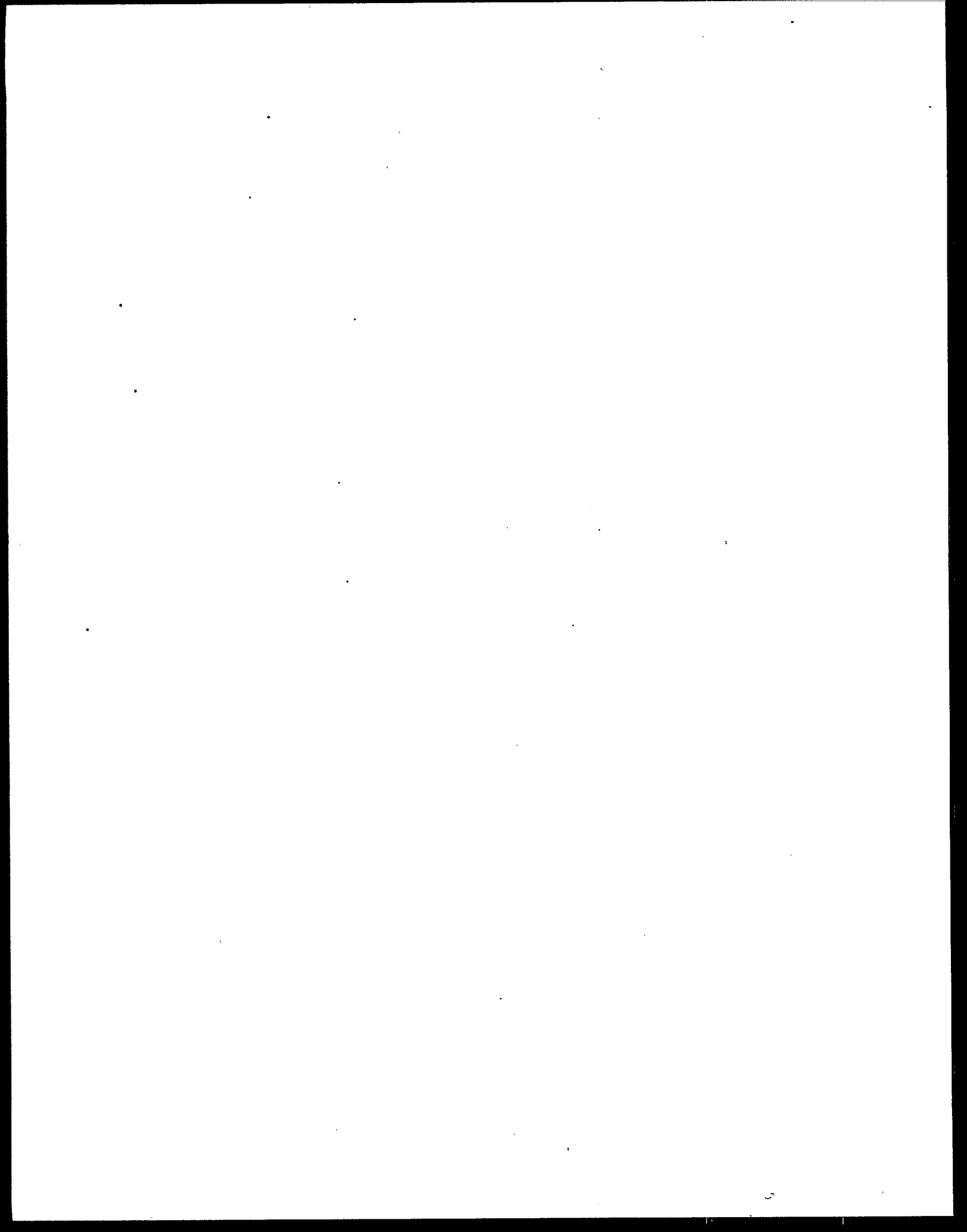
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1. SUMMARY

Regulations for chromium (Cr) emissions from comfort cooling towers (CCT's) are being developed because hexavalent chromium (Cr^{+6}), the form of Cr used in CCT's, is considered to be a potent carcinogen. Nationwide annual Cr emissions from CCT's are estimated to be about 7.2 to 206 Megagrams (16,000 to 453,000 pounds) (based on an average nationwide utilization rate of 46 percent). These emissions result in a health risk estimate of 4 to 112 cancer cases per year. This range reflects the lower- and upper-bound emission estimates and the upper-bound unit risk factor.

Two regulatory alternatives were evaluated for CCT's: nonchromium option and a high-efficiency drift eliminator option (HEDE). The least burdensome regulatory alternative is a standard that prohibits the use of chromium-based chemicals in CCT's and the sales of these chemicals for use in CCT's. Such a standard can reduce the risk by 100 percent, and this benefit can be achieved without operating problems or unreasonable costs.

A standard requiring retrofit of existing CCT's with HEDE's would be less effective (85 percent reduction in risk, or less). In addition, implementation of an HEDE standard would be impossible at some existing sites because of tower configuration. Where retrofit would be possible or in new CCT's, an HEDE standard would be much more complex than switching to nonchromium treatment. An annual inspection of the drift eliminator for proper sealing with the tower structure and an initial certification program to verify that selected drift eliminators can achieve the required emission rate would be required. This inspection and certification process would be more costly for operators than switching to nonchromium treatment programs. Furthermore, the certification process may take several years to complete.

Comfort cooling towers are used extensively as components of heating, ventilation, and air conditioning (HVAC) or refrigeration systems. The HVAC systems are installed in hospitals; hotels; shopping malls; and office, educational, and other commercial buildings. Refrigeration systems are used for ice skating rinks, cold storage (food) warehouses, and other commercial operations.

Hexavalent chromium is used in CCT water to inhibit corrosion in the heat exchanger of the HVAC or refrigeration equipment and in the connecting piping. Hexavalent chromium has long provided the best corrosion protection at a reasonable cost. However, environmental concerns (primarily wastewater discharges) have prompted many operators to switch to nonchromate water treatments. Currently, an estimated 75 to 90 percent of the 250,000 CCT's nationwide use nonchromium treatment programs or no water treatment. Although the remaining CCT's do not operate under special conditions that require the use of Cr^{+6} , many operators are reluctant to change from a treatment procedure with which they are familiar to one that will require more attention to achieve the same results.

A regulation eliminating Cr^{+6} emissions from CCT's is most effectively accomplished under Section 6 of the Toxic Substances Control Act (TSCA). Under TSCA, both owner/operator use of Cr^{+6} in CCT's and vendor sales of Cr^{+6} for use in CCT's could be prohibited. Under the Clean Air Act (CAA), the thrust of the rule would be on compliance by the owners and operators of the CCT's. The population of distributors (20+ major and approximately 400 total) is much smaller than the population of CCT's (approximately 250,000) that would have to be inspected to ensure implementation of the standard. Thus, TSCA is the best authority for regulating the use of Cr^{+6} chemicals in CCT's. By prohibiting the sales of the chemicals and also making the chemical sales companies liable, it is expected that the burden of ensuring compliance with the regulation would be reduced for both EPA and owners/operators of CCT's.

2. REGULATORY AUTHORITY

Regulation of chromium emissions from comfort cooling towers (CCT's) can be accomplished under either the Toxic Substances Control Act (TSCA) or the Clean Air Act (CAA). Under Section 112 of the CAA, it would not be possible to prohibit the sales of a chemical. However, it would be possible to prohibit indirectly the use of chromium chemicals in CCT's by setting a zero emission standard. Under the CAA, the recordkeeping requirements extend to "any person who owns or operates any emission source or who is subject to any requirements of this chapter." This would allow EPA to require the CCT owners and operators to maintain records, but, because the source category is so large, enforcement would be difficult. The thrust of regulations under the CAA would be on compliance with the emission limitations by the CCT owners and operators.

The TSCA provides EPA with broad authority to assess and regulate chemical substances in the environment, in the workplace, and in commercial products. Under Section 6(a) of TSCA, EPA is authorized to impose regulatory controls if the Agency finds that there is a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance presents or will present an unreasonable risk of injury to human health or the environment. To determine whether a risk is unreasonable, EPA balances the probability that harm will occur from the chemical substance under consideration against the social and economic costs to society of placing restrictions on the substance.

If the EPA Administrator determines that an unreasonable risk exists, one or more of several regulatory measures may be applied to the extent necessary to protect adequately against the risk. Those measures include prohibiting or limiting the manufacture, processing, or distribution in

commerce; labeling; prohibiting or otherwise regulating any manner or method of commercial use or disposal; requiring the revision of quality control procedures; and requiring that chemical manufacturers notify the public of unreasonable risks associated with a chemical substance. The EPA Administrator is required by TSCA to apply the least burdensome requirement(s) to protect adequately against the risks.

3. COMFORT COOLING TOWERS

3.1 GENERAL

This section provides a description of the source category and the major users of comfort cooling towers (CCT's); the cooling tower system; heating, ventilating, and air conditioning (HVAC) and refrigeration systems served by the cooling towers; cooling water chemical treatment programs; the mechanism by which hexavalent chromium (Cr^{+6}) is emitted, and the emission control techniques.

3.2 DEFINITION OF SOURCE CATEGORY

There are two broad categories of cooling towers, comfort and industrial. Comfort cooling towers are used to maintain a specified environment or refrigeration system. Industrial process cooling towers are used to control the temperatures of process fluids in industrial production units. The EPA is evaluating industrial towers separately because the cooling system conditions under which industrial towers operate may make controlling corrosion in an industrial tower more complex and difficult. The conditions that distinguish these towers and that make controlling Cr^{+6} emissions from CCT's less difficult than controlling Cr^{+6} emissions from industrial towers include a lower potential for corrosion because lower water temperatures typically are encountered; a lower utilization rate; the extensive use of heat exchangers constructed of copper, which is less susceptible to corrosive attack; little opportunity for upsets in the chemical treatment programs from contamination of the cooling water; and a lower potential for significant economic loss should alternative chemicals not perform satisfactorily. Usually only one heat exchanger is integrated into a single cooling tower system in CCT systems whereas a single industrial tower may support many heat exchangers.

Comfort cooling towers are used in all States in the U.S., primarily in urban areas. Major users of CCT's with HVAC systems include hospitals, hotels, educational facilities, office buildings, and shopping malls. Refrigeration systems that may operate with CCT's include ice skating rinks, cold storage (food) warehouses, and other commercial operations. Estimates from the two largest manufacturers of cooling towers (each represents a 40 percent market share) indicate that the nationwide population of CCT's is between 200,000 and 300,000.^{1,2} An estimate slightly lower than 200,000 was provided by a smaller, regional manufacturer.³ The 300,000 estimate was provided by the manufacturer that appears to have the higher percentage of the CCT market. Water treatment vendors estimated that 10 to 25 percent of CCT's use chromium-based water treatment chemicals.⁴⁻⁶ For analysis purposes, it is assumed that the nationwide population of CCT's is 250,000 units and that 15 percent of CCT's (about 37,500) use chromium-based water treatment chemicals. Hexavalent chromium use in CCT's appears to be distributed randomly across the country.

3.3 COMFORT COOLING SYSTEM COMPONENTS

3.3.1 Cooling Tower

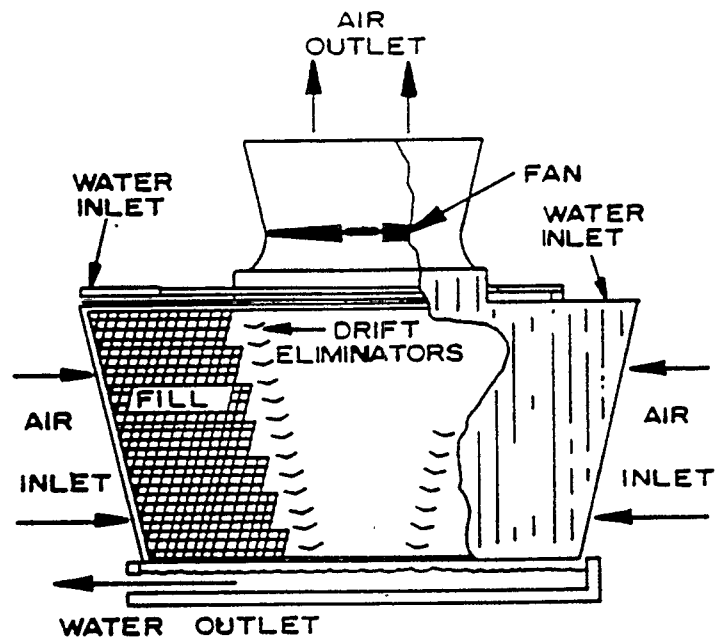
Cooling towers are devices that cool warm water by contacting it with ambient air that is drawn or forced through the tower. For most cooling towers, about 80 percent of the cooling occurs from evaporation of water as the air flowing through the tower contacts water cascading from the top to the bottom of the tower.⁷ Most tower systems are designed with recirculating water systems to conserve water resources or reduce costs of purchasing water. Typically, the CCT is an open recirculating system, but some are closed recirculating systems. The major cooling tower components include the fan(s), fill material, water distribution deck or header, drift eliminator, structural frame, and cold water basin. Other components that affect tower operation include the pumps and pipes necessary to circulate the cooling water through the cooling tower and heat exchanger loops.

Cooling towers are designed with mechanically induced-, mechanically forced-, or natural-draft airflow. Induced draft is provided by a propeller-type fan located in the stack at the top of the tower.

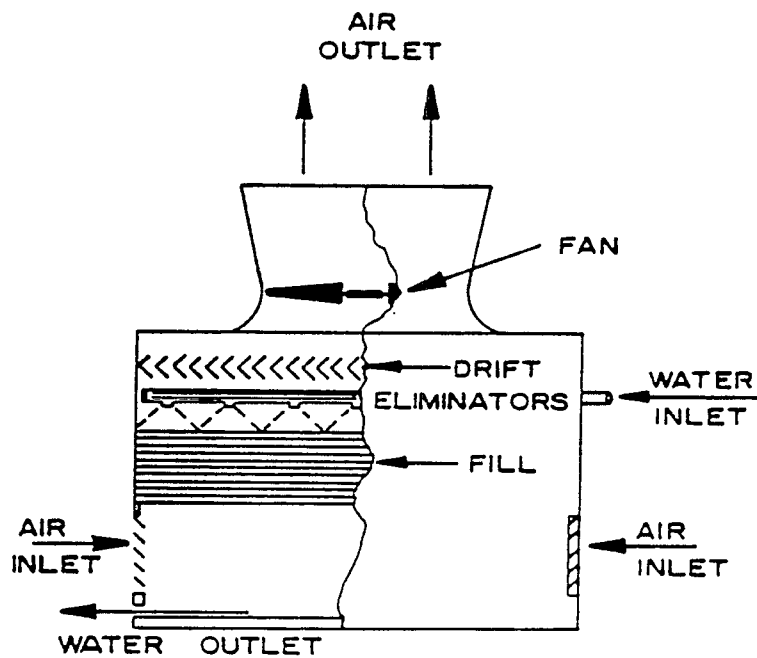
Forced-draft towers are usually smaller than induced-draft towers and have either centrifugal fans located at the base of the tower, which is constructed as a plenum to provide positive-pressure airflow through the fill material, or axial fans located on the side of the tower. Natural-draft airflow, which is not used in CCT's, relies on buoyancy created by temperature differences between the air in the tower and the atmosphere. When the cooling demands are minimal and the air temperature is low enough, water can be circulated through the tower and cooled sufficiently without using the fans. In these instances, a natural draft is created in a mechanical-draft tower. In addition, the direction of the airflow through a mechanical-draft tower is either crossflow or counterflow. Crossflow refers to horizontal airflow through the fill, and counterflow refers to upward vertical airflow. Schematics of counterflow and crossflow cooling towers are presented in Figure 3-1. Comfort cooling towers typically are designed with crossflow air configuration.

Fill material is used to maintain an even distribution of water across the horizontal plane of the tower and to create as much water surface as practical to enhance evaporation and sensible heat exchange. A large water-to-air interface is provided by either a large number of water droplets or many thin vertical sheets (or tubes) of water. The two types of fill, splash and film, are shown in Figure 3-2. Splash fill is constructed as successive layers of staggered impact surfaces. Small droplets are formed as warm water falls through the fill and splashes off each layer. Film fill is constructed of sheets of material in a "honeycomb" configuration. The fill is oriented such that water enters the open end of the honeycomb and flows vertically in sheets along the surface of the fill material. Typically, fill materials are wood, polyvinyl chloride (PVC), polystyrene, polypropylene, asbestos cement board, or cellulose.

The distribution of the warm water over the fill material is accomplished in one of two ways depending on the type of tower. In crossflow towers, there is a water distribution deck above the fill material at the top of the tower. The floor of this deck contains gravity flow nozzles, and the water level in the deck controls the rate of water flow onto the fill. In counterflow towers, the water distribution system



MECHANICAL DRAFT
CROSS-FLOW TOWER



MECHANICAL DRAFT
COUNTER-FLOW TOWER

Figure 3-1. Internals of crossflow and counterflow cooling towers.
(Reprinted from Drift Technology for Cooling Towers,
The Marley Company, 1973)

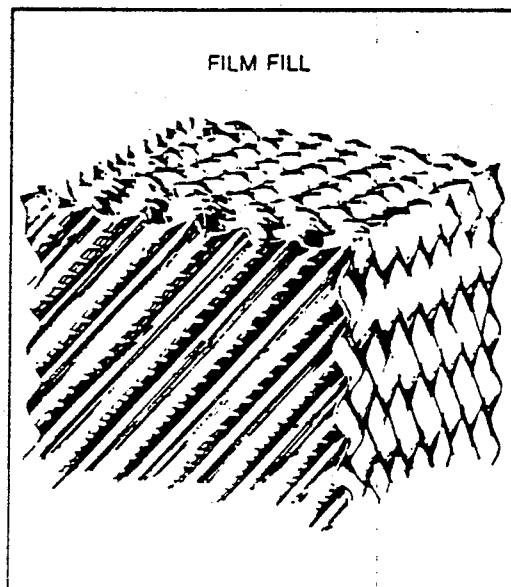
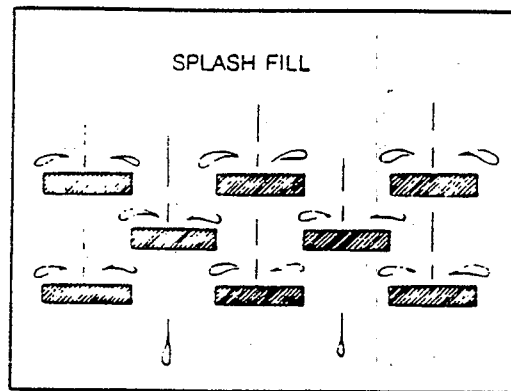


Figure 3-2. Details of splash fill and film fill.
(Reprinted from Custodis-Cottrell product brochure)

is constructed of a series of header pipes connected to pressure flow nozzles placed above the fill material. In both systems, the nozzles are arranged such that even water distribution over the fill material is provided.

Water droplets and the dissolved solids they contain that are entrained in the air and emitted from the CCT stack are referred to as drift. (Drift formation is discussed in Section 3.6.) Drift eliminators can be installed at the exit of the fill sections to reduce the drift in the exiting airflow. The drift removal efficiency of a drift eliminator is a function of its design. Figure 3-3 presents schematics of the three major drift eliminator designs: blade-type, waveform, and cellular. A fourth drift eliminator design, herringbone, is similar to the blade-type except that the blades in one row are offset from the blades in the next row. Typically, herringbone and blade-type units are the least efficient, waveform units are moderately efficient, and cellular units are the most efficient. However, some cellular designs may be less efficient than some waveform designs, and some waveform designs may be less efficient than some herringbone designs. Drift eliminators are constructed of wood, PVC, metal, asbestos-cement, polystyrene, or cellulose. Currently, the material most often specified is PVC. Drift eliminators installed in towers built in the last several years are more likely to be higher efficiency waveform or cellular units, but a large number of older towers still have lower efficiency herringbone and waveform eliminators.

The structural frame of cooling towers can be wood, concrete, masonry, steel, and combinations of these materials. The cold water basins (reservoirs) typically are located directly below the fill material at the base of the cooling tower. Basin size is affected by the size of the tower and by the necessity to accommodate any expected short-term fluctuations in the water volume of the system.

3.3.2 HVAC and Refrigeration Equipment

The components of an HVAC or a refrigeration system include the cooling distribution system, a heat rejection system, and the refrigeration machine, commonly referred to as a chiller system. The cooling distribution system consists of the air handling units, and the heat rejection system consists of the cooling tower. The chiller system

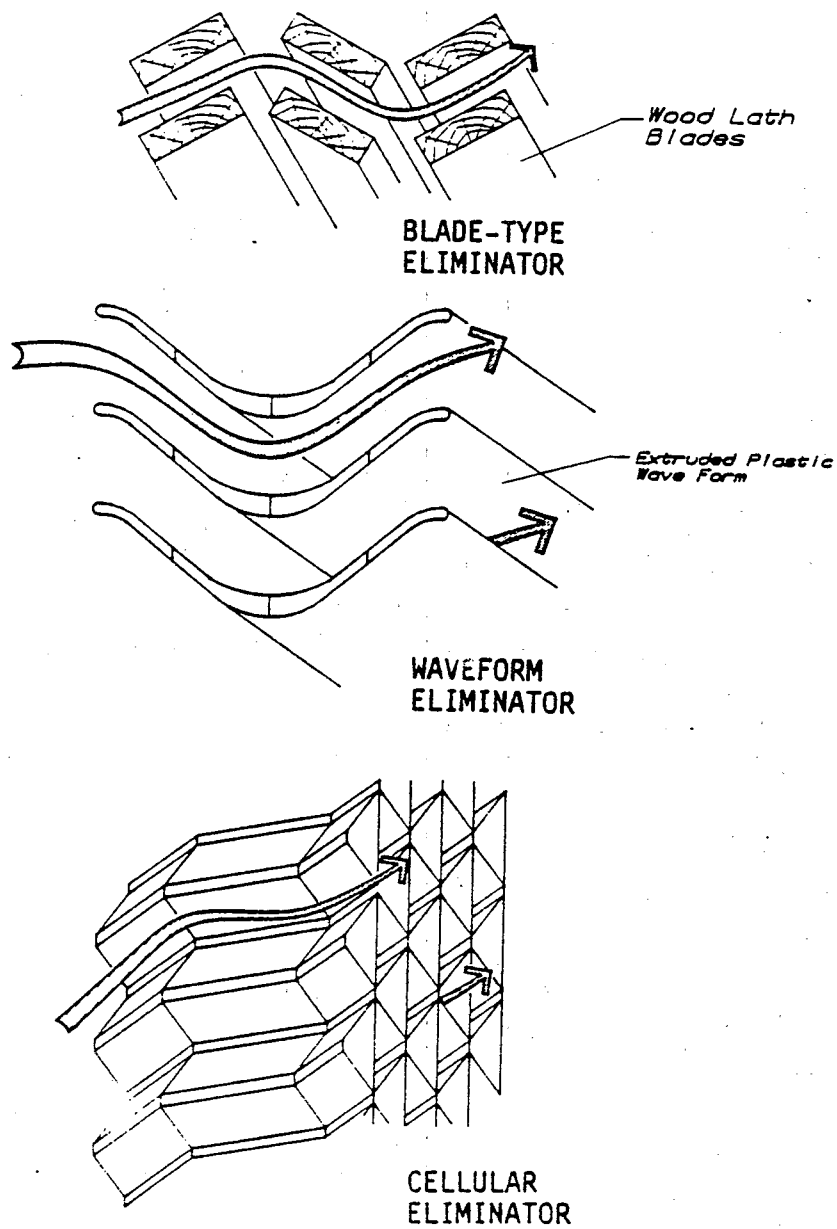


Figure 3-3. Operating principles of various drift eliminators.
(Reprinted from Reference No. 7)

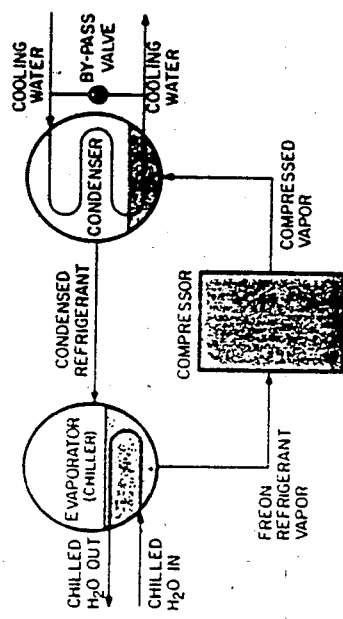
can be either a compression-cycle or an absorption type (see Figure 3-4). In both systems, cooling water is required to condense the refrigerant vapor (i.e., Freon® in a compression-cycle system and water in most absorption-type systems). (Note: Water-ammonia compression systems also have been used with ammonia as the refrigerant. However, in HVAC systems, water/lithium bromide compression systems predominate.) In the absorption system, cooling water also is required for the absorber. Water is supplied from a cooling tower at about 29°C (85°F), and it returns to the tower at about 35°C (95°F). The condenser typically is constructed of copper tubes and a cast steel shell. The condensed refrigerant passes to the evaporator where warm water from the air handling units transfers heat that evaporates the refrigerant, thereby chilling the water. The chilled water is pumped back to the air handling units.^{8,9}

The required tower size for a given air conditioning load depends on the type of chiller system used. Compression-type equipment is designed for a temperature difference of 5.6°C (10°F) across the tower and a recirculating rate of 11.6 liters per minute (ℓ/min) (3 gallons per minute [gal/min]) per ton of air conditioning. Absorption-type equipment is designed for a temperature difference of 8.3°C (15°F) across the tower and a recirculating rate of 15.1 ℓ/min (4 gal/min) per ton of air conditioning. A ton of air conditioning is defined as 3,514 Watts (W) (12,000 Btu/hour [h]). Compression-type equipment will reject 4,392 W (15,000 Btu/h) to the cooling tower because for each ton of air conditioning, an additional 878 W (3,000 Btu/h) is required to perform the work needed to compress the refrigerant. When absorption-type equipment is used, 8,785 W (30,000 Btu/h) are rejected at the cooling tower for each ton of air conditioning because 5,270 W (18,000 Btu/h) are required to drive the process. Water is evaporated at the rate of 7.2 ℓ (1.9 gal) and 14.0 ℓ (3.7 gal) per hour per ton of cooling in the cooling towers used with compression and absorption systems, respectively.¹⁰

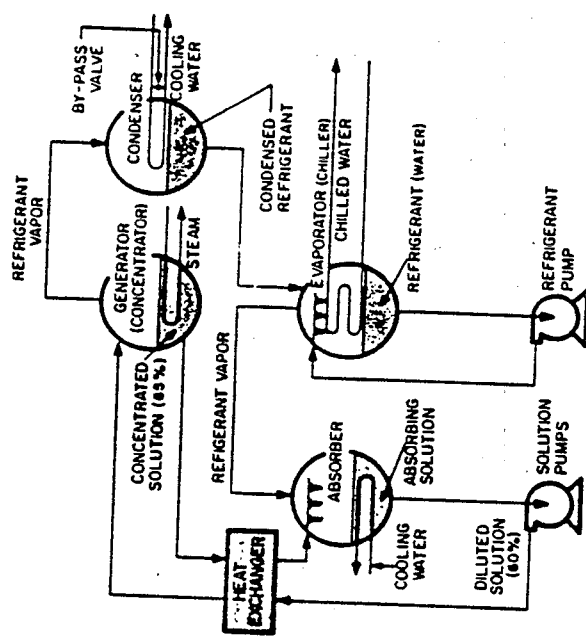
3.4 CHEMICAL TREATMENT PROGRAMS

3.4.1 Purpose

Chemicals are added to the recirculating cooling water to inhibit the corrosive effects of the water, to control the rate of scaling and fouling, and to control the growth of micro-organisms in both the cooling tower and the heat exchangers. As evaporation occurs during cooling, the



COMPRESSION-CYCLE
COOLING SYSTEM



ABSORPTION-TYPE
COOLING SYSTEM

Figure 3-4. Cooling systems served by comfort cooling towers.
(Reprinted from Reference No. 10)

chemical constituents of the water become concentrated. A percentage of the recirculating water is intentionally discharged (blowdown) to maintain acceptable concentrations of suspended and dissolved solids. Also, as water cascades through the tower, some is entrained and emitted from the stack as drift. Fresh water is added to make up for the losses resulting from evaporation, blowdown, and drift.

Typical water treatment program chemicals include (1) a corrosion inhibitor, (2) an antiscalant, (3) an antifoulant, (4) a dispersant, (5) a surfactant, (6) a biocide, and (7) an acid and/or caustic soda for pH control. Chromium-based chemicals are corrosion inhibitors. Other chemicals fall into one or more categories, and many combinations of various chemicals are used. The quality of the cooling tower water supply directly affects the type and quantity of chemicals required to maintain satisfactory protection. The three problems--corrosion, scaling and fouling, and microbiological growth--and the chemicals used to control them are discussed later in this section.

Major water chemistry parameters that affect the selection of chemical treatment programs include pH, calcium hardness (calcium ion concentration), alkalinity (bicarbonate, carbonate, and hydroxide ions), chloride, sulfate, silica, dissolved solids (conductivity), and suspended solids. Water quality also directly affects the number of cycles of concentration that can be maintained. The number of cycles of concentration is defined as the ratio of conductivity or calcium hardness of the recirculating water to that of the makeup water. The maximum level of either parameter established is based on the chemical treatment program and the acceptable rates of corrosion and scaling.

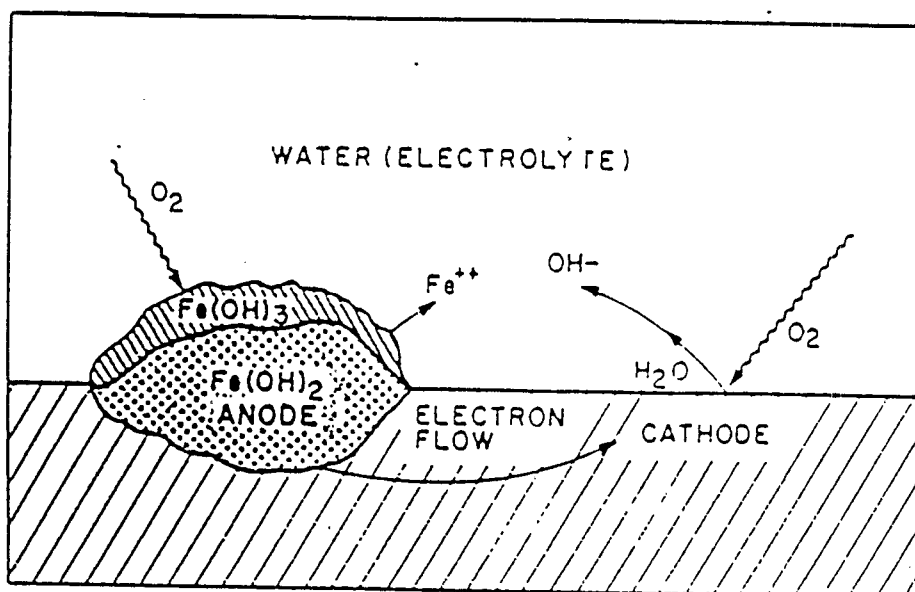
3.4.2 Corrosion.

3.4.2.1 Description. Corrosion is the oxidation of a metal by some oxidizing agent in the environment. The area over which metal is oxidized (corroded) is called the anode; the area over which the oxidizing agent is reduced is called the cathode. Many metals contain both anodic and cathodic areas. As corrosion proceeds, electrons flow through the metal from the anode to the cathode. In water, an electrochemical cell is formed as cations migrate toward the cathode and anions move toward the anode. The water is the conducting fluid or electrolyte. The flow of

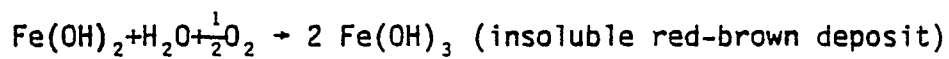
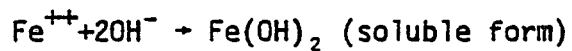
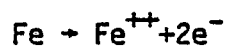
electrons through the metal (external circuit) is the corrosion current, which is limited by the rate at which electrons are accepted by the oxidizing agent at the cathode. Figure 3-5 illustrates the mechanisms for corrosion in a single metal. Galvanic corrosion occurs when two different metals are in physical contact. Depending on their relative characteristics, one of the metals will function as an anode and the other as a cathode, and the anodic metal will corrode. Conditions that increase the conductivity of the water (e.g., high dissolved solids content or high temperature) increase the rate of corrosion.

Several types of corrosion occur in cooling water systems including general etching, pitting, tuberculation, and crevice corrosion. The least harmful is the general etching that occurs uniformly over the surface of the metal. Pitting is the formation of small holes from corrosive attack at the metal surfaces, and tuberculation refers to the corrosion products cap that forms over a pit. Crevice corrosion occurs where metallic and nonmetallic materials contact. Corrosion can be retarded, but not totally prevented, and the rate of corrosion that is acceptable varies among systems. Inhibitors are added primarily to protect the heat transfer surfaces, which are the most critical metal components in the system, from corrosion. The terms and corrosion rates presented in Table 3-1 are generally used to describe the severity of carbon steel and copper corrosion.

Chemicals used in a recirculating water system are either anodic or cathodic corrosion inhibitors, and the mechanisms by which they protect the metal are passivation, precipitation, and/or adsorption. Anodic corrosion inhibitors function by providing a barrier film or deposit at anodic areas that prevents the electrolytic half-cell reaction from occurring. Cathodic inhibitors prevent the other half-cell reaction from occurring by providing a barrier film or deposit at cathodic areas. Table 3-2 lists various anodic and cathodic inhibitors. The barrier created by passivation is an oxide that forms on the metal surface, and the barrier created by precipitation is an insoluble precipitate that coats the metal surface. Generally, anodic inhibitors are passivators, and cathodic inhibitors are precipitators. Molecules that have polar properties provide a barrier by adsorbing on the entire metal surface. Adsorption inhibitors are usually organic compounds.¹⁰⁻¹²



ANODIC REACTIONS



CATHODIC REACTIONS

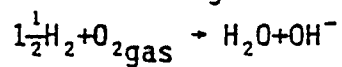
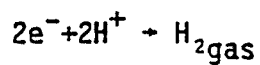


Figure 3-5. Corrosion mechanism on carbon steel surface.
(Reprinted from Reference No. 10)

TABLE 3-1. CORROSION RATES OF METALS^{1,2}

Description	Corrosion rates, $\mu\text{m/yr}$ (mil/yr)	
	Carbon steel	Copper alloy
Negligible	<25.4-50.8 (<1-2)	<2.54 (<0.1)
Mild	50.8-127.0 (2-5)	3.81-5.08 (0.15-0.2)
Moderate	127.0-254.0 (5-10)	5.08-8.89 (0.2-0.35)
Severe	>254.0 (>10)	12.7-25.4 (0.5-1)

3.4.2.2 Chromium-Based Inhibitors. Chromates historically have provided the best protection against corrosion for the money and effort. Very little monitoring and control of concentration are required. Even if the inhibitor feed is temporarily interrupted, the existing film will continue to provide protection for several days.

Chromate concentration typically must be maintained above 200 parts per million (ppm) if the chromates are used alone in the recirculating water. However, chromates (which are anodic inhibitors) typically are used in combination with cathodic inhibitors. In these combinations, less chromate provides the same corrosion protection that is provided by high concentrations of chromate alone. Vendors provide many chromate-based combinations for use in CCT's; and definitions of low-, very low-, and ultra-low-chromate concentrations vary. In all cases, the chromate concentration is less than 30 ppm. For the purposes of this document, all of these treatment program classifications will be considered low-chromate.

The chemicals most commonly added to chromate-based formulations are zinc and phosphate; but organic compounds, polysilicates, and molybdates also have been used. (The same chemicals are used in treatment programs without chromates and are discussed in greater detail in Section 5.1.1.) Table 3-3 provides concentrations and typical operating conditions of some of the formulations discussed in various publications, which generally focus on industrial tower systems.¹⁰⁻¹² However, at those facilities that use chromates in the CCT's, the same treatment program is used in both the CCT's and the industrial process cooling systems. Chromate is an excellent copper corrosion inhibitor, but many publications indicate that it is common to add the organic triazole inhibitors to low-chromate formulations that are used in systems with copper heat transfer surfaces; this was confirmed by some of the EPA studies of chemical treatment programs used at CCT's (case studies).¹³⁻¹⁷ However, this does not mean that triazoles are more effective or even as effective as chromate at protecting copper from corrosion. The addition of triazoles also protects copper surfaces from reactions with phosphonate dispersants.

The cathodic half-cell reaction controls the rate of corrosion at the anode. Thus, for a given cathodic reaction rate, the same mass of the anode will corrode. If the cathodic reaction is not controlled by

TABLE 3-2. ANODIC AND CATHODIC CORROSION INHIBITORS

Anodic	Cathodic
Chromate	Polyphosphate
Molybdate	Zinc
Orthophosphate	Polysilicate
Nitrites	
Orthosilicate	

TABLE 3-3. CHROMATE-BASED CORROSION INHIBITORS^{10-12,18}

Combination ^a	Concentration, ppm ^b	Operating conditions
Chromate/zinc	5-20/2.5-10	pH 6.5-7.0
Chromate/orthophosphate	20-25/3-3.5 5-10/10	pH 7.0-7.5 pH 6.2-6.8
Chromate/phosphate/zinc ^c	15-25/2-5/2-5	pH 6.0-7.0
Chromate/polyphosphate/zinc	10-30/3-5/3-5 20-25/5-10/2.5-3.0 5/10/unk	pH 6.5-7.0 CaH 100-600 ppm ^d pH 6.0-6.5 CaH <400-600 ppm pH 6.5-7.2
Chromate/zinc/phosphonate	15-25/2-4/3-5 2-3/2-3/5-10	pH 6.5-7.5 pH 6.5-7.0
Chromate/phosphonate	5-10/3-5	Not specified
Chromate/phosphonate/dispersant	5-15/2-6/2-6	pH 7.5-8.5
Chromate/dispersant	3-5/30	pH 7.5-8.5
Chromate/polysilicate	5-10/5-10	pH >7.5 Si <10 ppm
Chromate/zinc/dispersant	10-20/1-2/1.5-10	pH 7.0-9.0
Chromate/molybdate	10-30/1-5	pH >7.5

^aIn all combinations except chromate/polysilicate, the organic triazole corrosion inhibitors should be included at 1 to 10 ppm when the system contains copper.

^bThe components of some combinations can be formulated differently for different applications.

^cPolyphosphate and/or orthophosphate.

^dCaH is calcium hardness.

cathodic inhibitors or triazoles and if only small spots of the anodic surface remain unprotected, pitting may occur. Although chromate is an excellent inhibitor, the likelihood that small areas will remain unprotected is greater with lower chromate treatments than it is with higher chromate treatments.

3.4.3 Scaling and Fouling

3.4.3.1 Description. Scale formation occurs when dissolved solids and gases in cooling water reach their limit of solubility and precipitate out onto piping and heat transfer surfaces. Fouling occurs when deposits of dirt, leaves, and/or flocs of insoluble salts or hydrous oxides from corrosion agglomerate in the heat exchanger tubes. Scaling reduces the heat transfer capacity of heat exchangers, and fouling hinders the flow of water through heat exchangers. These conditions also contribute to pitting-type corrosion by creating corrosion cells and preventing the corrosion inhibitor from contacting the surface of the metal. Calcium carbonate is the most common scale found in cooling water systems, but calcium sulfate and calcium phosphate also can be formed in many systems. All three scales become less soluble, and, therefore, more likely to precipitate at higher temperatures. Calcium sulfate is more likely to precipitate at lower pH and the other two scales are more likely to precipitate at higher pH. Control of scaling and fouling depends on the control of deposition onto surfaces. The deposition can be affected by changing the solubility of scale-related salts, reducing the crystalline growth capacity of scale-related salts, and dispersing constituents that form fouling-related flocculations.

3.4.3.2 Antiscalants and Antifoulants

Chemical compounds that are commonly used and are the most effective in controlling the rate of scaling include polyphosphates and phosphonates. These compounds reduce the crystalline growth capacity of calcium salts. Certain phosphonate compounds affect the solubility of the calcium salts and reduce the formation of scale. Polymeric dispersants (with a molecular weight less than 20,000) reduce the potential for fouling.¹⁰⁻¹²

The phosphonates typically are added to chromate-zinc formulations as an alternative to phosphate, and scaling is better controlled than it is

with phosphate. Also, the amount of chromate can be reduced since the phosphonate system can be operated at a slightly higher pH.

The powerful oxidizing potential of chlorine can promote corrosion of copper if phosphonates also are present in the system. The addition of benzotriazole (or other azoles) and dispersants can minimize this effect. Phosphonates are also subject to biological oxidation, which results in the release of orthophosphate ions that can cause fouling as well as reduction of the recommended concentration of phosphonate. However, this fouling problem is much less severe than that produced in systems treated with polyphosphates.¹²

3.4.4 Microbiological Control

Three types of microorganisms are found in cooling tower water systems: bacteria, fungi, and algae. Bacteria are dispersed in the water, fungi invade wood components, and algae attach to surfaces in the tower. Slime produced by bacteria can coat and aggregate debris on heat exchanger surfaces, thereby reducing the efficiency of heat transfer. Biological deposits on metal surfaces also can accelerate pitting corrosion. Fungi can cause decay of wood either by surface attack (soft rot) or internal attack of the cellulose (white rot). Algal growth can coat the fill material and reduce the effectiveness of the water droplet formation and, thus, the effectiveness of heat transfer in the tower.

Microbiocides can be classified as oxidizing agents, enzyme poisons, organic chemical compounds, and miscellaneous compounds. The oxidizing agents include chlorine, bromine, and iodine. Enzyme poisons include methylene bithiocyanate, acrolein, and heavy metals (e.g., copper sulfate, copper citrate, tin, phenylmercuric acetate, methyl mercury). Acrolein and the heavy metals are not widely used and are not known to be used in CCT's. Organic compounds normally require high dosage rates and include dodecylquamide hydrochloride and quaternary ammonia salts. Most microbiocides used for treating cooling water are included in the categories above, but dithiocarbamates are a class of miscellaneous compounds that also are effective microbiocides. However, they reduce chromate and, thus, cannot be used in chromate-treated systems.^{10,12}

Organic chemical compounds which either hydrolyze to relatively nontoxic forms or can be detoxified are also used as microbiocides. Hydrolyzable materials include 2,2-dibromo-3-nitrilopropionamide, chlorinated cyanurates, and halogenated hydantoin. Chemicals which are both hydrolyzable and detoxifiable are methylene bis-thiocyanate and bromonitrostyrene. Isothiazolin is a widely used biocide that can be detoxified.^{10,18}

3.5 MAINTENANCE REQUIREMENTS

The maintenance requirements for CCT's and associated heat exchangers are affected by the effectiveness of the chemical treatment programs. The effectiveness of the corrosion inhibitor is important to the life expectancy of metal surfaces exposed to the recirculating water in both the tower and heat exchanger. Excessive corrosion will cause premature replacement of equipment and additional maintenance. Metal structural components of the tower such as steel columns and beams, connector plates and bolts, piping and pumps, valves, and controller equipment corrode from exposure to the cooling tower water. However, the most critical corrosion occurs in the heat exchangers. Many CCT operators have Eddy-current tests conducted periodically (every 1 to 5 years) to detect heat exchanger tubes in danger of failing, and these tubes are either replaced or plugged.¹⁹⁻²⁵ Some loss of efficiency or cooling capacity because of plugged tubes can usually be tolerated because cooling systems are often designed with a margin of safety.

Scaling occurs on the surfaces of CCT components and heat exchangers. Scaling in the CCT can reduce tower heat rejection capacity by interfering with splash or film fill water distribution and the formation of water droplets. Airflow characteristics also can be altered when airflow passages in the fill and drift eliminator become blocked; this increases the pressure drop across the system and reduces cooling efficiency. The tower fill and drift eliminator surfaces typically are inspected annually and cleaned if necessary. Winter is the most common time to perform the work since the demand, if any, on the system is minimal. Scaling and fouling in heat exchanger tubes reduce the heat transfer capacity because of the low conductivity of the crystalline film created on the tube surfaces and flow restrictions that result. The scale

and foulants can be removed physically by a process called rodding, by water blasting, or by flushing with acids. Physical cleaning methods require that the heat exchanger be taken out of service until the maintenance is completed. In CCT systems, the heat exchangers are routinely inspected and cleaned, if necessary, each winter when the system demand is low. Chemical cleaning can take place while the system is in service, but the effectiveness of this method depends upon the level of scaling or fouling. If strong acids are to be used, the heat exchanger will be taken out of service to protect ancillary cooling water system components. Increases in scaling and fouling can result from changes or variations in the water treatment program, which may also increase the level of maintenance required.

3.6 FORMATION OF DRIFT

Water droplets are formed as water splashes down through the fill material and from the shearing action of the airflow along the water surfaces within the tower. Water droplets and the dissolved solids they contain that become entrained in the air and are emitted from the stack are referred to as drift. The amount of drift is a function of both the water and air flow rates through the tower, but the airflow rate has the largest impact on the drift rate.^{27,28} The rate of water flow through the fill material is referred to as "water loading," and the typical range of water loading in cooling towers is 81.5 to 204 liters per minute per square meter (l/min/m^2) (2 to 5 gallons per minute per square foot [gal/min/ft^2]).⁸ In some CCT's, however, the water loading may be as high as 610 l/min/m^2 (15 gal/min/ft^2).²⁷

The velocity of the airflow in the fill typically is 91.4 to 213 meters per minute (m/min) (300 to 700 feet per minute [ft/min]). At 91.4 m/min (300 ft/min), a 370-micrometer (μm) (14.6 thousands-of-an-inch [mils]) water droplet will become entrained in the airflow. At 213 m/min (700 ft/min), an 800- μm (31.5- mils) water droplet will become entrained in the airflow.²⁶ A drift eliminator manufacturer indicated that the drift rates are highest when the air velocity is at either end of the range. Most towers are designed with an airflow rate that produces a drift rate as near to the minimum as is practical. In addition, better drift eliminators expand the range of airflow rates that produce minimum drift

rates and they reduce the effect of substantially higher or lower airflow rates on the drift rate.²⁸

All droplets evaporate to some extent while they are entrained. Table 3-4 presents the sizes that various droplets will attain after 3 seconds in environments of 80 and 90 percent relative humidity at 26.7°C (80°F). These conditions probably are comparable with those in a CCT. The final droplet sizes presented in Table 3-4 indicate that droplets that are created at 30 μm (1.2 mils) and below will undergo a significant reduction in size as they evaporate and cause concentration of the solids in those droplets.

Data from EPA-sponsored emissions tests indicate that a number of droplets larger than 1,000 μm (39.4 mils) were emitted from the stack. As discussed above, entrainment of these droplets in the airflow through the fill would not be expected. However, the air velocity may not be uniform across the face of the fill. The variation is minimized in the most effective tower designs, but, in many towers, the variation is significant. Thus, droplets larger than 370 μm and 800 μm can be entrained in the higher velocity portions of the air stream. Also, because of the angularity of flow out of the last pass of the eliminator, the air velocity leaving the eliminators is higher than that through the fill. Another possible explanation for larger droplets than expected being emitted is that the large droplets are created in the stack. The sides of the stack, the fan blades, and other support structures in the stack are constantly bombarded with drift droplets. Eventually, the surface tension is overcome and large droplets fall off. Because of the high velocity (average of about 457 m/min [1,500 ft/min]) in the stack, larger droplets can be entrained in the stack than can be entrained in the fill. Also, large droplets may be created from smaller droplets impacting with each other because of the turbulence created by the fan.

TABLE 3-4. EFFECT OF EVAPORATION ON DROPLET SIZE

Original droplet size, μm (mils)	Particle size at dryness, μm (mils) ^a	Droplet size, μm (mils) ^b		Solids concentration, ppm ^a 80 percent relative humidity
		80 percent relative humidity	90 percent relative humidity	
500 (19.69)	36.0 (1.4)	499.3 (19.66)	499.7 (19.67)	1,004
300 (11.81)	21.6 (0.85)	298.9 (11.77)	299.5 (11.79)	1,007
100 (3.94)	7.2 (0.28)	96.6 (3.80)	98.4 (3.87)	1,109
50 (1.97)	3.6 (0.14)	42.7 (1.68)	46.7 (1.84)	1,605
30 (1.2)	2.2 (0.09)	15.0 (0.59)	24.2 (0.95)	8,000

^aAssumes total dissolved solids content of droplets is 1,000 $\mu\text{g}/\text{ml}$ (0.0624 lb/ft^3) and that the dissolved solids are primarily calcium carbonate (35 percent), magnesium carbonate (48 percent), and sodium carbonate (17 percent). Also assumes that the specific gravity of resulting dry particulate is the same as the weighted average of the specific gravity of the three major components.

^bAssumes an evaporation time of 3 seconds and 26.7°C (80°F) dry bulb temperature. See Reference 29 for the equation used to calculate the droplet size.

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4. MODEL COMFORT COOLING TOWER SYSTEMS

This chapter provides a discussion of six model comfort cooling towers (CCT's) that were developed to represent the CCT population nationwide. It has been assumed that the sizes and types of towers are evenly distributed among all of the building types in the source category. The parameters used to estimate the nationwide economic and health risk impacts attributable to regulatory alternatives for controlling hexavalent chromium (Cr^{+6}) emissions are presented. Specific items discussed include factors related to cooling towers, refrigeration equipment/heat exchangers, chemical treatment programs, and baseline emissions.

4.1 MODEL TOWER PARAMETERS

Model tower design parameters and associated assumptions are summarized in Table 4-1 and are discussed in further detail below. Sample calculations are presented in Appendix F.

4.1.1 Building Size

Data on the number of commercial buildings in the U.S. were obtained from a Department of Energy (DOE) study.¹ Total floorspace was used to distribute the buildings into seven categories: buildings with 465 square meters (m^2) (5,000 square feet [ft^2]) or less of floorspace, those between 465 and 929 m^2 (5,001 and 10,000 ft^2), those between 929 and 2,323 m^2 (10,001 and 25,000 ft^2), those between 2,323 and 4,645 m^2 (25,001 and 50,000 ft^2), those between 4,645 and 9,290 m^2 (50,001 and 100,000 ft^2), those between 9,290 and 18,581 m^2 (100,001 and 200,000 ft^2), and those with more than 18,581 m^2 (200,000 ft^2). An average building size was determined for each size range. These building sizes were then used as model buildings (to determine the cooling requirements for model CCT's), which also are presented in Table 4-1. A model for buildings under 465 m^2

(5,000 ft²) was not developed because it is not cost effective for buildings of that size to have a CCT.

4.1.2 Cooling Requirements

Table 4-1 also presents the cooling requirements for the model towers. The required cooling capacity of central HVAC systems for large buildings is based on the amount of floorspace in the building. Central HVAC cooling capacities typically range from about 107 watts (W)/m² (34 Btu/h/ft²) for office buildings to 158 W/m² (50 Btu/h/ft²) for buildings such as shopping malls that accommodate a greater concentration of people or such as hospitals that have heat-generating equipment.^{2,3} However, the capacity of the cooling tower must be about 25 percent greater than the capacity of the HVAC system to account for the heat added to compress the refrigerant. Thus, the cooling requirement for CCT's ranges from 134 W/m² (43 Btu/h/ft²) to 198 W/m² (63 Btu/h/ft²). The cooling requirements for the model towers are based on 142 W/m² (45 Btu/h/ft²), a value near the low end of the range, because office buildings are by far the most prevalent type of commercial building.

4.1.3 Recirculation Rate

To determine the recirculation rate, a heat balance based on the defined cooling requirement for the tower was performed using Equation 1.⁴ It was assumed that the cooling range is 5.6°C (10°F) (a typical temperature range derived from case studies and vendor information).⁵⁻¹³

where:

$$\text{Recirculation rate} = \frac{\text{Heat duty}}{(\text{Heat capacity of water})(\Delta T \text{ of water})} \quad (1)$$

Recirculation rate [=] L/min (gal/min)

Heat duty [=] W (Btu/min)

Heat capacity of water = 4.18 J/g•°C (1.0 Btu/lb•°F)

ΔT of water = 5.6°C (10°F)

4.1.4 Evaporation Rate

Evaporation rates based on an empirical relationship were calculated using Equation 2.¹⁴

$$\text{Evaporation rate} = (0.00085)(\text{Recirculation rate})(\Delta T \text{ of water}) \quad (2)$$

where:

Evaporation rate [=] g/min (gal/min).

4.1.5 Blowdown Rate

Blowdown rates depend on cycles of concentration as shown in Equation 3.⁴ Cycles of concentration can vary widely with the treatment program used and the makeup water quality. Cycles of concentration ranging from 2 to 8 have been reported. A uniform assumption of 5 cycles of concentration (the midpoint of the range) was used for all six model towers. The assumption is supported by several CCT operators.^{6, 11-13}

$$\text{Blowdown rate} = \frac{\text{Evaporation rate}}{(\text{Cycles of concentration} - 1)} \quad (3)$$

4.1.6 Hexavalent Chromium Emissions

Data on chromate concentrations in CCT water treatment programs vary from less than 1 ppm to 20 ppm chromate.^{9, 15, 16} Although a large amount of data has shown that the average concentration of chromate in industrial process cooling towers is 13 ppm, there are not sufficient data on CCT systems to justify using a concentration other than the midpoint of the observed range.¹⁷⁻²⁵ Therefore, the chromate concentration in the recirculating water for the model CCT's is assumed to be 10 ppm (10 ppm chromate is equal to 4.48 ppm Cr^{+6}).

Four chromium emission factors developed from EPA-sponsored tests performed on two industrial cooling towers equipped with lower efficiency drift eliminators are presented in Table 4-2.^{26, 27} These emission factors relate chromium emissions to the chromium concentration in the recirculation water in units of milligrams of Cr^{+6} emitted per ppm Cr^{+6} in the recirculating water per liter of recirculating water ($\text{mg Cr}^{+6}/\text{ppm Cr}^{+6}/\text{l H}_2\text{O}$) (pounds of Cr^{+6} emitted per ppm of Cr^{+6} in the recirculating water per gallon of recirculating water [$\text{lb Cr}^{+6}/\text{ppm Cr}^{+6}/\text{gal H}_2\text{O}$]). Because the product of the recirculating water flow rate and the Cr^{+6} concentration in the water is the recirculating Cr^{+6} flow rate, the emission factor also can be expressed as $\text{mg Cr}^{+6} \text{ emitted}/\text{mg Cr}^{+6} \text{ recirculating}$ ($\text{lb Cr}^{+6}/\text{lb Cr}^{+6}$). The recirculation rates, chromate

concentrations, and cooling ranges are lower for CCT's than for industrial towers. However, because the emission factors are independent of these parameters, they should be applicable to CCT's as well as to industrial towers. The lowest emission factor for an individual riser cell was 6.6×10^{-5} mg Cr^{+6} /mg Cr^{+6} (6.6×10^{-5} lb Cr^{+6} /lb Cr^{+6}), and the highest was 1.874×10^{-3} mg Cr^{+6} /mg Cr^{+6} (1.874×10^{-3} lb Cr^{+6} /lb Cr^{+6}). The lowest emission factor is incorrect because some of the Cr^{+6} in the samples was retained on the walls of the beakers used to concentrate the samples. Because of this phenomenon, the aliquots that were analyzed were not representative of the original sample, and the resulting Cr^{+6} concentrations are lower than the actual Cr^{+6} concentrations. Thus, the lowest emission factor should be higher than 6.6×10^{-5} mg Cr^{+6} /mg Cr^{+6} , but it is not expected that the amount of Cr^{+6} retained on the walls of the beakers accounts for most of the difference between the lowest and highest emission factors. The wide differences between emission factors indicate that emissions may vary substantially with time for an individual tower as well as from tower to tower. Because the national average Cr^{+6} emission cannot be estimated accurately with the available data, CCT emissions have been calculated using both emission factors to provide an emissions rate range for each model tower. Thus, the emission rate range for each model tower was calculated by multiplying the emission factors by the model recirculation rate in liters per minute and the Cr^{+6} concentration of 4.48 ppm as shown by Equation 4.

$$\text{Cr}^{+6} \text{ emissions} = K \cdot C_{\text{Cr}^{+6}} \cdot R \quad (4)$$

where:

Cr^{+6} emissions [=] mg Cr^{+6} /hour (lb Cr^{+6} /hour)

K = Cr^{+6} emission factor, mg Cr^{+6} /mg Cr^{+6} (lb Cr^{+6} /lb Cr^{+6})

$C_{\text{Cr}^{+6}}$ = concentration of Cr^{+6} in cooling water, ppm.

(For the model towers, this equals 4.48 ppm)

R = recirculation rate of cooling water, liters/hour (gal/hour)

(1 liter of water equals 1,000,000 mg of water)

(1 gallon of water equals 8.33 lb of water)

4.1.7 Stack Parameters

Table 4-3 lists the stack parameters developed to perform dispersion modeling on all model CCT's. To define these parameters, it was necessary to estimate the airflow rates through each model tower. A leading CCT manufacturer indicated that fans and stacks are designed to maintain stack velocities between 365 and 670 meters per minute (m/min) (1,200 and 2,200 feet per minute [ft/min]).²⁸ Also, the liquid-to-gas ratio (L/G) for an individual tower can vary from 0.5 to 2.5:1. The typical L/G ratio for a CCT of 1.5:1 was used to calculate the airflow rate for each model tower.²⁸ Next, the airflow rate and a velocity of 520 m/min (1,700 ft/min) were used to calculate model stack diameters. Finally, because standard diameter fans are not available in fractions of a foot, the calculated diameter was rounded to the nearest whole number. The stack velocity was then recalculated, and, in each case, it was within the design range of 365 to 670 m/min (1,200 to 2,200 ft/min). The range of recalculated velocities was 424 to 556 m/min (1,390 to 1,824 ft/min).

Actual stack heights (distance from the base of the tower to the top of the stack) for the larger towers were determined from manufacturer's product literature, and the heights of the smallest towers were extrapolated from the available information. Comfort cooling towers are most commonly mounted at ground level near a building or on the roof of the building they serve. Table 4-3 presents stack heights corresponding to both ground-mounted and roof-mounted CCT's. An average number of floors for each model building was determined from DOE data, and it was assumed that each floor adds 3.7 m (12 ft) to the building height.¹

As mentioned above, heat transfer occurs because of evaporation (heat of vaporization) and sensible heat differences. The dry bulb temperature and the relative humidity of the ambient air determine both the relative effect of each type of heat transfer and the temperature of the air in the stack. For the typical case in which heat of vaporization accounts for 80 percent of the heat transfer and sensible heat accounts for 20 percent of the heat transfer, the dry bulb temperature of the air in the stack would be several degrees (Fahrenheit) warmer than the dry bulb temperature of the ambient air. A CCT is most likely to operate during the spring, summer, and fall. Therefore, the mean nationwide dry bulb temperature of

the air in the stack for these three seasons of the year should be used in the dispersion modeling; it has been assumed that 27°C (80°F) reasonably approximates this value.

4.1.8 Maintenance

The towers are assumed to be shut down for at least 2 weeks in winter. At this time, the nozzles can be cleaned, broken slats can be repaired, drift eliminator spaces can be cleared, and any other routine repairs can be performed.

4.2 MODEL HEAT EXCHANGER PARAMETERS

Information from the case studies has indicated that compression-type refrigeration units are used in nearly all CCT applications and that the heat exchangers have copper tubes and a cast steel shell.^{5-11,29-31} Thus, these features have been assumed in the development of model equipment.

Because the CCT operators contacted during the case studies and limited corrosion data indicate that it is possible to obtain equivalent corrosion protection with nonchromate treatment programs, it has been assumed for the model system that equipment life is not affected by the choice of corrosion inhibitor.^{6,7,10,11,13,29-32} The case studies also have confirmed that systems using nonchromates do not require more frequent heat exchanger maintenance than when chromates are used. Therefore, it has been assumed that maintenance on the heat exchanger will be performed annually in both cases.

4.3 BASELINE EMISSIONS

From information supplied by industry vendors, it was assumed for purposes of analysis that there are approximately 250,000 CCT's nationwide and that 15 percent (approximately 37,500) of all CCT's use chromates.³³⁻³⁸ To estimate nationwide emissions, these 37,500 CCT's were apportioned among the model plants. The DOE study contains data concerning the number of buildings that have central cooling in each of the building size categories.¹ However, not all of these cooling systems use CCT's. General HVAC design principles indicate that the larger the building, the more likely that CCT's would be chosen for HVAC cooling. Also, as the square footage exceeds 9,290 m² (100,000 ft²), HVAC design criteria make CCT's the overwhelming choice for central cooling. However, little data are available concerning the actual distribution of CCT's over

the various size ranges. Thus, the following size distribution was based on engineering judgments: 5 percent of buildings between 465 and 929 m² (5,001 and 10,000 ft²) were assumed to have CCT's, 25 percent in the 929 to 2,323 m² (10,001 to 25,000 ft²) range, 40 percent in the 2,323 to 4,645 m² (25,001 to 50,000 ft²) range, 60 percent in the 4,645 to 9,290 m² (50,001 to 100,000 ft²) range, 90 percent in the 9,290 to 18,581 m² (100,001 to 200,000 ft²) range, and 95 percent over 18,581 m² (200,000 ft²). The data do not indicate that the percentage of CCT's using chromates varies with CCT size. Therefore, it was assumed that 15 percent of the CCT's in each size range use chromates. The number of buildings with CCT's in each size range and the estimated number of model CCT's using chromates are presented in Table 4-4.

The Cr⁺⁶ emissions per State were estimated from the number of model towers in the State and from the Cr⁺⁶ emissions for individual model towers in each State. Table 4-5 presents the number of model towers assigned to each State as determined by the population of each State from the 1980 census and assuming that the proportion of each model tower size is constant among the States. The Cr⁺⁶ emissions for individual model towers in each State are dependent upon the utilization rate for the State. For the purposes of analysis, the utilization rate is the percentage of the number of days that the fan operates annually. The utilization rate depends on the climate at the CCT site and the building use; but for an approximation of the rate, it was assumed that the fan is not used on days when the average temperature is below 15.6°C (60°F).³⁹ This rough approximation incorporates two errors that may offset each other: it is known that some towers do operate when the temperature is much less than 15.6°C (60°F) and that they do not necessarily operate for 24 hours on days when the temperature exceeds 15.6°C (60°F). Meteorological data were examined to determine the percentage of days that the average temperature is above 15.6°C (60°F) in each State.³⁹ Table 4-6 presents the percentages for each State, which range from 0 percent in Alaska to 100 percent in Hawaii. The average nationwide utilization rate of 46 percent was determined by multiplying each State utilization rate by the number of towers in the State and then dividing the sum of the products by the total number of towers nationwide.

The annual Cr^{+6} emissions from individual model towers in each State were estimated by calculating annual emissions from the hourly emissions presented in Table 4-1 and multiplying by the utilization rate for the State. The estimated individual emission rates for the six model tower sizes in each State were then multiplied by the respective number of CCT's of that model size in the State to obtain the Statewide Cr^{+6} emissions from each model tower size. The total Cr^{+6} emission rate for each State was determined by summing the Statewide Cr^{+6} emissions for each of the model tower sizes. By summing the emissions for all States, nationwide Cr^{+6} emissions were estimated to be 7.2 to 206 Mg/yr (8 to 227 tons/yr). The average emission rate per person for each State was estimated by dividing the total Cr^{+6} emission rate for the State by the population of the State. Table 4-6 presents the annual Cr^{+6} emissions from individual model towers in each State. Table 4-7 presents the Statewide and nationwide annual Cr^{+6} emission rates per model tower size and the average annual Cr^{+6} emissions per person for each State.

Risk analysis was performed using the area source model contained in EPA's Human Exposure Model (HEM).⁴⁰ (A description of the HEM is provided in Appendix B). Using this modeling technique with the lower-bound and upper-bound emission estimates, the incidence of cancer from Cr^{+6} emissions from CCT's is estimated to be from 4 to 112 cases per year. Table 4-8 presents the nationwide risk for each model and the entire category.

TABLE 4-1. MODEL COMFORT COOLING TOWERS AND HOURLY BASELINE EMISSIONS

Model tower	Model building size, m ² (ft ²)	Model tower cooling requirements W (Btu/h)	Flow rates, gal/min (gal/min)			Chromium emissions per tower, mg/h (1h/1,000 h)	
			Recirculation rate	Evaporation rate	Blowdown rate		
1	673 (7,240)	95,400 (325,800)	27 (65)	246 (65)	2.08 (0.55)	0.53 (0.14)	4.4-124 (0.0097-0.265)
2	1,460 (15,720)	207,100 (707,400)	59 (141)	534 (141)	4.54 (1.20)	1.14 (0.30)	9.5-270 (0.021-0.595)
3	3,405 (36,650)	482,900 (1,649,000)	137 (330)	1,250 (330)	10.6 (2.80)	2.65 (0.70)	22-630 (0.049-1.39)
4	6,224 (66,990)	882,900 (3,015,000)	251 (602)	2,280 (602)	19.4 (5.12)	4.85 (1.28)	40-1,150 (0.088-2.54)
5	12,338 (132,800)	1,750,000 (5,976,000)	498 (1,194)	4,520 (1,194)	38.4 (10.15)	9.61 (2.54)	80-2,300 (0.176-5.07)
6	37,626 (405,000)	5,338,000 (18,230,000)	1,520 (3,642)	13,800 (3,642)	117.0 (30.96)	29.3 (7.74)	240-6,950 (0.529-15.3)

Assumptions:

Wet bulb temperature = 23.9°C (75°F)
 Hot water temperature = 29.4°C (85°F)
 Cooling range = 5.6°C (10°F)
 Cooling requirements = 142 W/m² floorspace (45 Btu/ft²/h)
 Cycles of concentration = 5
 Latent heat/total heat = 0.8
 Chromate concentration = 10 ppm

Lower-bound chromium emission factor = 0.000066 mg Cr⁺⁶/(ppm Cr⁺⁶)(liter H₂O)
 [5.508x10⁻⁵ lb Cr⁺⁶/ppm Cr⁺⁶/gal H₂O]

Upper-bound chromium emission factor = 0.001874 mg Cr⁺⁶/(ppm Cr⁺⁶)(liter H₂O)
 [1.564x10⁻³ lb Cr⁺⁶/ppm Cr⁺⁶/gal H₂O]

TABLE 4-2. EMISSION FACTORS FROM EPA-SPONSORED TESTS

Plant/location	Tower/ fan cells	Flow type	Emission factor
			mg Cr ⁺⁶ /mg Cr ⁺⁶ or lb Cr ⁺⁶ /lb Cr ⁺⁶
Department of Energy, Paducah, Ky. ^a	1/7,8	Crossflow	0.000075
	1/9,10	Crossflow	0.000066
Exxon, Baytown, Tex.	68/1,2,3,4	Counterflow	0.001063
	68/5	Crossflow	0.001874
Mean (Exxon, Baytown) ^b			0.00147

^aThese emission factors are incorrect because some of the Cr⁺⁶ in the samples was retained on the walls of the beakers used to concentrate the samples. Thus, the actual Cr⁺⁶ emission factors are higher than those indicated in this table. This phenomenon also occurred with the samples in other tests, but the beakers were subsequently rinsed with aqua regia. Both the concentrated sample and the rinse were then reanalyzed. The amount of Cr⁺⁶ recovered increased by an average of 3.1 times using this rinse procedure.

^bData obtained in the test at the Department of Energy have been omitted from the mean because of the situation described above. The mean is presented because crossflow and counterflow CCT's are evenly distributed.

TABLE 4-3. STACK PARAMETERS FOR MODEL CCT's

Model tower	Stack diameter, m (ft)	Ground-mounted stack height, m (ft)	Roof-mounted stack height, m (ft)	Exit velocity, m/s (ft/s)	Exit temperature, °C (°F)
1	0.6 (2)	1.5 (5)	8.8 (29)	8.2 (27.0)	27 (80)
2	0.9 (3)	2.4 (8)	9.8 (32)	7.9 (26.0)	27 (80)
3	1.2 (4)	3.0 (10)	14.0 (46)	10.4 (34.2)	27 (80)
4	1.8 (6)	4.9 (12)	19.5 (64)	8.5 (27.8)	27 (80)
5	2.4 (8)	6.4 (16)	24.7 (81)	9.4 (31.0)	27 (80)
6	4.6 (15)	7.6 (25)	44.2 (145)	8.2 (26.9)	27 (80)

TABLE 4-4. NUMBER OF MODEL CCT'S

Model cooling tower	Model building size, m ² (ft ²)	Buildings with central cooling, thousands	Percent of buildings with CCT's	No. of CCT's, thousands	Percent using chromates	CCT's using chromate, thousands	Percent- age of total CCT's in each size range
1	673 (7,240)	371	5	18.55	15	2.78	7.4
2	1,460 (15,720)	334	25	83.50	15	12.53	33.3
3	3,405 (36,650)	128	40	51.20	15	7.68	20.4
4	6,224 (66,990)	70	60	42.00	15	6.30	16.8
5	12,338 (132,800)	35	90	31.50	15	4.73	12.6
6	37,626 (405,000)	25	95	23.75 250.50	15	3.56 37.58	9.5 100

TABLE 4-5. DISTRIBUTION OF CHROMIUM-USING CCT's PER STATE

STATE	POPULATION	MODEL NO.					
		1	2	3	4	5	6
ALABAMA	4,030,000	48	217	133	109	82	62
ALASKA (a)	448,000	0	0	0	0	0	0
ARIZONA	3,010,000	36	162	99	81	61	46
ARKANSAS	2,400,000	29	129	79	65	49	37
CALIFORNIA	24,800,000	296	1332	817	670	503	379
COLORADO	3,110,000	37	167	102	84	63	48
CONNECTICUT	3,130,000	37	168	103	85	63	48
DELAWARE	610,000	7	33	20	16	12	9
FLORIDA	10,600,000	127	570	349	286	215	162
GEORGIA	5,710,000	68	307	188	154	116	87
HAWAII	1,020,000	12	55	34	28	21	16
IDaho	1,020,000	12	55	34	28	21	16
ILLINOIS	11,500,000	137	618	379	311	233	176
INDIANA	5,570,000	66	299	184	151	113	85
IOwa	2,940,000	35	158	97	79	60	45
KANSAS	2,410,000	29	129	79	65	49	37
KENTUCKY	3,790,000	45	204	125	102	77	58
LOUISIANA	4,360,000	52	234	144	118	88	67
MAINE	1,170,000	14	63	39	32	24	18
MARYLAND	4,330,000	52	233	143	117	88	66
MASSACHUSETTS	5,780,000	69	311	190	156	117	88
MICHIGAN	9,400,000	112	505	310	254	191	144
MINNESOTA	4,160,000	50	224	137	112	84	64
MISSISSIPPI	2,600,000	31	140	86	70	53	40
MISSOURI	5,010,000	60	269	165	135	102	77
MONTANA	826,000	10	44	27	22	17	13
NEBRASKA	1,600,000	19	86	53	43	32	24
NEVADA	891,000	11	48	29	24	18	14
NEW HAMPSHIRE	981,000	12	53	32	27	20	15
NEW JERSEY	7,450,000	89	400	245	201	151	114
NEW MEXICO	1,390,000	17	75	46	38	28	21
NEW YORK	17,400,000	208	935	573	470	353	266
NORTH CAROLINA	6,110,000	73	328	201	165	124	93
NORTH DAKOTA	667,000	8	36	22	18	14	10
OHIO	10,800,000	129	580	356	292	219	165
OKLAHOMA	3,170,000	38	170	104	86	64	48
OREGON	2,800,000	33	150	92	76	57	43
PENNSYLVANIA	11,800,000	141	634	389	319	239	180
RHODE ISLAND	953,000	11	51	31	26	19	15
SOUTH CAROLINA	3,280,000	39	176	108	89	66	50
SOUTH DAKOTA	700,000	8	38	23	19	14	11
TENNESSEE	4,790,000	57	257	158	129	97	73
TEXAS	15,100,000	180	811	497	408	306	231
UTAH	1,580,000	19	85	52	43	32	24
VERMONT	530,000	6	28	17	14	11	8
VIRGINIA	5,590,000	67	300	184	151	113	85
WASHINGTON	4,310,000	51	232	142	116	87	66
WEST VIRGINIA	2,000,000	24	107	66	54	41	31
WISCONSIN	4,820,000	58	259	159	130	98	74
WYOMING	514,000	6	28	17	14	10	8
WASHINGTON, DC	508,000	7	32	20	16	12	9
TOTAL FOR U.S. (b)	233,120,000	2783	12525	7580	6300	4725	3563

^aMeteorological data for Alaska indicate that, on average, there are no days when the mean temperature exceeds 60°F. Thus, Alaska was not considered to have chromium emissions from CCT's.

^bExcludes population of Alaska.

TABLE 4-6a. LOWER- AND UPPER-BOUND ESTIMATES OF Cr⁺⁶ EMISSIONS FROM INDIVIDUAL MODEL TOWERS PER STATE (METRIC)

State	Utiliza- tion, %	Cr ⁺⁶ emissions per model CCT, kg/yr				
		1	2	3	4	5
Alabama	59	0.0226-0.6420	0.0491-1.3939	0.1145-3.2497	0.2092-5.9400	0.4147-11.7753
Alaska	0	0.0000-0.0000	0.0000-0.0000	0.0000-0.0000	0.0000-0.0000	0.0000-0.0000
Arizona	55	0.0211-0.5984	0.0458-1.2294	0.1067-3.0294	0.1950-5.5372	0.3866-10.9770
Arkansas	56	0.0215-0.6093	0.0466-1.3230	0.1086-3.0845	0.1986-5.6379	0.3936-11.1765
California	54	0.0207-0.5876	0.0449-1.2758	0.1048-2.9743	0.1915-5.4366	0.3796-10.7774
Colorado	29	0.0111-0.3155	0.0241-0.6851	0.0563-1.5973	0.1028-2.9196	0.2038-5.7878
Connecticut	33	0.0126-0.3591	0.0275-0.7796	0.0640-1.8176	0.1170-3.3223	0.2320-6.5862
Delaware	33	0.0126-0.3591	0.0275-0.7796	0.0640-1.8176	0.1170-3.3223	0.2320-6.5862
Florida	89	0.0341-0.9684	0.0741-2.1026	0.1727-4.9021	0.3156-8.9603	0.6256-17.7627
Georgia	59	0.0226-0.6420	0.0491-1.3939	0.1145-3.2497	0.2092-5.9400	0.4147-11.7753
Hawaii	100	0.0383-1.0881	0.0832-2.3625	0.1940-5.5080	0.3546-10.0677	0.7029-19.9581
Idaho	21	0.0080-0.2285	0.0175-0.4961	0.0407-1.1567	0.0745-2.1142	0.1476-4.1912
Illinois	42	0.0161-0.4570	0.0349-0.9923	0.0815-2.3134	0.1489-4.2284	0.2952-8.3824
Indiana	42	0.0161-0.4570	0.0349-0.9923	0.0815-2.3134	0.1489-4.2284	0.2952-8.3824
Iowa	38	0.0146-0.4135	0.0316-0.8978	0.0737-2.0930	0.1347-3.8257	0.2671-7.5841
Kansas	42	0.0161-0.4570	0.0349-0.9923	0.0815-2.3134	0.1489-4.2284	0.2952-8.3824
Kentucky	42	0.0161-0.4570	0.0349-0.9923	0.0815-2.3134	0.1489-4.2284	0.2952-8.3824
Louisiana	65	0.0249-0.7072	0.0541-1.5356	0.1261-3.5802	0.2305-6.5440	0.4569-12.9728
Maine	21	0.0080-0.2285	0.0175-0.4961	0.0407-1.1567	0.0745-2.1142	0.1476-4.1912
Maryland	46	0.0176-0.5005	0.0383-1.0868	0.0892-2.5337	0.1631-4.6311	0.3233-9.1807
Massachusetts	33	0.0126-0.3591	0.0275-0.7796	0.0640-1.8176	0.1170-3.3223	0.2320-6.5862
Michigan	33	0.0126-0.3591	0.0275-0.7796	0.0640-1.8176	0.1170-3.3223	0.2320-6.5862
Minnesota	29	0.0111-0.3155	0.0241-0.6851	0.0563-1.5973	0.1028-2.9196	0.2038-5.7878
Mississippi	59	0.0226-0.6420	0.0491-1.3939	0.1145-3.2497	0.2092-5.9400	0.4147-11.7753
Missouri	42	0.0161-0.4570	0.0349-0.9923	0.0815-2.3134	0.1489-4.2284	0.2952-8.3824
Montana	25	0.0096-0.2720	0.0208-0.5906	0.0485-1.3770	0.0886-2.5169	0.1757-4.9895
Nebraska	38	0.0146-0.4135	0.0316-0.8978	0.0737-2.0930	0.1347-3.8257	0.2671-7.5841
Nevada	39	0.0149-0.4243	0.0325-0.9214	0.0757-2.1481	0.1383-3.9264	0.2741-7.7837
New Hampshire	27	0.0103-0.2938	0.0225-0.6379	0.0524-1.4872	0.0957-2.7183	0.1898-5.3887
New Jersey	42	0.0161-0.4570	0.0349-0.9923	0.0815-2.3134	0.1489-4.2284	0.2952-8.3824
New Mexico	39	0.0149-0.4243	0.0325-0.9214	0.0757-2.1481	0.1383-3.9264	0.2741-7.7837
New York	33	0.0126-0.3591	0.0275-0.7796	0.0640-1.8176	0.1170-3.3223	0.2320-6.5862
North Carolina	53	0.0203-0.5767	0.0441-1.2522	0.1028-2.9192	0.1879-5.3359	0.3725-10.5778
North Dakota	25	0.0096-0.2720	0.0208-0.5906	0.0485-1.3770	0.0886-2.5169	0.1757-4.9895
Ohio	39	0.0149-0.4243	0.0325-0.9214	0.0757-2.1481	0.1383-3.9264	0.2741-7.7837

(continued)

TABLE 4-6a. (continued)

State	Utiliza- tion, %	Cr ⁶⁺ emissions per model CCT, kg/yr				
		1	2	3	4	5
Oklahoma	54	0.0207-0.5876	0.0449-1.2758	0.1048-2.9743	0.1915-5.4366	0.3796-10.7774
Oregon	23	0.0088-0.2503	0.0191-0.5434	0.0446-1.2668	0.0816-2.3156	0.1617-4.5904
Pennsylvania	39	0.0149-0.4243	0.0325-0.9214	0.0757-2.1481	0.1383-3.9264	0.2741-7.7837
Rhode Island	33	0.0126-0.3591	0.0275-0.7796	0.0640-1.8176	0.1170-3.3223	0.2320-6.5862
South Carolina	59	0.0226-0.6420	0.0491-1.3939	0.1145-3.2497	0.2092-5.9400	0.4147-11.7753
South Dakota	33	0.0126-0.3591	0.0275-0.7796	0.0640-1.8176	0.1170-3.3223	0.2320-6.5862
Tennessee	50	0.0192-0.5440	0.0416-1.1813	0.0970-2.7540	0.1773-5.0339	0.3515-9.9790
Texas	63	0.0241-0.6855	0.0524-1.4884	0.1222-3.4700	0.2234-6.3427	0.4428-12.5736
Utah	31	0.0119-0.3373	0.0258-0.7324	0.0601-1.7075	0.1099-3.1210	0.2179-6.1870
Vermont	25	0.0096-0.2720	0.0208-0.5906	0.0485-1.3770	0.0886-2.5169	0.1757-4.9895
Virginia	42	0.0161-0.4570	0.0349-0.9923	0.0815-2.3134	0.1489-4.2284	0.2952-8.3824
Washington	20	0.0077-0.2176	0.0166-0.4725	0.0388-1.1016	0.0709-2.0135	0.1406-3.9916
West Virginia	42	0.0161-0.4570	0.0349-0.9923	0.0815-2.3134	0.1489-4.2284	0.2952-8.3824
Wisconsin	31	0.0119-0.3373	0.0258-0.7324	0.0601-1.7075	0.1099-3.1210	0.2179-6.1870
Wyoming	25	0.0096-0.2720	0.0208-0.5906	0.0485-1.3770	0.0886-2.5169	0.1757-4.9895
Washington, D.C.	50	0.0192-0.5440	0.0416-1.1813	0.0970-2.7540	0.1773-5.0339	0.3515-9.9790

^a Meteorological data indicate that, on average, there are no days when the mean temperature exceeds 60°F in Alaska. Thus, Alaska was not considered to have Cr⁶⁺ emissions from CCT's.

TABLE 4-6b. LOWER- AND UPPER-BOUND ESTIMATES OF Cr⁺⁶ EMISSIONS FROM INDIVIDUAL MODEL TOWERS PER STATE (ENGLISH)

State	Utiliza- tion, %	Cr ⁺⁶ emissions per model CCT, lb/yr				
		1	2	3	4	5
Alabama	59	0.0498-1.4153	0.1082-3.0730	0.2523-7.1644	0.4612-13.0953	0.9143-25.9600
Alaska	0	0.0000-0.0000	0.0000-0.0000	0.0000-0.0000	0.0000-0.0000	0.0000-0.0000
Arizona	55	0.0465-1.3193	0.1009-2.8646	0.2352-6.6787	0.4299-12.2075	0.8523-24.2000
Arkansas	56	0.0473-1.3433	0.1027-2.9167	0.2395-6.8001	0.4378-12.4295	0.8678-24.6400
California	54	0.0456-1.2953	0.0991-2.8126	0.2309-6.5573	0.4221-11.9856	0.8368-23.7600
Colorado	29	0.0245-0.6957	0.0532-1.5104	0.1240-3.5215	0.2267-6.4367	0.4494-12.7600
Connecticut	33	0.0279-0.7916	0.0605-1.7188	0.1411-4.0072	0.2580-7.3245	0.5114-14.5200
Delaware	33	0.0279-0.7916	0.0605-1.7188	0.1411-4.0072	0.2580-7.3245	0.5114-14.5200
Florida	89	0.0752-2.1349	0.1633-4.6355	0.3806-10.8073	0.6957-19.7540	1.3792-39.1610
Georgia	59	0.0498-1.4153	0.1082-3.0730	0.2523-7.1644	0.4612-13.0953	0.9143-25.9600
Hawaii	100	0.0845-2.3988	0.1834-5.2084	0.4277-12.1431	0.7817-22.1955	1.5497-44.0000
Idaho	21	0.0177-0.5037	0.0385-1.0938	0.0898-2.5500	0.1642-4.6611	0.3254-9.2400
Illinois	42	0.0355-1.0075	0.0770-2.1875	0.1796-5.1001	0.3283-9.3221	0.6509-18.4800
Indiana	42	0.0355-1.0075	0.0770-2.1875	0.1796-5.1001	0.3283-9.3221	0.6509-18.4800
Iowa	38	0.0321-0.9115	0.0697-1.9792	0.1625-4.6144	0.2971-8.4343	0.5889-16.7200
Kansas	42	0.0355-1.0075	0.0770-2.1875	0.1796-5.1001	0.3283-9.3221	0.6509-18.4800
Kentucky	42	0.0355-1.0075	0.0770-2.1875	0.1796-5.1001	0.3283-9.3221	0.6509-18.4800
Louisiana	65	0.0549-1.5592	0.1192-3.3855	0.2780-7.8930	0.5081-14.4271	1.0073-28.6000
Maine	21	0.0177-0.5037	0.0385-1.0938	0.0898-2.5500	0.1642-4.6611	0.3254-9.2400
Maryland	46	0.0389-1.1034	0.0844-2.3959	0.1967-5.5858	0.3596-10.2099	0.7129-20.2400
Massachusetts	33	0.0279-0.7916	0.0605-1.7188	0.1411-4.0072	0.2580-7.3245	0.5114-14.5200
Michigan	33	0.0279-0.7916	0.0605-1.7188	0.1411-4.0072	0.2580-7.3245	0.5114-14.5200
Minnesota	29	0.0245-0.6957	0.0532-1.5104	0.1240-3.5215	0.2267-6.4367	0.4494-12.7600
Mississippi	59	0.0498-1.4153	0.1082-3.0730	0.2523-7.1644	0.4612-13.0953	0.9143-25.9600
Missouri	42	0.0355-1.0075	0.0770-2.1875	0.1796-5.1001	0.3283-9.3221	0.6509-18.4800
Montana	25	0.0211-0.5997	0.0459-1.3021	0.1069-3.0358	0.1954-5.5489	0.3874-11.0000
Nebraska	38	0.0321-0.9115	0.0697-1.9792	0.1625-4.6144	0.2971-8.4343	0.5889-16.7200
Nevada	39	0.0329-0.9355	0.0715-2.0313	0.1668-4.7358	0.3049-8.6562	0.6044-17.1600
New Hampshire	27	0.0228-0.6477	0.0495-1.4063	0.1155-3.2786	0.2111-5.9928	0.4184-11.8800
New Jersey	42	0.0355-1.0075	0.0770-2.1875	0.1796-5.1001	0.3283-9.3221	0.6509-18.4800
New Mexico	39	0.0329-0.9355	0.0715-2.0313	0.1668-4.7358	0.3049-8.6562	0.6044-17.1600
New York	33	0.0279-0.7916	0.0605-1.7188	0.1411-4.0072	0.2580-7.3245	0.5114-14.5200
North Carolina	53	0.0448-1.2714	0.0972-2.7605	0.2267-6.4358	0.4143-11.7636	0.8213-23.3200
North Dakota	25	0.0211-0.5997	0.0459-1.3021	0.1069-3.0358	0.1954-5.5489	0.3874-11.0000
Ohio	39	0.0329-0.9355	0.0715-2.0313	0.1668-4.7358	0.3049-8.6562	0.6044-17.1600

(continued)

TABLE 4-6b. (continued)

State	Utiliza- tion, %	Cr ⁶⁺ emissions per model CCT, lb/yr				
		1	2	3	4	5
Oklahoma	54	0.0456-1.2953	0.0991-2.8126	0.2309-6.5573	0.4221-11.9856	0.8368-23.7600
Oregon	23	0.0194-0.5517	0.0422-1.1979	0.0984-2.7929	0.1798-5.1050	0.3564-10.1200
Pennsylvania	39	0.0329-0.9355	0.0715-2.0313	0.1668-4.7358	0.3049-8.6562	0.6044-17.1600
Rhode Island	33	0.0279-0.7916	0.0605-1.7188	0.1411-4.0072	0.2580-7.3245	0.5114-14.5200
South Carolina	59	0.0498-1.4153	0.1082-3.0730	0.2523-7.1644	0.4612-13.0953	0.9143-25.9600
South Dakota	33	0.0279-0.7916	0.0605-1.7188	0.1411-4.0072	0.2580-7.3245	0.5114-14.5200
Tennessee	50	0.0422-1.1994	0.0917-2.6042	0.2138-6.0715	0.3909-11.0977	0.7748-22.0000
Texas	63	0.0532-1.5112	0.1156-3.2813	0.2694-7.6501	0.4925-13.9832	0.9763-27.7200
Utah	31	0.0262-0.7436	0.0569-1.6146	0.1326-3.7644	0.2423-6.8806	0.4804-13.6400
Vermont	25	0.0211-0.5997	0.0459-1.3021	0.1069-3.0358	0.1954-5.5489	0.3874-11.0000
Virginia	42	0.0355-1.0075	0.0770-2.1875	0.1796-5.1001	0.3283-9.3221	0.6509-18.4800
Washington	20	0.0169-0.4798	0.0367-1.0417	0.0855-2.4286	0.1563-4.4391	0.3099-8.8000
West Virginia	42	0.0355-1.0075	0.0770-2.1875	0.1796-5.1001	0.3283-9.3221	0.6509-18.4800
Wisconsin	31	0.0262-0.7436	0.0569-1.6146	0.1326-3.7644	0.2423-6.8806	0.4804-13.6400
Wyoming	25	0.0211-0.5997	0.0459-1.3021	0.1069-3.0358	0.1954-5.5489	0.3874-11.0000
Washington, D.C.	50	0.0422-1.1994	0.0917-2.6042	0.2138-6.0715	0.3909-11.0977	0.7748-22.0000

^a Meteorological data indicate that, on average, there are no days when the mean temperature exceeds 60°F in Alaska. Thus, Alaska was not considered to have Cr⁶⁺ emissions from CCT's.

TABLE 4-7a. LOWER- AND UPPER-BOUND ESTIMATES OF TOTAL Cr⁺⁶ EMISSIONS PER STATE
AND ANNUAL Cr⁺⁶ EMISSIONS PER PERSON (METRIC)

State	Utilization, percent	Model No.						Total Cr+6 emissions, kg/yr	Annual Cr+6 emissions per person, kgx10,000/yr
		Cr+6 emissions, kg/yr							
		1	2	3	4	5	6		
ALABAMA	59	1.09 - 30.9	10.6 - 302	15.2 - 431	22.8 - 647	33.9 - 962	77.9 - 2,212	161 - 4,585	4.01 - 113.8
ALASKA (a)	0	0.00 - 0.0	0.0 - 0	0.0 - 0	0.0 - 0	0.0 - 0	0.0 - 0	0 - 0	0.0 - 0.0
ARIZONA	55	0.76 - 21.5	7.4 - 210	10.6 - 300	15.9 - 450	23.6 - 670	54.2 - 1,540	112 - 3,192	3.74 - 106.1
ARKANSAS	56	0.61 - 17.5	6.0 - 171	8.6 - 244	12.9 - 366	19.1 - 544	44.0 - 1,250	91 - 2,592	3.80 - 108.0
CALIFORNIA	54	6.13 - 174.0	59.9 - 1,700	85.6 - 2,430	128.3 - 3,644	190.8 - 5,417	438.8 - 12,458	903 - 25,823	3.67 - 104.1
COLORADO	29	0.41 - 11.7	4.0 - 114	5.8 - 164	8.6 - 245	12.6 - 365	29.5 - 839	61 - 1,739	1.97 - 55.9
CONNECTICUT	33	0.47 - 13.4	4.6 - 131	6.6 - 187	9.9 - 281	14.7 - 418	33.8 - 961	70 - 1,992	2.24 - 63.6
DELAWARE	33	0.09 - 2.6	0.9 - 26	1.3 - 37	1.9 - 55	2.9 - 81	6.6 - 187	14 - 388	2.24 - 63.6
FLORIDA	89	4.32 - 122.5	42.2 - 1,197	60.3 - 1,712	90.4 - 2,567	134.4 - 3,816	309.1 - 8,776	641 - 18,191	6.04 - 171.6
GEORGIA	59	1.54 - 43.8	15.1 - 428	21.5 - 611	32.3 - 917	48.0 - 1,363	110.4 - 3,134	229 - 6,496	4.01 - 113.8
HAWAII	100	0.47 - 13.2	4.6 - 129	6.5 - 185	9.8 - 278	14.5 - 413	33.4 - 949	69 - 1,967	6.79 - 192.8
IDAHO	21	0.10 - 2.8	1.0 - 27	1.4 - 39	2.1 - 58	3.1 - 87	7.0 - 199	15 - 413	1.43 - 40.5
ILLINOIS	42	2.21 - 62.7	21.6 - 613	30.9 - 876	46.3 - 1,314	68.8 - 1,964	158.2 - 4,493	328 - 9,313	2.85 - 81.0
INDIANA	42	1.07 - 30.4	10.5 - 297	15.0 - 425	22.4 - 636	33.3 - 946	76.6 - 2,176	159 - 4,511	2.85 - 81.0
IOwa	38	0.51 - 14.5	5.0 - 142	7.1 - 203	10.7 - 304	15.9 - 452	36.6 - 1,039	76 - 2,154	2.58 - 73.3
KANSAS	42	0.46 - 13.1	4.5 - 128	6.5 - 184	9.7 - 275	14.4 - 409	33.2 - 942	69 - 1,952	2.85 - 81.0
KENTUCKY	42	0.73 - 20.7	7.1 - 202	10.2 - 289	15.3 - 433	22.7 - 644	52.2 - 1,481	108 - 3,069	2.85 - 81.0
LOUISIANA	65	1.30 - 36.8	12.7 - 360	18.1 - 514	27.2 - 771	40.4 - 1,146	92.9 - 2,636	192 - 5,465	4.41 - 125.3
MAINE	21	0.11 - 3.2	1.1 - 31	1.6 - 45	2.4 - 67	3.5 - 99	8.0 - 229	17 - 474	1.43 - 40.5
MARYLAND	46	0.91 - 25.9	8.9 - 253	12.7 - 361	19.1 - 542	28.4 - 806	65.3 - 1,853	135 - 3,641	3.12 - 86.7
MASSACHUSETTS	33	0.87 - 24.8	8.5 - 242	12.2 - 346	18.3 - 519	27.2 - 772	62.5 - 1,774	130 - 3,678	2.24 - 63.6
MICHIGAN	33	1.42 - 40.3	13.9 - 394	19.8 - 563	29.7 - 844	44.2 - 1,255	101.6 - 2,886	211 - 5,981	2.24 - 63.6
MINNESOTA	29	0.55 - 15.7	5.4 - 153	7.7 - 219	11.6 - 328	17.2 - 488	39.5 - 1,122	82 - 2,326	1.97 - 55.9
MISSISSIPPI	59	0.70 - 19.9	6.9 - 195	9.8 - 278	14.7 - 417	21.9 - 621	50.3 - 1,427	104 - 2,956	4.01 - 113.8
MISSOURI	42	0.96 - 27.3	9.4 - 267	13.4 - 382	20.2 - 573	30.0 - 851	68.9 - 1,957	143 - 4,057	2.85 - 81.0
MONTANA	25	0.09 - 2.7	0.9 - 26	1.3 - 37	2.0 - 56	2.9 - 84	6.8 - 192	14 - 396	1.70 - 48.2
NEBRASKA	38	0.28 - 7.9	2.7 - 77	3.9 - 110	5.8 - 165	8.7 - 246	19.9 - 566	41 - 1,172	2.58 - 73.3
NEVADA	39	0.16 - 4.5	1.6 - 44	2.2 - 63	3.3 - 95	5.0 - 141	11.4 - 323	24 - 670	2.65 - 75.2
NEW HAMPSHIRE	27	0.12 - 3.4	1.2 - 34	1.7 - 48	2.5 - 72	3.8 - 107	8.7 - 246	18 - 511	1.83 - 52.1
NEW JERSEY	42	1.43 - 40.6	14.0 - 397	20.0 - 568	30.0 - 851	44.6 - 1,266	102.5 - 2,911	212 - 6,034	2.85 - 81.0

(cont inued)

TABLE 4-7a. (continued)

State	Utilization, percent	Cr+6 emissions, kg/yr						Total Cr+6 emissions, kg/yr	Annual Cr+6 emissions per person, kg/10,000/yr
		Model No.							
		1	2	3	4	5	6		
NEW MEXICO	39	0.25 - 7.0	2.4 - 69	3.5 - 98	5.2 - 147	7.7 - 219	17.8 - 504	37 - 1,045	2.65 - 75.2
NEW YORK	33	2.63 - 74.6	25.7 - 729	36.7 - 1,042	55.0 - 1,562	81.8 - 2,323	188.1 - 5,342	390 - 11,072	2.24 - 63.6
NORTH CAROLINA	53	1.48 - 42.1	14.5 - 411	20.7 - 588	31.0 - 881	46.1 - 1,310	106.1 - 3,013	220 - 6,244	3.60 - 102.2
NORTH DAKOTA	25	0.08 - 2.2	0.7 - 21	1.1 - 30	1.6 - 45	2.4 - 67	5.5 - 155	11 - 322	1.70 - 48.2
OHIO	39	1.93 - 54.7	18.8 - 535	26.9 - 764	40.4 - 1,146	60.0 - 1,704	138.0 - 3,918	286 - 8,122	2.65 - 75.2
OKLAHOMA	54	0.78 - 22.2	7.7 - 217	10.9 - 311	16.4 - 466	24.4 - 692	56.1 - 1,592	116 - 3,301	3.67 - 104.1
OREGON	23	0.29 - 8.4	2.9 - 82	4.1 - 117	6.2 - 175	9.2 - 261	21.1 - 599	44 - 1,242	1.56 - 44.3
PENNSYLVANIA	39	2.11 - 59.8	20.6 - 584	29.4 - 835	44.1 - 1,252	65.6 - 1,862	150.8 - 4,281	313 - 8,674	2.65 - 75.2
RHODE ISLAND	33	0.14 - 4.1	1.4 - 40	2.0 - 57	3.0 - 86	4.5 - 127	10.3 - 293	21 - 606	2.24 - 63.6
SOUTH CAROLINA	59	0.69 - 25.1	6.7 - 246	12.4 - 351	18.5 - 527	27.6 - 783	63.4 - 1,800	131 - 3,732	4.01 - 113.6
SOUTH DAKOTA	33	0.11 - 3.0	1.0 - 29	1.5 - 42	2.2 - 63	3.3 - 93	7.6 - 215	16 - 445	2.24 - 63.6
TENNESSEE	50	1.10 - 31.1	10.7 - 304	15.3 - 435	22.9 - 652	34.1 - 969	78.5 - 2,228	163 - 4,618	3.40 - 96.4
TEXAS	63	4.35 - 123.6	42.5 - 1,208	60.8 - 1,726	91.2 - 2,588	135.5 - 3,848	311.7 - 8,850	646 - 18,343	4.28 - 121.5
UTAH	31	0.22 - 6.4	2.2 - 62	3.1 - 89	4.7 - 133	7.0 - 198	16.0 - 456	33 - 944	2.11 - 59.8
VERMONT	25	0.06 - 1.7	0.6 - 17	0.8 - 24	1.3 - 36	1.9 - 54	4.3 - 123	9 - 255	1.70 - 48.2
VIRGINIA	42	1.07 - 30.5	10.5 - 296	15.0 - 426	22.5 - 639	33.4 - 950	76.9 - 2,184	159 - 4,527	2.85 - 81.0
WASHINGTON	20	0.39 - 11.2	3.9 - 109	5.5 - 156	8.3 - 235	12.3 - 349	28.2 - 802	59 - 1,662	1.36 - 38.6
WEST VIRGINIA	42	0.38 - 10.9	3.8 - 107	5.4 - 152	8.0 - 229	12.0 - 340	27.5 - 781	57 - 1,620	2.85 - 81.0
WISCONSIN	31	0.68 - 19.4	6.7 - 190	9.5 - 271	14.3 - 407	21.3 - 604	49.0 - 1,390	101 - 2,881	2.11 - 59.8
WYOMING	25	0.06 - 1.7	0.6 - 16	0.8 - 23	1.2 - 35	1.8 - 52	4.2 - 120	9 - 248	1.70 - 48.2
WASHINGTON, DC	50	0.14 - 3.9	1.4 - 39	1.9 - 55	2.9 - 83	4.3 - 123	10.0 - 283	21 - 586	3.40 - 96.4
TOTAL FOR U.S. (b)		49 - 1,392	479 - 13,602	685 - 19,445	1,027 - 29,156	1,527 - 43,349	3,511 - 99,689	7,277 - 206,633	

a Alaska was assumed to have no CCl₄ because, on average, there are no days when the mean temperature exceeds 60°F.

b The population of Alaska was subtracted from the national population prior to the calculation of the national annual Cr⁶ emissions per person.

TABLE 4-7b. LOWER- AND UPPER-BOUND ESTIMATES OF TOTAL Cr⁺⁶ EMISSIONS PER STATE
AND ANNUAL Cr⁺⁶ EMISSIONS PER PERSON (ENGLISH)

State	Utilization, percent	Cr ⁺⁶ emissions, lb/yr						Total Cr ⁺⁶ emissions, lb/yr	Annual Cr ⁺⁶ emissions per person, lb/10,000/yr
		1	2	3	4	5	6		
ALABAMA	59	2.40 - 58.1	23.4 - 665	33.5 - 951	50.2 - 1,426	74.7 - 2,120	171.7 - 4,876	356 - 10,108	8.83 - 251
ALASKA (a)	0	0.00 - 0.0	0.0 - 0	0.0 - 0	0.0 - 0	0.0 - 0	0.0 - 0	0 - 0	0.00 - 0
ARIZONA	55	1.67 - 47.4	16.3 - 463	23.3 - 662	35.0 - 993	52.0 - 1,476	119.6 - 3,395	248 - 7,038	8.23 - 234
ARKANSAS	56	1.36 - 38.5	13.2 - 376	18.9 - 538	28.4 - 806	42.2 - 1,199	97.1 - 2,756	201 - 5,713	8.38 - 238
CALIFORNIA	54	13.51 - 383.5	132.0 - 3,748	188.7 - 5,357	282.9 - 8,033	420.6 - 11,943	967.3 - 27,466	2,005 - 56,930	8.08 - 230
COLORADO	29	0.91 - 25.8	8.9 - 252	12.7 - 361	19.1 - 541	28.3 - 804	65.1 - 1,850	135 - 3,834	4.34 - 123
CONNECTICUT	33	1.04 - 29.6	10.2 - 289	14.6 - 413	21.8 - 620	32.4 - 921	74.6 - 2,118	155 - 4,391	4.94 - 140
DELAWARE	33	0.20 - 5.8	2.0 - 56	2.8 - 81	4.3 - 121	6.3 - 180	14.5 - 413	30 - 856	4.94 - 140
FLORIDA	89	9.51 - 270.2	93.0 - 2,640	132.9 - 3,774	199.3 - 5,659	296.3 - 8,413	681.4 - 19,348	1,412 - 40,105	13.32 - 378
GEORGIA	59	3.40 - 96.5	33.2 - 943	47.5 - 1,348	71.2 - 2,021	105.8 - 3,064	243.3 - 6,909	504 - 14,321	8.83 - 251
HAWAII	100	1.03 - 29.2	10.1 - 285	14.4 - 408	21.5 - 612	32.0 - 910	73.7 - 2,092	153 - 4,336	14.97 - 425
IDAHO	21	0.22 - 6.1	2.1 - 60	3.0 - 86	4.5 - 128	6.7 - 191	15.5 - 439	32 - 911	3.14 - 89
ILLINOIS	42	4.87 - 138.3	47.6 - 1,352	68.1 - 1,932	102.0 - 2,897	151.7 - 4,307	348.9 - 9,966	723 - 20,533	6.29 - 179
INDIANA	42	2.36 - 67.0	23.1 - 655	33.0 - 936	49.4 - 1,403	73.5 - 2,086	169.0 - 4,798	350 - 9,945	6.29 - 179
IOWA	38	1.13 - 32.0	11.0 - 313	15.7 - 447	23.6 - 670	35.1 - 996	80.7 - 2,291	167 - 4,749	5.69 - 162
KANSAS	42	1.02 - 29.0	10.0 - 283	14.3 - 405	21.4 - 607	31.8 - 903	73.1 - 2,076	152 - 4,303	6.29 - 179
KENTUCKY	42	1.61 - 45.6	15.7 - 445	22.4 - 637	33.6 - 955	50.0 - 1,420	115.0 - 3,265	238 - 6,767	6.29 - 179
LOUISIANA	65	2.86 - 81.2	27.9 - 793	39.9 - 1,134	59.9 - 1,700	89.0 - 2,527	204.7 - 5,812	424 - 12,048	9.73 - 276
MAINE	21	0.25 - 7.0	2.4 - 69	3.5 - 98	5.2 - 147	7.7 - 219	17.7 - 504	37 - 1,044	3.14 - 89
MARYLAND	46	2.01 - 57.0	19.6 - 557	28.1 - 797	42.1 - 1,195	62.6 - 1,776	143.9 - 4,085	298 - 8,467	6.89 - 196
MASSACHUSETTS	33	1.92 - 54.6	18.8 - 534	26.9 - 763	40.3 - 1,144	59.9 - 1,701	137.8 - 3,912	286 - 8,108	4.94 - 140
MICHIGAN	33	3.13 - 86.8	30.6 - 868	43.7 - 1,241	65.5 - 1,861	97.4 - 2,766	224.1 - 6,362	464 - 13,187	4.94 - 140
MINNESOTA	29	1.22 - 34.5	11.9 - 338	17.0 - 483	25.5 - 724	37.9 - 1,076	87.1 - 2,474	181 - 5,128	4.34 - 123
MISSISSIPPI	59	1.55 - 43.9	15.1 - 429	21.6 - 614	32.4 - 920	48.2 - 1,368	110.8 - 3,146	230 - 6,521	8.83 - 251
MISSOURI	42	2.12 - 60.3	20.7 - 589	29.6 - 842	44.5 - 1,262	66.1 - 1,877	152.0 - 4,316	315 - 8,945	6.29 - 179
MONTANA	25	0.21 - 5.9	2.0 - 58	2.9 - 83	4.4 - 124	6.5 - 184	14.9 - 424	31 - 878	3.74 - 106
NEBRASKA	38	0.61 - 17.4	6.0 - 170	8.6 - 243	12.8 - 365	19.1 - 542	43.9 - 1,247	91 - 2,585	5.69 - 162
NEVADA	39	0.35 - 10.0	3.4 - 97	4.9 - 139	7.3 - 208	10.9 - 310	25.1 - 713	52 - 1,477	5.84 - 166
NEW HAMPSHIRE	27	0.27 - 7.6	2.6 - 74	3.7 - 106	5.6 - 159	8.3 - 236	19.1 - 543	40 - 1,126	4.04 - 115
NEW JERSEY	42	3.16 - 85.6	30.8 - 876	44.1 - 1,252	66.1 - 1,877	98.3 - 2,790	226.0 - 6,417	468 - 13,302	6.29 - 179

(cont inued)

TABLE 4-7b. (continued)

State	Utilization, percent	Cr+6 emissions, lb/yr						Total Cr+6 emissions, lb/yr	Annual Cr+6 emissions per person, lbx10,000/yr
		Model No.							
		1	2	3	4	5	6		
NEW MEXICO	39	0.55 - 15.5	5.3 - 152	7.6 - 217	11.5 - 325	17.0 - 483	39.2 - 1,112	81 - 2,305	5.84 - 166
NEW YORK	33	5.79 - 164.4	56.6 - 1,607	80.9 - 2,297	121.3 - 3,444	180.3 - 5,121	414.7 - 11,776	860 - 24,410	4.94 - 140
NORTH CAROLINA	53	3.27 - 92.7	31.9 - 906	45.6 - 1,295	68.4 - 1,942	101.7 - 2,888	233.9 - 6,641	485 - 13,766	7.93 - 225
NORTH DAKOTA	25	0.17 - 4.8	1.6 - 47	2.3 - 67	3.5 - 100	5.2 - 149	12.0 - 342	25 - 709	3.74 - 106
OHIO	39	4.25 - 120.6	41.5 - 1,179	59.3 - 1,685	89.0 - 2,526	132.3 - 3,756	304.2 - 8,638	631 - 17,906	5.84 - 166
OKLAHOMA	54	1.73 - 49.0	16.9 - 479	24.1 - 685	36.2 - 1,027	53.8 - 1,527	123.6 - 3,511	256 - 7,277	8.08 - 230
OREGON	23	0.65 - 18.4	6.3 - 180	9.1 - 258	13.6 - 386	20.2 - 574	46.5 - 1,321	96 - 2,738	3.44 - 98
PENNSYLVANIA	39	4.64 - 131.8	45.4 - 1,288	64.8 - 1,841	97.2 - 2,760	144.5 - 4,104	332.4 - 9,438	689 - 19,563	5.84 - 166
RHODE ISLAND	33	0.32 - 9.0	3.1 - 88	4.4 - 126	6.6 - 189	9.9 - 280	22.7 - 645	47 - 1,337	4.94 - 140
SOUTH CAROLINA	59	1.95 - 55.4	19.1 - 542	27.3 - 774	40.9 - 1,161	60.8 - 1,726	139.8 - 3,569	290 - 8,227	8.85 - 251
SOUTH DAKOTA	33	0.23 - 6.6	2.3 - 65	3.3 - 92	4.9 - 139	7.3 - 206	16.7 - 474	35 - 982	4.94 - 140
TENNESSEE	50	2.42 - 68.6	23.6 - 670	33.7 - 958	50.6 - 1,437	75.2 - 2,136	173.0 - 4,912	359 - 10,181	7.49 - 213
TEXAS	63	9.59 - 272.4	93.8 - 2,662	134.0 - 3,806	201.0 - 5,706	298.8 - 8,484	687.1 - 19,510	1,424 - 40,440	9.43 - 268
UTAH	31	0.49 - 14.0	4.8 - 137	6.9 - 196	10.3 - 294	15.4 - 437	35.4 - 1,005	73 - 2,082	4.64 - 132
VERMONT	25	0.13 - 3.8	1.3 - 37	1.9 - 53	2.8 - 79	4.2 - 118	9.6 - 272	20 - 563	3.74 - 106
VIRGINIA	42	2.37 - 67.2	23.1 - 657	33.1 - 939	49.6 - 1,408	73.7 - 2,094	169.6 - 4,815	352 - 9,981	6.29 - 179
WASHINGTON	20	0.87 - 24.7	8.5 - 241	12.1 - 345	18.2 - 517	27.1 - 769	62.3 - 1,768	129 - 3,664	2.99 - 85
WEST VIRGINIA	42	0.85 - 24.1	8.3 - 235	11.8 - 336	17.7 - 504	26.4 - 749	60.7 - 1,723	126 - 3,571	6.29 - 179
WISCONSIN	31	1.51 - 42.8	14.7 - 418	21.1 - 598	31.6 - 896	46.9 - 1,333	107.9 - 3,064	224 - 6,352	4.64 - 132
WYOMING	25	0.13 - 3.7	1.3 - 36	1.8 - 51	2.7 - 77	4.0 - 115	9.3 - 264	19 - 546	3.74 - 106
WASHINGTON, DC	50	0.31 - 8.7	3.0 - 85	4.3 - 122	6.4 - 182	9.5 - 271	22.0 - 623	46 - 1,292	7.49 - 213
TOTAL FOR U.S. (b)		108 - 3,069	1,056 - 29,988	1,510 - 42,869	2,264 - 64,278	3,366 - 95,568	7,740 - 219,777	16,044 - 455,548	

^aAlaska was assumed to have no CCF's because, on average, there are no days when the mean temperature exceeds 60°F.
^bThe population of Alaska was subtracted from the national population prior to the calculation of the national annual Cr+6 emissions per person.

TABLE 4-8. ANNUAL INCIDENCE OF CANCER AS MODELED
BY EPA'S HUMAN EXPOSURE MODEL^a

Model tower	Range of annual incidence of cancer, cases/yr ^b
1	0.03-0.76
2	0.26-7.4
3	0.37-10.6
4	0.56-15.9
5	0.83-23.6
6	1.9-54.2
TOTAL	4-112

^aSee Appendix B for the methodology of risk modeling.

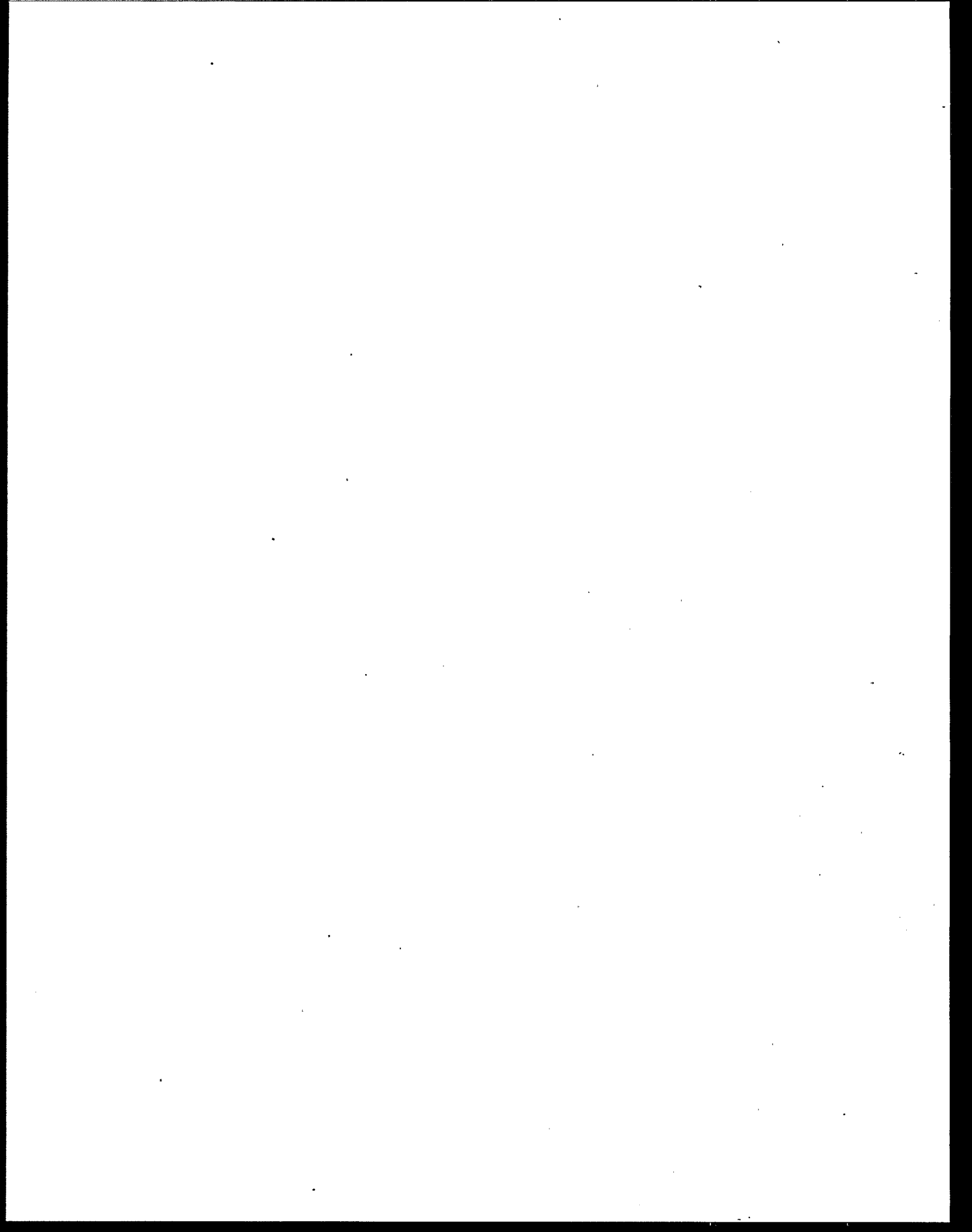
^bThis range reflects lower- and upper-bound emission estimates and the upper-bound unit risk factor.

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5. EMISSION CONTROL TECHNIQUES

5.1 CONTROL TECHNIQUES

Techniques for reducing hexavalent chromium (Cr^{+6}) emissions from comfort cooling towers (CCT's) include eliminating chromium-based chemicals from the water treatment programs and retrofitting towers with higher efficiency drift eliminators.

5.1.1 Nonchromium-Based Treatment Programs

Most nonchromate treatment formulations contain a combination of cathodic and anodic inhibitors along with antiscalants and dispersants. With all nonchromate inhibitors, monitoring and control are critical. It is necessary to control carefully the recommended pH, cycles of concentration, and inhibitor concentrations. Most vendors recommend that inhibitor feed, blowdown, and pH be controlled automatically. Also, microbiological control is more difficult with nonchromates because phosphates are nutrients and some of the other inhibitors are not compatible with chlorine. The compounds used in the nonchromate programs are essentially the same as those used in low-chromate programs described in Section 3.4.2.2. Nonchromate programs have become more successful as operators have become more experienced with automatic controllers used to regulate inhibitor feed and blowdown and as vendors have developed better products, especially antiscalants and dispersants.¹ Typical formulations used in CCT's are based on phosphates, molybdates, and organics. These, and less common programs, are discussed below.

5.1.1.1 Phosphates. Combinations of polyphosphates and ortho-phosphates can be used alone at concentrations of 10 to 30 ppm. However, it is more common to add phosphonate, polymeric dispersants, or both with the phosphates to reduce scaling. With these combinations, effective corrosion control can be achieved.

One successful formulation consists of a combination of orthophosphate, polyphosphate, phosphonate, and a dispersant. Virtually no calcium carbonate and calcium phosphate scale result if conscientious control is maintained at all times and calcium phosphate fouling is controlled with the dispersant. It is important that the water have a calcium hardness within the range of about 100 to 600 ppm, and pH should be maintained between about 7 and 8. When the pH exceeds 8.5, scaling may become a problem; if the system experiences a low pH excursion, the recovery is much slower than with chromate. At low pH (<6.5), rapid corrosion will occur. Chlorination up to 1 ppm is acceptable, as is the use of most nonoxidizing biocides; but because of the nutrient value of the polyphosphates, additional biocides are required. Azoles should be added if the system contains any copper alloy materials because phosphate does not adequately protect copper from corrosion.

5.1.1.2 Molybdates. Molybdates are not a common program primarily because of their cost. However, they are commonly blended with other inhibitors, dispersants, and antiscalants in a treatment program. For example, a combination of up to 15 ppm molybdates with an azole and phosphate can provide better corrosion protection than is achieved by the other nonchromate treatment programs. The pH should be maintained in the range of 7.5 to 8.0 because destruction of the metal oxide film occurs at lower pH levels. At higher pH levels, scale is more difficult to control, and its presence will interfere with film formation and repair. For best results, it is recommended that a passivating pretreatment with molybdate be conducted for up to 1 week at two to five times the maintenance dosage. Low levels of molybdate may permit pitting unless a small amount of zinc is also included in the formulation. Short-term pH excursions reportedly are not harmful; but scaling, fouling, and biological growth must be controlled carefully because deposition will interfere with film formations. Automatic pH control and blowdown are strongly recommended. Low water velocity should be avoided because it can cause fouling and deposition that damage the film.

5.1.1.3 Organics. A number of all-organic formulations can be used as corrosion inhibitors. Modified lignins and tannins and/or polyamines, phosphonides, phosphonium compounds, and heterocyclic nitrogen compounds

have been used as the primary corrosion inhibitor component. The most common heterocyclic nitrogen compounds are the azoles, which are excellent copper corrosion inhibitors. Azoles protect copper by repairing defects (penetration and areas of erosion) that occur in the naturally formed protective film of cupric oxide. They also act synergistically with the natural film of calcium carbonate precipitate. Although azoles protect copper, another inhibitor also is required to protect the carbon steel heat exchanger shell and the system piping. Tolyltriazole is one of the best of the organic compounds, but it is also the most difficult to formulate. Another effective organic compound is 2-mercaptobenzotriazole, but chlorine oxidizes it to the inactive disulfide. These treatments are more costly than chromate, and the protective films decay faster than those produced by chromate. The total organic formulation is required in concentrations of 50 to 150 ppm, and pH should be maintained in the range of 7.5 to 8.5. Microbiological growth must be strictly controlled to avoid interference with film formation. The alkaline conditions that organic treatments require also decrease the toxicity of some biocides (i.e., chlorine and methylene bithiocyanate), which results in greater consumption of biocides. Effective protection with little pitting can be attained if pH, alkalinity, blowdown, and inhibitor concentrations are all controlled as recommended. The best results can be achieved when the system is controlled automatically.

5.1.1.4 Zinc. To be most effective, zinc must be used with combinations of phosphates, phosphonates, organics, or polymeric dispersants. When zinc is used alone, the recommended pH can vary between 6.8 and 8.5 depending on the materials, water quality, and temperature. At higher pH, zinc hydroxides are insoluble. However, the use of various organic phosphorus compounds and polymeric dispersants, and the use of automatic blowdown and pH control help prevent a fouling problem.

When the calcium content of the water is low, zinc is a beneficial addition to the orthophosphate-phosphate-phosphonate treatment program, especially in all-ferrous systems. If the system contains copper, as do CCT's, azoles are required. Excessive orthophosphate, however, can precipitate zinc and create a fouling problem. An azole-zinc-phosphate formulation also is effective.

5.1.1.5 No Corrosion Inhibitor. A treatment program without a corrosion inhibitor is not common. Only scale and fouling control agents are added, and pH is controlled (kept high but varies depending on temperature). The intent is to use calcium carbonate scale to prevent corrosion but also to avoid scale buildup from reaching the point where it would hamper heat transfer. Therefore, makeup water must have calcium hardness, and the amount in the recirculating water must be monitored closely. Automatic controllers help prevent problems. If antiscalants and dispersants are not added, the number of cycles of concentration would have to decrease to prevent deposition, and blowdown would have to be increased. Scaling would still probably occur, and the maintenance effort would increase.

5.1.1.6 Others. Nitrites and orthosilicates are two anodic inhibitors that are often used in closed systems, but they are rarely used in open systems. Nitrites are required in very high concentrations, are attacked by oxidizing agents and certain bacteria, are toxic to animal life, and are only about two-thirds as effective as chromates. Orthosilicates also must be used in high dosages, are slow to take effect, and are not as effective as the other nonchromate inhibitors.

5.1.1.7 Chromate Versus Nonchromate Treatment Programs. Actual experience with CCT's at NASA's Langley Research Center indicates that equal or better corrosion protection is provided when the control parameters of a phosphate-based program are carefully monitored and maintained. The NASA facility has been operating light industrial and CCT's on phosphate-based programs for the past 2 years. Prior to this period, chromate programs were used at concentration levels in the range of 5 to 10 ppm. The NASA facility does not have a target corrosion rate for CCT systems, but the life expectancy of the heat exchangers is about 30 years. Carbon steel corrosion coupons have been used to evaluate the effectiveness of the phosphate-based program. Preliminary information indicates that a corrosion rate of about $50.8 \mu\text{m yr}$ (2 mil/yr) was achieved in the 3 to 4 months ending in February 1986. More recent data are scarce, but early indications are that the current corrosion rate is even slower. Because the corrosion rate of copper is about an order of magnitude less than the corrosion rate of carbon steel, the copper

condenser tubes may be corroding at about $5.1 \mu\text{m yr}$ (0.2 mil/yr).² Because the NASA personnel are conscientiously attending to the program, the corrosion control results are excellent. Data from the chromate-based treatment are not available, but the operators do not believe there has been an increase in the corrosion rate since the switch to nonchromates. Also, there has been no change in the preventive maintenance schedule of general maintenance at 1-year intervals; cleaning, if necessary, every other year; and overhaul every 5 years.

Nonchromates also have been used successfully in CCT's when the makeup water is of poor quality (high chlorides content, high calcium concentration, and/or high conductivity). The total dissolved solids concentration in the Chesapeake, Virginia, water often is as high as 3,000 ppm (conductivity greater than approximately 3,000 μmhos) during the summer, but nonchromates are used in CCT's because publicly owned treatment works discourage the use of chromates.³ For example, the CCT at the Greenbrier Mall in Chesapeake, Virginia, has been treated with nonchromates for 5 years. The chemical feed rate, blowdown, and pH are controlled automatically to maintain operating parameters within vendor recommended control ranges. During the summer, however, the maximum recommended conductivity often is exceeded even though the blowdown rate is maximized. However, each winter the chiller tubes are inspected, and they typically are found to be quite clean and the amount of general corrosion is acceptable.⁴

At most sites where chromates have been discontinued in favor of nonchromates, quantitative costs and maintenance requirements have not been available. In general, it has been claimed that equivalent protection from corrosion has been achieved. However, some comments have been received that mention increased chemical cost; increased monitoring; necessity for automatic controllers (especially when the water quality is poor); increased number and frequency of analyses; and increased use of biocides, antiscalants, and dispersants.

5.1.1.8 Health Effects. The amount of information in the scientific literature on the health effects of the substitutes for chromium in CCT's is limited for some of the pollutants, especially specific triazole compounds, polyphosphates, and polyacrylates. However, the information

available indicates that the health risk is less (and, in most cases, much less) from exposure to the substitutes than to chromium.⁵

Hexavalent chromium is a very potent lung carcinogen when the exposure route is by inhalation. The EPA currently believes that a level cannot be identified below which there is no increased risk of cancer. Therefore, any exposure is associated with some finite increased health risk. In addition to cancer, exposure to Cr^{+6} at concentrations as low as about $100 \mu\text{g}/\text{m}^3$ (as low as $1 \mu\text{g}/\text{m}^3$ for chromic acid) has been associated with a number of adverse respiratory effects that increase in severity with increasing exposure duration and concentration. Many Cr^{+6} compounds are strong oxidizers, which explains their toxic properties and their role as an irritant.

Studies of the substitutes have not clearly shown any of them to be potentially carcinogenic. Although the triazoles are mutagenic in several assays, this alone is not enough to consider the compounds to be carcinogenic. Animal studies were inconclusive. One animal study with molybdenum salts reported an increased number of lung tumors among Strain A mice exposed by intraperitoneal injection. That particular test system has not been demonstrated to be predictive of cancer, and, therefore, the results should be given little weight.

For noncancer health effects of the substitutes, the triazoles appear to be the most toxic. At high concentrations, a number of toxic effects have been reported including respiratory and neurological symptoms, chronic liver morphological and functional changes, and alteration of female reproductive function. Benzotriazole is considered to be a severe acute respiratory hazard as defined by the Federal Hazardous Substances Act because of one study that reported an LC_{50} value (concentration required to kill 50 percent of the test animals) below $2,000 \mu\text{g}/\text{m}^3$ ($1,910 \mu\text{g}/\text{m}^3$ for benzotriazole). Information from a Russian study suggests a value of $10 \mu\text{g}/\text{m}^3$ as that level below which no adverse health effects would be observed. The maximum hourly value of benzotriazole predicted from CCT emissions is estimated to be in the range of 0.008 to $0.2 \mu\text{g}/\text{m}^3$.⁶ Although the risks are difficult to predict accurately, it is unlikely that anyone exposed to this concentration would suffer significant adverse health effects.

Molybdenum compounds appear to be the next most toxic of the alternatives. The primary health effects of molybdenum compounds are acute and respiratory system changes and anemia. The threshold limit value (TLV) for molybdenum compounds is 5 mg/m^3 , a concentration that industrial hygienists believe workers may be exposed to continuously for 8 hours per day without adverse health effects. The maximum hourly value estimated for molybdates from CCT's is $5 \text{ } \mu\text{g/m}^3$, a value one thousand times lower than the TLV.⁶

There is little information available on polyacrylic acid; however for acrylic acid monomer and methylacrylate, the TLV's are 30 mg/m^3 and 35 mg/m^3 , respectively. The maximum hourly value estimated for polyacrylate from CCT's is $0.5 \text{ } \mu\text{g/m}^3$, about four orders of magnitude lower.⁶ Polyphosphates and phosphate esters are rapidly hydrolyzed to orthophosphates (some are insoluble), and toxic effects in animals are rarely reported. Some diphosphonates that are relatively nontoxic are used as pharmacologic agents for diagnosis and treatment of bone disease.

5.1.2 High-Efficiency Drift Eliminators

5.1.2.1 Design and Performance of Drift Eliminators. Historically, the purpose of drift reduction has been to alleviate nuisance problems related to deposition of drift on nearby buildings or on personal property such as automobiles. Installation of drift eliminators is the most common way to reduce drift. Splash fill towers inherently produce the most drift.

Drift eliminators are designed with very low pressure drops compared to other water-based air pollution control equipment and rely primarily upon the impaction of water droplets on drift eliminator surfaces to reduce the concentration of drift from the exit air of cooling towers. The blades of drift eliminators are configured to require directional changes in the airflow such that the momentum of water droplets will carry the droplets out of the airflow stream and onto the blade surfaces. The major differences among drift eliminators that affect efficiency are the number of directional airflow changes, the spacing between the blade surfaces, the angle of directional change, and the ability to return the collected water to a quiescent area of the plenum.

Figure 3-3 shows sketches of various types of drift eliminator designs. Lower efficiency drift eliminators include herringbone, some waveform (sinusoidal), and some cellular designs. Herringbone designs are constructed to create two or three major directional changes in the air. The blades are sloped in opposing directions in a manner that provides drainage of the accumulated drift into the fill area. The blades typically are constructed of wood, but other materials (e.g., metal) are also used. Waveform designs are configured in a sinusoidal wave pattern such that two major directional changes in the airflow are created. The sinusoidal blades are constructed of asbestos cement board or PVC material. Cellular designs are configured with thinner blades in a honeycomb pattern. The airflow directional changes are usually greater in number but less abrupt than in herringbone and waveform styles. Closer spacing of the airflow passages in the cellular design reduces the distance a droplet must travel across the stream to impact on the surface. Asbestos cement board and PVC are typically used as the construction material for low-efficiency drift eliminators. Also, drainage of the collected water to prevent reentrainment is not a design criteria.

Higher efficiency drift eliminators include some cellular and sinusoidal designs. The cellular designs that achieve the higher efficiencies use complex configurations and airflow passages that contain numerous, closely constructed airflow changes. Thin materials of construction are used to reduce the area of blockage to the airflow and minimize the pressure drop that is created by the eliminator. The higher efficiency sinusoidal designs are spaced closer together than are the lower efficiency designs, and the exit is configured with a tip for draining captured water that normally is partially reentrained in the airflow. Typically, drainage of water into a quiescent area of the tower or back into the fill is a major design consideration of higher efficiency drift eliminators.

For a given tower design, factors that affect the performance of the drift eliminators include airflow velocity through the eliminator passages and the particle size distribution of the drift entering the eliminator. The pressure drop across the eliminator is a direct result of the velocity

of the airflow through the passages. The drift size distribution is affected by both the size of droplet created in the tower and the evaporation rate that occurs. The rate of evaporation directly affects the droplet size reduction that results as water evaporates from the surface of the droplet when it is traveling through the fill zone of the tower. Reentrainment of drift because of water drainage problems resulting from the eliminator design can reduce performance. The shearing action of air on water draining off a drift eliminator can result in the formation of droplets that can be reentrained. A drift eliminator design that incorporates a structural modification to direct water to a quiescent area of the tower can result in lower drift rates. The air velocity through gaps between the drift eliminator panels and the walls, distribution deck, other panels, structural members, and the basin will be greater than the velocity through the drift eliminator because the gaps are areas of decreased flow resistance. Thus, the drift emissions will be greater from towers with gaps than from sealed towers.

Drift is often expressed as the percentage of the recirculating water flow rate that is emitted. A major drift eliminator manufacturer uses a drift rate of 0.008 percent to distinguish between higher and lower efficiency drift eliminators. This manufacturer further states that higher efficiency drift eliminators can achieve drift rates as low as 0.001 percent of the recirculating water flow rate and lower efficiency drift eliminators can achieve drift rates as high as 0.02 percent of the recirculating water flow rate.⁷⁻⁹ Another way to express drift is as the mass of droplets emitted per mass of airflow. Test results have indicated that the drift loss from lower efficiency drift eliminators (herringbone) averages 200 to 350 ppm and that higher efficiency drift eliminators can reduce the drift loss to about 20 ppm.¹⁰ The drift rates presented as a percentage of the recirculating rate do not necessarily correlate directly with the drift rates reported as a concentration because the rates were probably determined in tests with different drift eliminators and with different liquid-to-gas ratios.

Drift eliminator manufacturers indicate that higher efficiency drift eliminators can remove up to 80 to 90 percent of the amount of drift discharged from lower efficiency drift eliminators. These drift

eliminator efficiencies are based on pilot-scale cooling tower tests using test methods that have not been verified by EPA. Emission tests of drift eliminators performed by EPA at three facilities indicate that the average nationwide control achieved by higher efficiency drift eliminators is 80 percent more effective than that achieved by lower efficiency drift eliminators. Of the two cooling towers tested by EPA with higher efficiency drift eliminators, the average emissions for the tower with the highest average emissions were 0.3×10^{-3} milligram of Cr^{+6} per milligram of Cr^{+6} recirculating ($\text{mg Cr}^{+6}/\text{mg Cr}^{+6}$) (0.3×10^{-3} pound of Cr^{+6} emitted per pound of Cr^{+6} recirculating [$\text{lb Cr}^{+6}/\text{lb Cr}^{+6}$]). As indicated in Section 4.1.6, EPA emission tests of the two cooling towers with lower efficiency herringbone drift eliminators provide an estimate of average national emissions of 1.5×10^{-3} $\text{mg Cr}^{+6}/\text{mg Cr}^{+6}$ (1.5×10^{-3} $\text{lb Cr}^{+6}/\text{lb Cr}^{+6}$).

The individual isokinetic emission test runs used to determine the average emissions for both higher and lower efficiency drift eliminators were highly variable, which indicates uncertainty in the calculated difference between the two average levels of emissions. Additional testing is planned to determine the cause of this variability and to provide additional data for estimating the incremental effectiveness of higher efficiency drift eliminators.

In addition to isokinetic emission tests to determine Cr^{+6} emissions from four cooling towers, tests by the sensitive paper technique were conducted by EPA to determine the mass emissions and size spectra of water droplets greater than about 30 μm in diameter. Tests by the absorbent paper technique were conducted to determine the emissions of Cr^{+6} in droplets greater than about 30 μm in diameter. The results of these tests consistently indicated that greater than 90 percent of the Cr^{+6} emissions were contained in drift droplets smaller than 30 μm in diameter. It has been reported that the collection efficiency of older design drift eliminators for droplets or particles less than 50 μm (2.0 mils) is relatively insignificant.¹¹

The size of the drift droplets determine, in part, whether the drift droplets are dispersed in the air or deposited on the ground upon leaving the cooling tower. After leaving the exhaust plume of the cooling tower,

all droplets fall at their terminal settling velocity. In addition, evaporation of the droplets will increase after they leave the exhaust plume. In the atmosphere, droplets and particles smaller than about 10 μm act as a gas. As indicated in Table 3-4, for 80 percent relative humidity and 26.7°C (80°F) (close to expected worst-case meteorological conditions), a 30- μm droplet will evaporate to 15 μm in about 3 seconds. By the same procedure, a 30- μm droplet will evaporate to 10 μm in about 3.5 seconds. In half this time, it will evaporate to 22 μm . In addition, the settling velocity of a droplet can be calculated from Equation 1.¹²

$$V = \frac{(P_p - P_g)(g)(d_p)^2}{18 \mu g} \quad (\text{Eq. 1})$$

where, V = velocity, cm/s

P_p = density of droplet, 1.0 g/cm³

P_g = density of air, 1.163 x 10⁻³ g/cm³

g = acceleration of gravity, 981 cm/s²

d_p = diameter of droplet, cm

μg = viscosity of air, 1.983 x 10⁻⁴ g/cm/s

The settling rate of a 22- μm droplet is about 1.3 cm/s (0.51 in./s); this also is the average settling rate of a 30- μm droplet evaporating to 10 μm . Thus, the droplet would fall less than 5 cm in 3 seconds. This distance is insignificant compared to the release height of drift from a CCT (especially if the CCT is mounted on the roof of a building). Thus, because EPA-sponsored emission tests indicated that more than 90 percent of the Cr⁺⁶ is contained in droplets less than 30 μm , it is reasonable to assume that more than 90 percent of the Cr⁺⁶ emitted from these towers will remain airborne to be dispersed over a large area.

5.1.2.2 Retrofit Problems with Drift Eliminators. Vendors have indicated that most existing CCT's have lower efficiency drift eliminators. One cooling tower manufacturer with 40 percent of the market indicates that all its towers have drift eliminators and its older towers do not have the higher efficiency drift eliminators that the company uses in newer installations. Other manufacturers do not routinely install higher efficiency eliminators.^{13,14} Thus, a large market exists for retrofits of high-efficiency drift eliminators.

Cooling tower manufacturers have indicated that 50 percent of all CCT's are counterflow towers and 50 percent are crossflow towers. Manufacturers also have indicated that retrofit can be accomplished by replacing the drift eliminator in all counterflow towers and in about 50 percent of the crossflow towers. Although it is not possible to replace the drift eliminator in the remaining 50 percent of crossflow towers because the eliminators are molded integrally with the fill sheets, a second drift eliminator could be installed above the existing units in about 90 percent of these towers. This procedure would increase the electricity requirements by about 15 percent if the same airflow must be maintained. Also, extensive electrical and mechanical modifications including installation of a larger motor may be required by 50 to 75 percent of the towers to accommodate the increased electrical load. The remaining 10 percent of the towers utilizing drift eliminators that are molded integrally with the fill sheets (2.5 percent of all towers) would have to be rebuilt because they do not have the necessary clearance to have a second drift eliminator installed.^{14,15}

Rather than retrofit high-efficiency drift eliminators, it is likely that the owners of the towers that would incur higher electricity costs and possibly require extensive modification or rebuilding (25 percent of all CCT's) would switch to nonchromate treatment. Some towers already have high-efficiency drift eliminators. However, because a drift eliminator retrofit regulation that specifies a Cr^{+6} emission limit has not been developed, it is not known what percentage of existing towers would be required to retrofit. Thus, it has been assumed that all towers are affected and that for the 37,500 CCT's using chromate treatment programs, the retrofit control technique would consist of drift eliminator replacement for 75 percent of the towers and a switch to nonchromate treatment for 25 percent of the towers.

Retrofits on towers in systems that are over designed for the actual heat load and that have more than one tower or more than one cell per tower could be performed any time during the year. However, to avoid inconvenience to the user, systems that are operating at capacity could be retrofit only when weather conditions do not require tower use. This time could be as short as a few weeks in the southern United States.

Prior to implementation of a regulation requiring the retrofit of higher efficiency drift eliminators, those drift eliminators would have to be certified as higher efficiency using a standard test method to be developed by the Agency. Furthermore, proper installation and sealing are critical to the operation of any drift eliminator. Any maintenance performed on the tower that requires drift eliminator removal or adjustment also may result in improper sealing. Thus, periodic inspections by owners and enforcement personnel would be required to ensure compliance.

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6. REGULATORY CONTROL ALTERNATIVES

This section discusses the regulatory control alternatives available for reducing or eliminating the risks from hexavalent chromium (Cr^{+6}) emissions from comfort cooling towers (CCT's). The alternatives available include eliminating chromium-based treatment programs and retrofitting CCT's with high-efficiency drift eliminators.

Prohibiting the use of Cr^{+6} -based water treatment chemicals in CCT's has been shown to be a feasible control technique. Alternative treatment programs are as effective as chromium at inhibiting corrosion if used as recommended and are readily available. The majority of CCT's use nonchromium chemicals and a few CCT's use no corrosion inhibitors (about 85 percent). As discussed in Section 5.1.1.7, present information indicates that these systems do not experience significant adverse impacts from corrosion. Also, cooling tower and water treatment vendors have stated that switching from chromium to nonchromium corrosion inhibitors is not expected to cause any operation or maintenance problems with the chiller components (heat exchanger) of the cooling system. Automated monitoring and control systems are readily available to control chemical feed (including corrosion inhibitor, biocides, antiscalants, and dispersants), makeup, and blowdown. In addition, this option results in the maximum level of environmental protection because Cr^{+6} emissions are completely eliminated.

Retrofitting existing CCT's with higher efficiency drift eliminators is not possible at all sites and would be much more complex than switching to nonchromates at most of the remaining sites. As discussed in Section 5.1.2, retrofitting a CCT with a high-efficiency drift eliminator would achieve at most an 80 percent reduction in airborne emissions of Cr^{+6} from the CCT. However, because 25 percent of existing CCT's would be

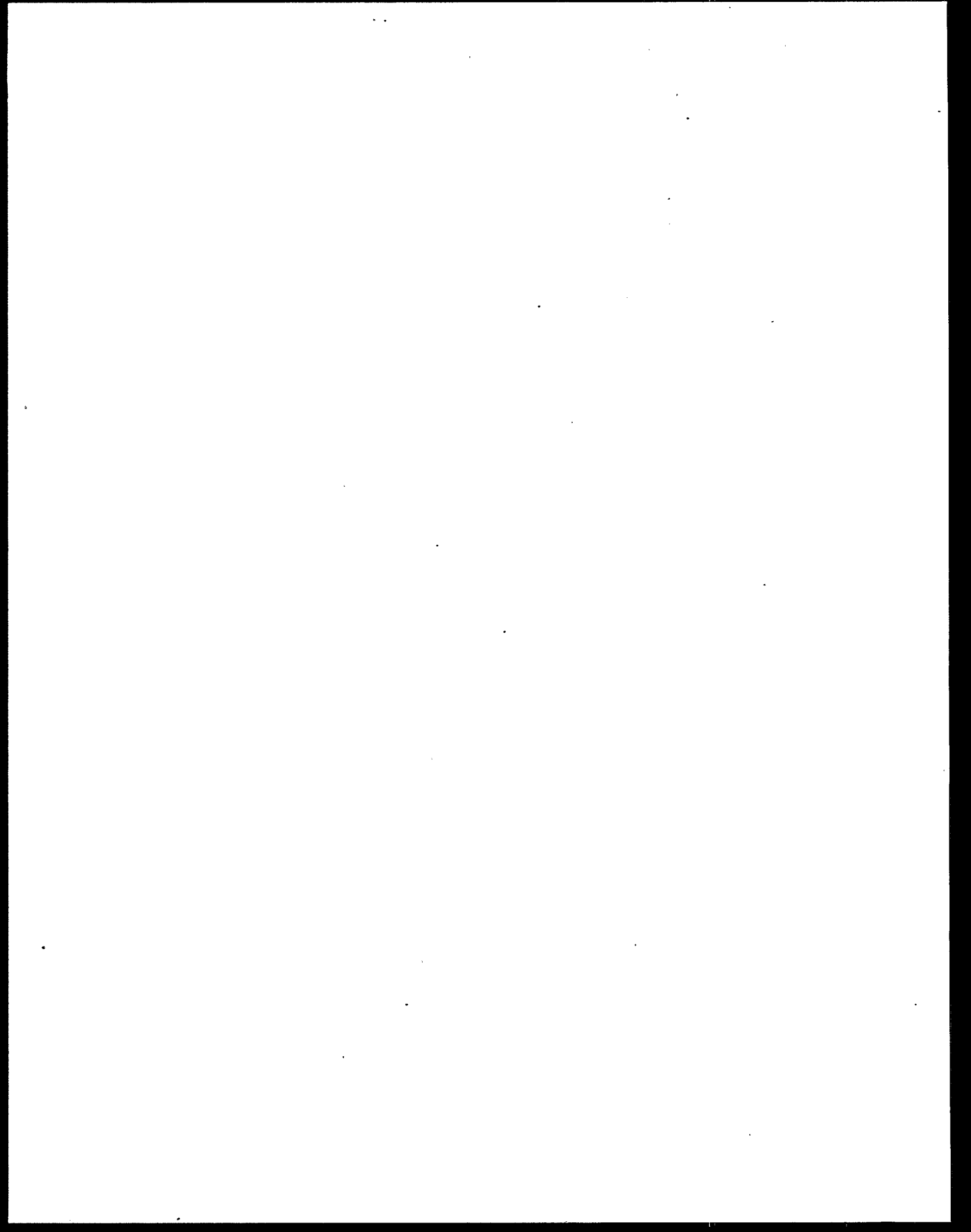
expected to switch to nonchromate water treatment programs, a high-efficiency drift eliminator retrofit regulatory control alternative would reduce the nationwide emissions of Cr^{+6} by up to 85 percent below baseline.

At the present time, there is no standard high-efficiency drift eliminator design; at least three manufacturers produce what they claim are higher efficiency drift eliminators, but the designs and physical parameters of each are different. In addition, it is unclear how emission rates or efficiencies of these drift eliminators are related to their design. Therefore, the information is not available currently to specify design requirements for a high-efficiency drift eliminator.

To implement an effective standard based on the use of high-efficiency drift eliminators, some combination of equipment specifications, performance testing, random inspection, and/or product certification would be necessary in addition to an annual inspection of the drift eliminator. The Agency also would need to develop a reference test method, develop a standard set of test conditions for certification testing related to actual operating conditions of a variety of types of cooling towers, and identify critical installation criteria to be specified in the installation instructions of the drift eliminator. It is unlikely that one set of installation criteria could be developed to include all possible situations. All installations (250,000 CCT's) would have to indicate the type of chemical treatment they use, and the sources using chromates (about 37,500) would be subject to the testing and inspection process. Thus, prohibiting the use of chromium would make enforcement more manageable than implementation and enforcement of a standard based on installation of higher efficiency drift eliminators.

Standards that prohibit chromium chemical use in CCT's could be implemented under the Toxic Substances Control Act (TSCA) or the Clean Air Act (CAA). Section 6 of TSCA would provide the authority not only to prohibit the use of chromium-based chemicals in CCT's but also to prohibit the sales of such chemicals for use in CCT's. Under Section 112 of the CAA, it would not be possible to prohibit the sales of a chemical. However, it would be possible to prohibit the use of chromium-based chemicals in CCT's by setting a zero emissions limit under the CAA. While

TSCA and the CAA could require equally stringent control levels, TSCA would provide a better mechanism for enforcement. Prohibiting the distribution or sales of chromium-based chemicals for use in CCT's and monitoring chemical treatment vendor (20+ major and approximately 400 total) sales and recordkeeping would be far less difficult for both regulatory agencies and sources than inspecting and permitting 37,500 individual users. Any complaint at a particular site could be traced to the vendor for determination of compliance.



7. COSTS

7.1 COSTS OF EMISSION CONTROL TECHNIQUES

This section presents the costs of the regulatory alternatives for controlling hexavalent chromium (Cr^{+6}) emissions from comfort cooling towers (CCT's). The first option is to use nonchromium-based chemicals in CCT's, and the second option is to install higher efficiency drift eliminators.

7.1.1 Nonchromium-Based Treatment Programs

Prohibiting the use of chromates in CCT's would require a switch to other more costly corrosion control chemicals such as phosphates and molybdates. Vendors have indicated that chromium-based water treatment programs typically cost between \$88 and \$132/M kg (\$40 and \$60/M lb) of blowdown. It has been assumed that the higher unit cost is representative of the baseline cost to CCT operators because they purchase smaller quantities of chemicals than industrial users. Vendors also estimated that alternative treatment programs (without always specifying the type of chemical) cost from 10 to 360 percent more than chromium-based programs.¹⁻⁷ Ranges of costs were provided because water quality and the size of the CCT affect the cost of the treatment program. Typically, the smaller the CCT, the smaller the difference in total cost because the cost of vendor service is greater than the chemical cost. Also, the cost difference will be less for systems with good water quality. The phosphate-based programs typically cost 10 to 100 percent more than chromium-based treatments, and molybdate-based treatments are the most costly alternative at up to 360 percent over the cost of chromium-based treatments. Phosphate-based and molybdate-based chemical treatments that cost 100 percent and 360 percent more than baseline chromate-based treatment, respectively, were selected to ensure that the economic impacts

were not underestimated. Thus, phosphate-based and molybdate-based chemical treatment unit costs are \$264 and \$608/M kg (\$120 and \$276/M lb) of blowdown, respectively. The cost of service has not been included in the unit cost because it has been assumed that the service requirements are similar for a given CCT regardless of the type of chemical treatment program being used. Cost data from several operating CCT's that are larger than 400 tons vary but the average cost is higher than the selected unit cost.⁸⁻¹⁰ Also, vendor-estimated costs of organic- and molybdate-based treatments for a given set of CCT operating conditions appear to be higher than the selected unit costs.¹¹ However, both sets of cost data include the cost of service.

To obtain the best results with alternative chemical programs, the chemical feed and blowdown must be controlled automatically based on conductivity of the water, and pH must be controlled within narrow ranges that are typically recommended by vendors. The purchase and installation cost of these automatic feed and monitoring systems would be about \$500 per tower.¹² Although many of the CCT's using chromium-based programs may have automatic feed systems, all towers currently using chromate are assumed to need these systems if they were switched to an alternative treatment. This assumption was made so that costs would not be underestimated.

The percentages of the CCT market that use the various alternative treatment chemicals are not known, but phosphate programs are the most prevalent and molybdate use is rare. It is expected that the CCT systems using chromates will switch to these two alternatives in the same relative proportion. Thus, phosphate-based treatment programs, which can be used in almost all situations and are the least costly alternative, were used to develop the individual and nationwide annualized costs incurred by switching to nonchromium-based chemical treatments.

The capital cost of automatic feed and monitoring equipment was annualized over 15 years, which is the estimated useful life of the feed equipment. An interest rate of 10 percent, which represents the rate of return considered reasonable for industry to expect in the current economy, was used in the calculation of the annualized cost. The total annualized cost of phosphate-based treatment was estimated by summing the

annualized cost of the feed equipment and the annual incremental cost of phosphate-based treatment over chromate-based treatment. Table 7-1 presents the total chemical costs and the cost effectiveness of eliminating chromium use in CCT's. The approximately 37,500 CCT's using chromium-based treatment would incur the costs of switching to nonchromium-based treatment, and the total annualized cost would be about \$9.4 million. Based on this cost and the reduction in the incidence of lung cancer to zero, the cost effectiveness of eliminating chromium-based treatment programs ranges from \$0.083 million to \$2.4 million per cancer case avoided.

7.1.2 Higher Efficiency Drift Eliminators

The second control technique is to retrofit all chromate-using CCT's with higher efficiency drift eliminators. As described in Section 5.1.2, approximately 75 percent of existing CCT's can be retrofitted. The remaining 25 percent of the towers would require extensive modifications or need to be totally rebuilt to accommodate a higher efficiency drift eliminator. Detailed estimates of the increased electrical and structural costs have not been presented because it has been assumed that rather than incur this prohibitive cost, this 25 percent of all CCT's would likely switch to nonchromium treatment programs.

Included in the cost of the control technique are the costs of the drift eliminator retrofits, annual inspections, and the drift eliminator certification program. The drift eliminator certification process was estimated to cost industry about \$2.3 million, and it was assumed that the total cost would be passed on to the CCT owner/operators that use chromates.¹³ Both the certification and retrofit costs were annualized over 15 years, and the interest rate used in the calculation was 10 percent.

The Cr^{+6} emissions obtained with low-efficiency drift eliminators are the baseline emissions. As mentioned in Section 5.1.2, it is assumed that drift from CCT's can be reduced by up to 80 percent by installing high-efficiency drift eliminators.

Table 7-2 presents the annualized costs and the cost effectiveness of the drift eliminator retrofit control technique for individual model tower units and nationwide. The nationwide annualized costs of the control

technique are about \$22 million. The cancer incidence is reduced by 3.4 to 96 cases per year, and the nationwide cost effectiveness ranges from \$0.23 million to \$6.5 million per cancer case avoided.

7.2 FIVE-YEAR SALES AND COSTS PROJECTIONS

Comfort cooling tower manufacturers have estimated that about 20,800 CCT's (including evaporative condensers and fluid coolers) will be sold in the next 5 years for use in new applications.^{14,15} Sales in the first 2 years will be slower because of the present building slowdown in many parts of the nation. In the following 3 years, sales growth will increase gradually. Table 7-3 presents the total annual sales, and Table 7-4 presents the annualized costs for both control techniques. The cost to switch 15 percent of the towers to phosphate-based treatment would cost about \$780,000, and requiring high-efficiency drift eliminator retrofits would cost about \$1.4 million.

TABLE 7-1. COSTS AND COST EFFECTIVENESS FOR NO-CHROMIUM OPTION^a

Model Tower No.	Unit cost of chromate treatment, \$/M lb of blowdown	Blowdown, kg/yr (lb/yr)	Cost of chromate, \$/yr/tower	Unit cost of phosphate treatment, \$/M kg (\$/M lb) of blowdown	Cost of phosphate treatment, \$/yr/tower	Unit cost of molybdate treatment, \$/M kg (\$/M lb) of blowdown	Cost of molybdate treatment, \$/yr/tower	Annualized incremental cost of phosphate over chromate, \$/yr/tower
1	60	126,300 (278,500)	17	264 (120)	34	608 (276)	78	17
2	60	274,200 (604,600)	36	264 (120)	72	608 (276)	166	36
3	60	639,400 (1,409,600)	85	264 (120)	170	608 (276)	391	85
4	60	1,168,700 (2,576,600)	155	264 (120)	310	608 (276)	713	155
5	60	2,316,900 (5,107,800)	306	264 (120)	612	608 (276)	1,408	306
6	60	7,065,700 (15,577,100)	935	264 (120)	1,870	608 (276)	4,300	935

^aThe unit costs for each of the treatment programs is for the annual chemical cost and does not include a cost for service by the vendor because it is assumed that the technical service costs are the same for each type of chemical treatment program.
^bAssumes capital cost of \$500 for automatic feed equipment is annualized over 15 years.
^cCost includes annualized cost of automatic feed equipment and the annual incremental cost of phosphate-based treatment over chromate-based treatment.

TABLE 7-1. (continued)

Model tower No.	Annualized capital cost of automatic feed system, \$/yr/tower ^b	Total annualized cost of phosphate substitution		Cancer incidence reduction, cases/yr	Cost effectiveness for lower-bound emissions		Cost effectiveness for upper-bound emissions		
		\$/yr/tower ^c	No. of CCT's		Nationwide	\$/cancer case avoided	10 ⁶ \$/Mg (10 ⁶ \$/ton)	\$/cancer case avoided	10 ⁶ \$/Mg (10 ⁶ \$/ton)
1	66	83	2,780	0.03-0.76	231,000	7,700,000	4.71 (4.27)	304,000	0.17 (0.15)
2	66	102	12,530	0.26-7.4	1,278,000	4,915,000	2.67 (2.42)	173,000	0.094 (0.085)
3	66	151	7,680	0.37-10.6	1,160,000	3,135,000	1.69 (1.54)	110,000	0.060 (0.054)
4	66	221	6,300	0.56-15.9	1,392,000	2,486,000	1.36 (1.23)	88,000	0.048 (0.044)
5	66	372	4,730	0.83-23.6	1,758,000	2,118,000	1.15 (1.04)	75,000	0.041 (0.037)
6	66	1,001	3,560	1.9-54.2	3,566,000	1,867,000	1.02 (0.93)	66,000	0.036 (0.033)
			37,580	4-112	9,385,000	2,370,000	1.29 (1.17)	83,000	0.045 (0.041)

TABLE 7-2. COSTS AND COST EFFECTIVENESS FOR HIGH-EFFICIENCY DRIFT ELIMINATOR RETROFITS ON CHROMIUM-USING CCT'S

Model tower No.	D.E. retrofit cost, \$ ^a	Annualized cost of retrofit			Cost of annual inspection, \$/yr/tower	Annualized cost of certification, \$/yr/tower ^b	Total retrofitable towers	Annualized cost of inspection and certification, \$/yr/nationwide
		\$/yr/tower	Total retrofitable towers	\$/yr/nationwide				
1	390	51	2,093	106,000	500	11	2,093	1,067,000
2	555	73	9,395	686,000	500	11	9,395	4,801,000
3	880	116	5,760	668,000	500	11	5,760	2,943,000
4	1,385	182	4,725	860,000	500	11	4,725	2,414,000
5	2,385	314	3,545	1,113,000	500	11	3,545	1,811,000
6	4,980	655	2,678	1,751,000	500	11	2,678	1,366,000
			28,196	5,184,000			28,196	14,402,000

^aThis is the cost for materials, labor, and freight.

^bAssumes \$2.3 million cost to develop certification facility and to conduct tests. This cost is distributed among the approximately 28,000 CCT's (about 75 percent of the 37,500 CCT's using chromate-based treatment) that use chromates and can be retrofitted with high-efficiency drift eliminators. The cost to each CCT is \$82.

^cAssumes towers with integral fill and drift eliminator will switch to nonchromate rather than rebuild the tower (about 25 percent of the 37,500 CCT's using chromate-based treatment).

^dSum of annualized cost of retrofit, annualized cost of inspection and certification, and annualized cost of phosphate in nonretrofitable towers.

^eReduction efficiency is based on the assumption that 25 percent of the existing CCT's would switch to nonchromate treatment programs and achieve 100 percent reduction and that 75 percent of CCT's would be retrofitted with high-efficiency drift eliminators and achieve 80 percent reduction.

TABLE 7-2. (continued)

Model tower No.	Annualized cost of phosphate in non-retrofitable towers ^c			Total annualized replacement cost, \$/yr/nationwide	Reduction efficiency, %	Cancer incidence reduction, No./yr	Cost effectiveness for lower-bound emissions		Cost effectiveness for upper-bound emissions	
	\$/yr/tower	No. of non-retrofitable towers	\$/yr/nationwide				\$/cancer case avoided	10^6 \$/Mg (10 ⁶ \$/ton)	\$/cancer case avoided	10^6 \$/Mg (10 ⁶ \$/ton)
1	83	698	58,000	1,231,000	85	0.026-0.65	47,346,000	29.3 (26.6)	1,906,000	1.04 (0.94)
2	102	3,132	319,000	5,806,000	85	0.22-6.3	26,391,000	14.3 (13.0)	923,000	0.50 (0.45)
3	151	1,920	290,000	3,901,000	85	0.31-9.0	12,584,000	6.7 (6.1)	434,000	0.24 (0.21)
4	221	1,575	348,000	3,622,000	85	0.48-13.5	7,546,000	4.1 (3.7)	268,000	0.15 (0.13)
5	372	1,182	440,000	3,364,000	85	0.71-20.0	4,738,000	2.6 (2.4)	168,000	0.091 (0.083)
6	1,001	893	892,000	4,009,000	85	1.6-46.1	2,475,000	1.3 (1.2)	87,000	0.047 (0.043)
		9,400	2,347,000	21,933,000		3.4-96	6,508,000	3.5 (3.2)	229,000	0.125 (0.113)

TABLE 7-3. 5-YEAR SALES PROJECTION OF CCT's FOR NEW INSTALLATIONS¹³

Year	Comfort cooling tower sales, No.
1987	3,700
1988	3,400
1989	4,300
1990	4,600
1991	4,800

TABLE 7-4. ANNUALIZED COSTS OF NONCHROMATE AND HIGH-EFFICIENCY DRIFT ELIMINATOR CONTROL TECHNIQUES

Model tower No.	No. of CCT's ^a	No. using chromates ^b	Annualized cost of phosphate treatment, \$/yr/nationwide ^c	Annualized cost of inspection, and certification, \$/yr/nationwide ^d
1	1,540	230	18,900	93,200
2	6,930	1,040	106,000	424,800
3	4,240	640	95,500	267,900
4	3,500	520	115,300	229,800
5	2,620	390	145,900	187,200
6	<u>1,980</u>	<u>300</u>	<u>295,200</u>	<u>187,400</u>
	20,800	3,120	776,900	1,390,000

^aAssumes that towers built in the future will be distributed in the same proportion as the existing towers.

^bAssumes 15 percent use chromates.

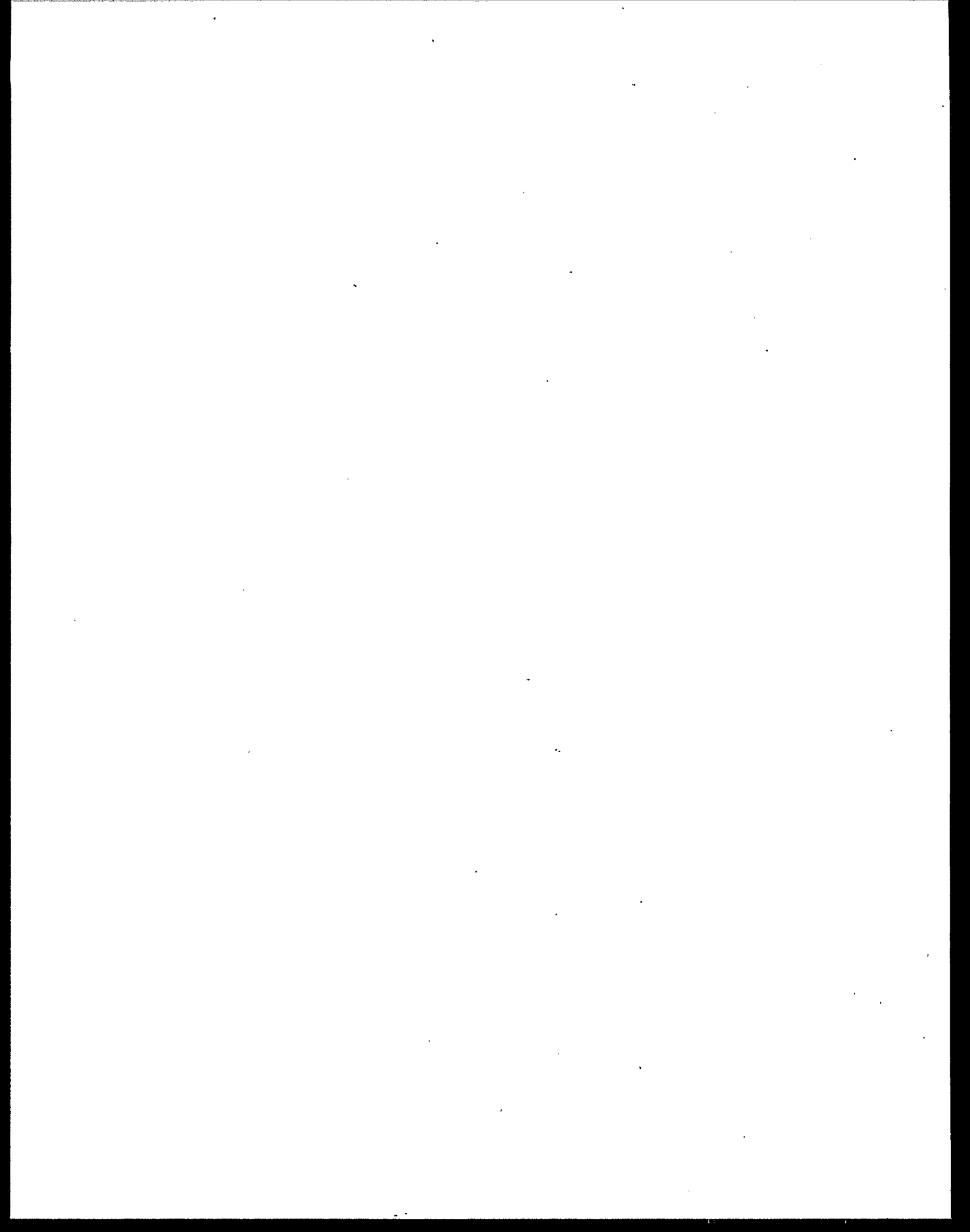
^cAssumes the same annualized cost per tower presented in Table 7-1.

^dAssumes 75 percent of the towers are initially constructed with HEDE's and 25 percent are switched to nonchromates. Also assumes the same annualized inspection and certification costs per tower that are presented in Table 7-2.

7.3 REFERENCES FOR CHAPTER 7

1. Telecon: R. Hathaway, MRI, with G. Sexton, Betz Laboratories. November 8, 1984. Costs of cooling tower water treatment chemicals.
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4. Telecon: C. Green, MRI, with R. Holtkamp, Hercules, Inc. April 2, 1985. Cost of cooling tower water treatment chemicals.
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7. Telecon: J. Glanville, MRI, with F. Foster, Unichem International. April 4, 1985. Cost of cooling tower water treatment chemicals.
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10. R. Gibson, MRI, to R. Myers, EPA:ISB. Trip report: North Carolina State University, Raleigh, North Carolina, on July 22, 1986.
11. Letter and attachments. Water treatment vendor, to Gibson, R., MRI. October 9, 1986. Cost of cooling tower water treatment chemicals.
12. R. Gibson, MRI, to R. Myers, EPA:ISB. Trip report: North Carolina State University, Raleigh, North Carolina, on June 17, 1986.
13. Memorandum from M. Putnam, MRI, to R. Myers, EPA:ISB. December 12, 1986. Drift eliminator certification cost estimate.
14. Telecon: D. Randall, MRI, with B. Cates, Baltimore Aircoil. November 7, 1986. Projection of total comfort cooling tower sales for 1987 through 1991.

15. Letter. Holmberg, J. D., The Marley Cooling Tower Company, to Crowder, J., EPA:ESED. February 24, 1987. Comment on draft Regulatory Impacts Analysis.



8. ECONOMIC IMPACTS

8.1 SUMMARY

This chapter discusses the economic consequences to suppliers of chromate corrosion inhibitors and commercial building owners and tenants of controlling hexavalent chromium (Cr^{+6}) emissions from comfort cooling towers (CCT's).

Estimates of the numbers of buildings by size and type that use chromates in CCT's also are presented along with estimates of the incremental costs to replace chromates with alternative corrosion inhibitors or to install high-efficiency drift eliminators (HEDE's). Control costs are expressed per unit area to evaluate potential building rent increases and are multiplied by the numbers of buildings by type and size to estimate the total nationwide cost of control.

This analysis has determined that the economic consequences of eliminating Cr^{+6} -based chemical use in CCT's are insignificant because rent increases for affected buildings would amount to less than 0.1 percent, and total nationwide annualized costs would not exceed \$9.4 million. The economic consequences of retrofitting CCT's with HEDE's also are insignificant because rent increases for affected buildings would amount to less than 1.0 percent and the total nationwide annualized costs would be about \$22 million.

8.2 INDUSTRY PROFILE

8.2.1 Size of Chromium-Based Corrosion Inhibitor Market

Sodium dichromate is the major chromium product used to control corrosion in CCT's; however, only 7 percent of all sodium dichromate consumed in the U.S. is estimated to be used in corrosion control applications, and less than 5 percent of that amount is used in CCT's.^{1,2} Thus, it is estimated that less than 0.35 percent of the total sodium dichromate consumed in the U.S. is used in CCT's.

The total annual value of corrosion inhibitor chemicals used in CCT applications is about \$85.1 million. Of this, chromate-based products account for approximately \$6.9 million; nonchromate substitutes account for the remaining \$78.2 million. These estimates have been developed based on chromate and nonchromate corrosion inhibitor costs and the cooling tower population data presented in Chapters 4 and 7, and the calculations used to derive the annual cost estimates are presented in Appendix E. The major suppliers of corrosion inhibitors for use in CCT's, light industry, and utilities and average market share each supplier holds are presented in Table 8-1.

8.2.2 Distribution of Cooling Towers by Building Size

As discussed in Section 4.1.1., a Department of Energy (DOE) survey distributed total U.S. commercial building floorspace into categories based on size. The category of 465 square meter (m^2) (5,000 square foot [ft^2]) or less has been excluded from this analysis because industry sources indicate it is unlikely that buildings that size would use cooling towers as part of central cooling systems.

Using the DOE data, the number of buildings in each size class having a central cooling system and the percentage believed to have CCT's were estimated. These estimates are presented in Section 4.3. Finally, assuming that 15 percent of all CCT's are chromate-using and that chromate-using towers are distributed evenly among all sizes and building types as classified by DOE, the number of buildings with CCT's that use chromates was estimated.⁵ The total number of buildings, the number of buildings with central cooling systems, the number of buildings with CCT's, and the number of CCT's using chromates are presented in Tables 8-2 to 8-5, respectively.

8.2.3 Commercial Building Rental Rates

If building owners and operators were required to use alternative corrosion inhibitors, the operating costs for any building currently using chromates are likely to increase. To estimate the significance of such cost increases, the economic analysis in the following sections compares the costs for two control options to average annual rents for the affected buildings on a unit area basis.

Data collected by the Urban Land Institute indicate that the national average rental rate for commercial buildings including all utilities and taxes is approximately $\$129/\text{m}^2/\text{yr}$ ($\$12/\text{ft}^2/\text{yr}$).⁶ Although rates vary according to building type and location, the lowest rates observed are those for large department stores. The national average rental rate for such stores is slightly over $\$22/\text{m}^2$ ($\$2/\text{ft}^2$). At the other end of the scale, rental rates for fast food restaurants and similar facilities run close to $\$215/\text{m}^2$ ($\$20/\text{ft}^2$). The wide range of rates is attributable to the level of facilities required for the rented space. For example, restaurants and similar facilities require services such as plumbing, other utilities, and solid waste disposal; department stores are essentially large open spaces that require relatively low levels of such services.

8.3 CONTROL COSTS

The costs to control Cr^{+6} emissions from CCT's are presented for two control alternatives: (1) completely prohibiting the use of chromates, thus requiring a shift to more costly nonchromates, and (2) requiring the installation of HEDE's. The costs of each of these alternatives are presented by building size and type and were developed based on Table 4-4 and the DOE survey of buildings by size and type.

Costs for nonchromate substitutes were presented in Table 7-1. These costs are based on a phosphate corrosion inhibitor system, which is the most prevalent substitute for chromates. Table 7-1 also shows the annual cost of using chromates and phosphates in individual towers as well as the incremental cost of switching from chromates to phosphates. In addition to the incremental costs, CCT users may also need to purchase an automatic feed system that controls chemical feed and blowdown. The purchase and installation costs of such systems also are shown in Table 7-1. These costs were annualized using a capital recovery factor that assumes a 15-year life, which is the estimated useful life of the feed equipment, and a 10-percent interest rate. Note that the costs presented in Table 7-1 represent purchase costs for the chromate corrosion inhibitors and feed system and do not include the costs of technical services required to ensure the proper operation of the CCT's. However, the costs of such technical services are believed to be largely unaffected by the choice of corrosion inhibitors.

The capital and annualized costs to retrofit drift eliminators were presented in Table 7-2 and they ranged from \$390 to \$4,980 and from \$51 to \$655, respectively. Capital costs are expressed on an annual basis through a capital recovery factor that approximates annual depreciation over a 15-year life and 10-percent interest rate. In addition to the cost to retrofit the drift eliminators, CCT operators will incur costs to have the towers inspected and certified. These costs are presented in Table 7-2. Inspection costs are estimated to be \$500 per year per tower, and certification costs are estimated to be \$2.3 million industrywide. The certification costs are assumed to be incurred once during the life of each tower and are, therefore, annualized by use of a capital recovery factor. The annualized certification cost distributed over all chromate-using towers is \$11.00 per tower per year.

Approximately 75 percent of chromate-using CCT's can be retrofitted with HEDE's. The remaining 25 percent would require extensive rebuilding. Therefore, it was assumed that CCT operators would switch to nonchromate corrosion inhibitors rather than incur the high cost of rebuilding the towers. Costs per unit area for each control alternative are shown in Tables 8-6 and 8-7. As shown in Table 8-6, the costs for substituting nonchromates are relatively low. The two smallest building size classes would incur costs of $\$0.12/\text{m}^2$ ($\$0.01/\text{ft}^2$) by changing to nonchromate corrosion inhibitors. The remaining four size classes would face even smaller increases. As shown in Table 8-7, the two smallest building size classes would face costs of $\$0.84/\text{m}^2$ ($\$0.08/\text{ft}^2$) and $\$0.4/\text{m}^2$ ($\$0.04/\text{ft}^2$) to retrofit with HEDE's.

In the following section, the control costs are used to estimate the total annual cost for each control alternative by building type and size. Percentage rent increases are also calculated to approximate the extent to which the occupants of such buildings might be affected by a regulation to control Cr^{+6} emissions from CCT's.

8.4 ECONOMIC IMPACTS

The change to nonchromate corrosion inhibitors is not expected to have a significant economic impact on owners or tenants of affected properties. While the previously noted average annual rental rate is about $\$129/\text{m}^2$ ($\$12/\text{ft}^2$), the incremental annualized control costs noted

above would add less than $\$0.12/\text{m}^2$ ($\$0.01/\text{ft}^2$) if all costs were passed through in the form of increased rental rates. Such costs would represent a rent increase of about 0.1 percent. Even those properties that are rented at the lowest rate of $\$22/\text{m}^2$ ($\$2/\text{ft}^2$) would incur rent increases of less than 1 percent if nonchromate alternatives are used.

The installation of HEDE's also is unlikely to have significant economic impacts on the owners of CCT's or their tenants. Those owners who retrofit their towers rather than switch to nonchromium-based inhibitors would face control costs of $\$0.84/\text{m}^2$ ($\$0.08/\text{ft}^2$). Assuming a $\$129/\text{m}^2$ ($\$12/\text{ft}^2$) rental rate, rents would increase by less than 1 percent if costs are fully passed through to the tenant. Properties in the smallest size class which are rented at $\$22/\text{m}^2$ ($\$2/\text{ft}^2$) would incur rental increases of 4 percent under the drift eliminator alternative. However, it is unlikely that these properties would retrofit the drift eliminators but would switch to nonchromate corrosion inhibitors.

The total nationwide costs of substituting nonchromate corrosion inhibitors for chromates is estimated to be under \$9.4 million. The use of HEDE's would entail nationwide costs of about \$22 million. Such estimates are detailed in Tables 8-8 and 8-9 and have been made based on the incremental annualized control costs presented in Tables 7-1 and 7-2 and the building counts by type and size presented in Table 8-5.

Finally, it is not expected that prohibiting the use of chromium-based corrosion inhibitors would have a significant effect upon either the chromate suppliers or the water treatment service companies that provide chromate corrosion inhibitors. This conclusion is based upon the insignificant use of sodium dichromate in CCT's relative to all other uses (i.e., less than 0.35 percent) mentioned in Section 8.2.1 above and the fact that most specialty chemical companies supply nonchromate as well as chromate corrosion inhibitors.

TABLE 8-1. MAJOR SUPPLIERS OF CORROSION INHIBITORS FOR CCT'S,
LIGHT INDUSTRY, AND UTILITIES^a

Company	Average market share, percent
NALCO Chemical Company	19.2
Mogul Division--Dexter Corp.	14.4
Betz Laboratories, Inc.	13.3
Drew Chemical Company	9.8
Dearborn Chemical Division--CHEMED Corp.	9.8
Calgon Corp. ^b	7.7
Others	25.8
TOTAL	100.0

^aIncludes chromates as well as nonchromates.

^bCalgon, indicated that they do not sell chemicals for use in CCT's.

TABLE 8-2. NUMBER OF BUILDINGS BY TYPE AND SIZE^a

Building type	Size, m ² (ft ²)						Total
	465 to 929 (5,001 to 10,000)	929 to 2,323 (10,001 to 25,000)	2,323 to 4,645 (25,001 to 50,000)	4,645 to 9,290 (50,001 to 100,000)	9,290 to 18,581 (100,001 to 200,000)	Over 18,581 (Over 200,000)	
Assembly	122,000	86,000	27,000	9,000	3,000	1,000	248,000
Educational	24,000	33,000	37,000	24,000	11,000	3,000	132,000
Food Sales/Services	49,000	35,000	6,000	3,000	0	0	93,000
Health Care	13,000	5,000	5,000	2,000	3,000	4,000	32,000
Lodging	23,000	19,000	14,000	5,000	2,000	1,000	64,000
Mercantile/Services	217,000	131,000	30,000	17,000	6,000	4,000	405,000
Office	109,000	81,000	27,000	14,000	8,000	7,000	246,000
Residential	37,000	48,000	13,000	3,000	4,000	1,000	106,000
Warehouse	64,000	75,000	36,000	18,000	7,000	4,000	204,000
Other	24,000	25,000	10,000	3,000	3,000	2,000	67,000
Vacant	43,000	29,000	17,000	9,000	3,000	2,000	103,000
TOTAL	725,000	567,000	222,000	107,000	50,000	29,000	1,700,000

^aReference 5.

TABLE 8-3. NUMBER OF BUILDINGS WITH CENTRAL COOLING SYSTEMS BY TYPE AND SIZE

Building type	Size, m ² (ft ²)						Total
	465 to 929 (5,001 to 10,000)	929 to 2,323 (10,001 to 25,000)	2,323 to 4,645 (25,001 to 50,000)	4,645 to 9,290 (50,001 to 100,000)	9,290 to 18,581 (100,001 to 200,000)	Over 18,581 (Over 200,000)	
Assembly	62,430	50,660	15,568	5,888	2,100	862	137,508
Educational	12,281	19,439	21,333	15,701	7,700	2,586	79,041
Food Sales/Services	25,074	20,617	3,459	1,963	0	0	51,114
Health Care	6,652	2,945	2,883	1,308	2,100	3,448	19,337
Lodging	11,770	11,192	8,072	3,271	1,400	862	36,567
Mercantile/Services	111,044	77,168	17,297	11,121	4,200	3,448	224,279
Office	55,778	47,714	15,568	9,159	5,600	6,034	139,853
Residential	18,934	28,275	7,495	1,963	2,800	862	60,329
Warehouse	32,750	44,180	20,757	11,776	4,900	3,448	117,811
Other	12,281	14,727	5,766	1,963	2,100	1,724	38,561
Vacant	22,004	17,083	9,802	5,888	2,100	1,724	58,601
TOTAL	371,000	334,000	128,000	70,000	35,000	25,000	963,000

TABLE 8-4. NUMBER OF BUILDINGS WITH COMFORT COOLING TOWERS BY TYPE AND SIZE

Building type	Size, m ² (ft ²)						Total
	465 to 929 (5,001 to 10,000)	929 to 2,323 (10,001 to 25,000)	2,323 to 4,645 (25,001 to 50,000)	4,645 to 9,290 (50,001 to 100,000)	9,290 to 18,581 (100,001 to 200,000)	Over 18,581 (Over 200,000)	
Assembly	3,122	12,665	6,227	3,533	1,890	819	28,255
Educational	614	4,860	8,533	9,421	6,930	2,457	32,815
Food Sales/Services	1,254	5,154	1,384	1,178	0	0	8,969
Health Care	333	736	1,153	785	1,890	3,276	8,173
Lodging	588	2,798	3,229	1,963	1,260	819	10,657
Mercantile/Services	5,552	19,292	6,919	6,673	3,780	3,276	45,492
Office	2,789	11,929	6,227	5,495	5,040	5,733	37,213
Residential	947	7,069	2,998	1,178	2,520	819	15,530
Warehouse	1,638	11,045	8,303	7,066	4,410	3,276	35,736
Other	614	3,682	2,306	1,178	1,890	1,638	11,308
Vacant	1,100	4,271	3,921	3,533	1,890	1,638	16,352
TOTAL	18,550	83,500	51,200	42,000	31,500	23,750	250,500

TABLE 8-5. NUMBER OF CCT'S USING CHROMATES BY BUILDING TYPE AND SIZE^a

Building type	Model building size, m ² (ft ²) ^a					Total
	673 (7,240)	1,460 (15,720)	3,405 (36,650)	6,224 (66,990)	12,338 (132,800)	37,626 (405,000)
Assembly	468	1,900	934	530	284	123
Educational	92	729	1,280	1,413	1,040	369
Food Sales/Services	188	773	208	177	0	0
Health Care	50	110	173	118	284	491
Lodging	88	420	484	294	189	123
Mercantile/Services	833	2,894	1,038	1,001	567	491
Office	418	1,789	934	824	756	860
Residential	142	1,060	450	177	378	123
Warehouse	246	1,657	1,245	1,060	662	491
Other	92	552	346	177	284	246
Vacant	165	641	588	530	284	246
TOTAL	2,780	12,530	7,680	6,300	4,730	3,560
						37,580

^aNumbers have been rounded; therefore, sums may exceed the actual totals shown.

TABLE 8-6. INCREMENTAL COST PER UNIT AREA FOR USING NONCHROMATE
CORROSION INHIBITORS
(1986 Dollars)

Model tower	Model building size, m ² (ft ²)	Total annual substitution cost, \$/yr/tower ^a	Incremental cost, \$/m ² (\$/ft ²)
1	673 (7,240)	83	0.12 (0.01)
2	1,460 (15,720)	102	0.07 (0.01)
3	3,405 (36,650)	151	0.04 (<0.01)
4	6,224 (66,990)	221	0.04 (<0.01)
5	12,338 (132,800)	372	0.03 (<0.01)
6	37,626 (405,000)	1,001	0.03 (<0.01)

^aCost includes annualized capital cost of automatic feed system and annual incremental cost of phosphate-based treatment over chromate-based treatment.

TABLE 8-7. INCREMENTAL COST PER UNIT AREA FOR RETROFITTING
DRIFT ELIMINATORS
(1986 Dollars)

Model tower	Model building size, m ² (ft ²)	Annual certifica- tion and inspection costs, \$/tower	Annualized retrofit cost, \$/tower	Total annual cost, \$/tower	Incremental cost, \$/m ² (\$/ft ²)
1	673 (7,240)	511	51	562	0.84 (0.08)
2	1,460 (15,720)	511	73	584	0.40 (0.04)
3	3,405 (36,650)	511	116	627	0.18 (0.02)
4	6,224 (66,990)	511	182	693	0.11 (0.01)
5	12,338 (132,800)	511	314	825	0.07 (0.01)
6	37,626 (405,000)	511	655	1,166	0.03 (<0.01)

TABLE 8-8. TOTAL INCREMENTAL COST OF USING NONCHROMATE CORROSION INHIBITORS BY BUILDING TYPE AND SIZE
(Thousands of 1986 Dollars)

Building type	Model building size, m ² (ft ²) ^a					Total
	673 (7,240)	1,460 (15,720)	3,405 (36,650)	6,224 (66,990)	12,338 (132,800)	37,626 (405,000)
Assembly	38.9	193.8	141.0	117.1	105.5	123.0
Educational	7.6	74.4	193.3	312.3	386.7	368.9
Food Sales/Services	15.6	78.9	31.3	39.0	0	0
Health care	4.1	11.3	26.1	26.0	105.5	491.9
Lodging	7.3	42.8	73.1	65.1	70.3	123.0
Mercantile/Services	69.1	295.2	156.7	221.2	210.9	491.9
Office	34.7	182.5	141.0	182.2	281.2	860.8
Residential	11.8	108.2	67.9	39.0	140.6	123.0
Warehouse	20.4	169.0	188.1	234.2	246.1	491.9
Other	7.6	56.3	52.2	39.0	105.5	245.9
Vacant	13.7	65.3	88.8	117.1	105.5	245.9
TOTAL	231	1,278	1,160	1,392	1,758	3,566
						9,385

^aNumbers have been rounded; therefore, sums may exceed the actual totals shown.

TABLE 8-9. TOTAL ANNUALIZED COST OF RETROFITTING DRIFT ELIMINATORS BY BUILDING TYPE AND SIZE
(Thousands of 1986 Dollars)^a

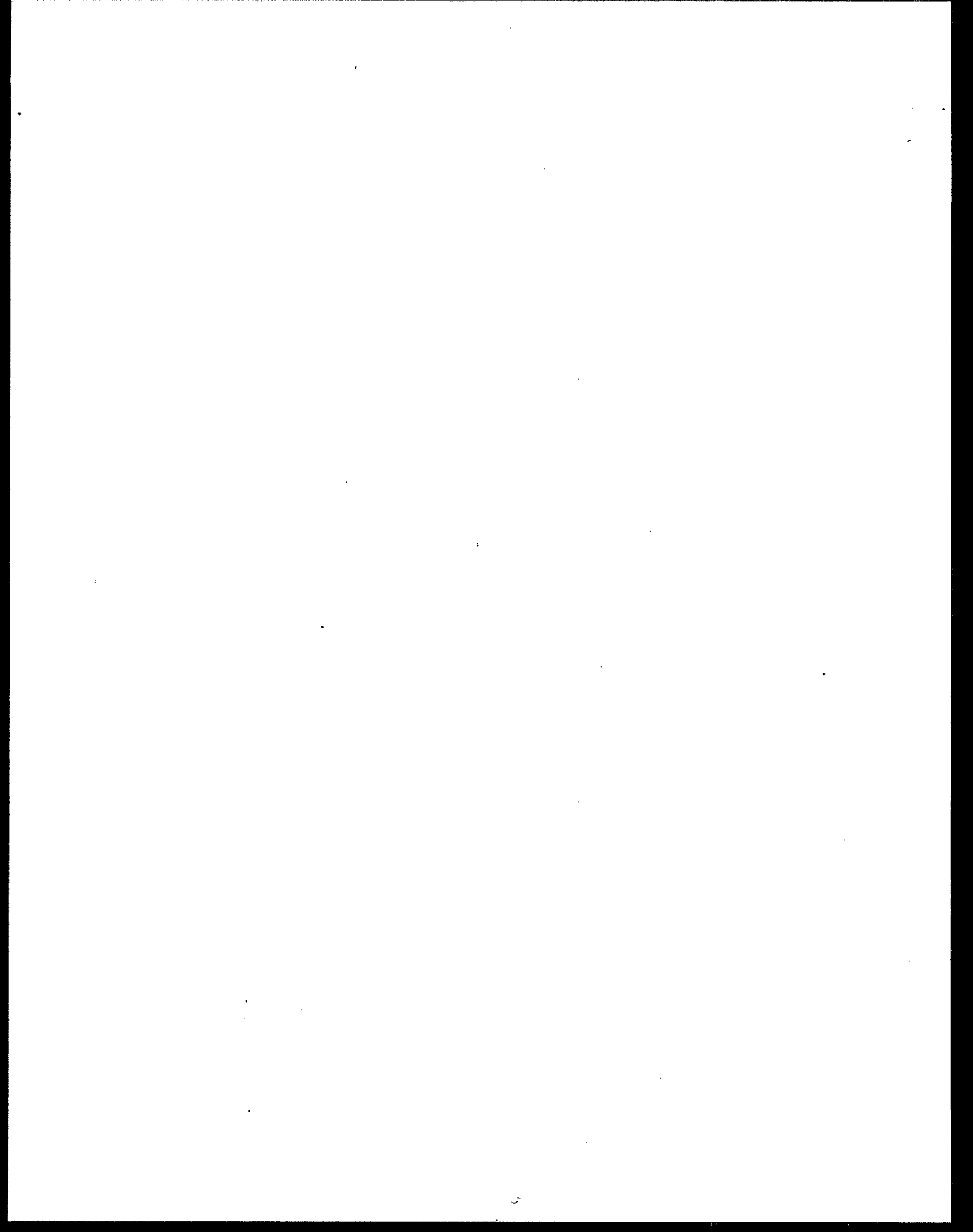
Building type	Model building size, m ² (ft ²) ^b						Total
	673 (7,240)	1,460 (15,721)	3,405 (36,650)	6,224 (66,990)	12,338 (132,800)	37,626 (405,000)	
Assembly	207.0	880.5	474.3	304.6	201.7	138.0	2,206.0
Educational	40.7	337.9	649.9	812.2	739.6	414.0	2,994.3
Food Sales/Services	83.1	358.4	105.4	101.5	0.0	0.0	648.4
Health Care	22.1	51.2	87.8	67.7	201.7	552.1	982.5
Lodging	39.0	194.5	245.9	169.2	134.5	138.0	921.2
Mercantile/Services	368.1	1,341.3	527.0	575.3	403.4	552.1	3,767.1
Office	184.9	829.3	474.3	473.8	537.9	966.1	3,466.3
Residential	62.8	491.5	228.4	101.5	268.9	138.0	1,291.1
Warehouse	108.6	767.9	632.4	609.1	470.7	552.1	3,140.7
Other	40.7	256.0	175.7	101.5	201.7	276.0	1,051.6
Vacant	72.9	296.9	298.6	304.6	201.7	276.0	1,450.8
TOTAL	1,230.0	5,805.0	3,900.0	3,621.0	3,362.0	4,003.0	21,920.0

^aAssumes 75 percent of the existing CCT's would retrofit with high-efficiency drift eliminators and 25 percent would switch to nonchromate water treatment programs.

^bNumbers have been rounded; therefore, sums may exceed the actual totals shown.

8.5 REFERENCES FOR CHAPTER 8

1. Chromium Products. Chemical Economics Handbook. SRI International, Inc., Menlo Park, California. p. 734.2000 C.
2. Memorandum from JACA Corp., to D. Gillette, EPA:SASD. Status report on the development of an economic impact analysis for cooling tower sources of chromium emissions. December 23, 1985.
3. Corrosion Inhibitors Market. Frost and Sullivan, Inc. 1983. p. 132.
4. Memorandum from C. Hester, MRI, to R. Myers, EPA:ISB. Technical Report--Cooling Towers. September 27, 1985. p. 3.
5. Characteristics of Commercial Buildings 1983. U.S. Department of Energy. Energy Information Administration. DOE/EIA-0246(83). July 1985.
6. Dollars and Cents of Shopping Centers: 1984. Urban Land Institute. pp. 30-35.
7. Telecon. P. Bellin, MRI, with G. Schweitzer, Calgon Corporation. May 22, 1985. Chromium use as a corrosion inhibitor in CCT's.



9. OTHER IMPACTS

This chapter discusses the other impacts attributable to each of the regulatory alternatives.

9.1 IMPACTS RESULTING FROM PROHIBITING CHROMIUM

Prohibiting chromium use in comfort cooling towers (CCT's) would eliminate air pollution and health risks from chromium emissions from CCT's. It is estimated that the use of nonchromium treatment chemicals would increase by about 18 percent (assuming 15 percent of the CCT's currently use chromium). None of the alternative treatments (phosphates, triazoles, or molybdates) are believed to be carcinogenic.

The effects of prohibiting chromium use in CCT's on bacteria such as Legionella pneumophila also have been investigated.¹ Chromium is used in cooling towers to control corrosion and not for microorganism control, and there is no definitive work currently to substantiate that chromium is biocidal against Legionella pneumophila. Usually when a problem with the bacteria arises, high concentrations of chlorine are used to reduce the growth of the bacteria.

Because some nonchromium treatment programs cannot use chlorine to control microorganisms, the Agency was concerned that the alternative chemical programs may not provide comparable control of Legionella pneumophila. All cooling towers that have been associated with outbreaks of Legionnaires disease were not following a good biocidal regimen using an EPA-approved biocide at the dosages recommended by the manufacturer.¹

Solid waste disposal would not be affected significantly because currently there are no known CCT facilities that are treating wastewater discharges for chromium onsite. However, many industrial and research facilities use chromium in both CCT's and industrial cooling towers and treat solid waste onsite. Thus, prohibiting chromium use in CCT's would

reduce slightly the amount of solid waste containing chromium. In cases where sewage treatment plants are receiving chromium in quantities large enough to treat, it is likely that sources other than CCT's contribute most of the chromium; thus, the effect of reducing chromium in CCT's would be negligible.

Water pollution from CCT discharges of chromium would be completely eliminated. As chromate users switch to nonchromate programs, the discharges of the nonchromates would increase. The percentage of CCT's currently using each of the nonchromate treatments is not known, but it is expected that the 37,500 CCT's using chromates would switch in the same proportion. Thus, discharges of each nonchromate chemical would increase by a maximum of about 18 percent ($15 \text{ percent} / 85 \text{ percent} = 18 \text{ percent}$) if these compounds are not also used as an additive to chromate treatments. Because phosphates, the most popular alternative treatment, are included in many chromate treatments, phosphate discharges would increase by less than 18 percent. In addition, even if all of the plants switched to phosphate treatments and none of the previously used chromate treatments included phosphate in the formulation, the nationwide increase in phosphorus discharges to sewage treatment plants would be less than 0.1 percent.²

Worker exposure to Cr^{+6} would be completely eliminated. At the present time, worker exposure to Cr^{+6} is expected to primarily involve dermal contact. Little inhalation exposure is expected because the chromate is expected to remain in solution as a dissociated salt. A worst-case scenario for dermal exposure to the chromate solutions would be for an operator who is not wearing gloves to open a valve connected to a drum of solution, fill a pail with solution, and then pour the contents of the pail directly into the tower basin. Assuming a concentration of chromate in the solution of 5 to 65 percent, dermal exposures to chromate could range from 65 mg/d (1.4×10^{-4} lb/d) to 2,500 mg/d (55×10^{-4} lb/d) if gloves are not worn. However, the trend in recent years has been to switch from manual to automated control of the feed pumps. Thus, less frequent exposure would occur during operation of the feed pumps. Potential exposure to chromate during sampling is negligible due to the low concentration of chromate in the water. If manual control is used,

the maximum potential worker population exposed is 75,000 based on estimates of 37,500 cooling towers that use chromates and one to two operators per site.

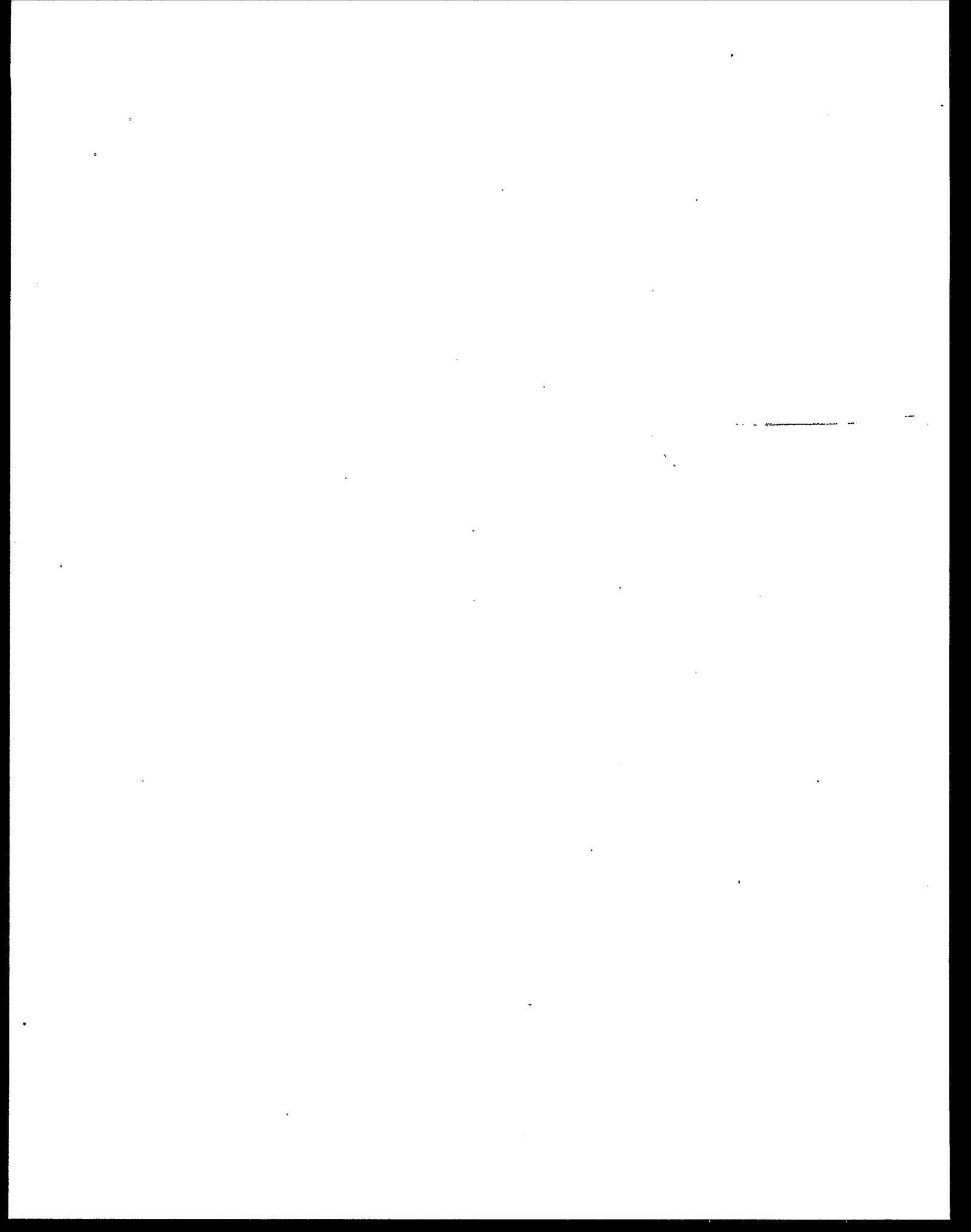
9.2 IMPACTS RESULTING FROM HIGHER EFFICIENCY DRIFT ELIMINATOR RETROFITS

Retrofit of higher efficiency drift eliminators may reduce the air pollution and health risk from chromium by 85 percent. Water pollution would not be reduced from the present discharge because the cycles of concentration, chromium concentration, and blowdown rate would not change.

New higher efficiency cellular drift eliminators have been designed with pressure drops lower than the older wood or asbestos-cement eliminators. Therefore, replacement of an existing lower efficiency drift eliminator with a higher efficiency drift eliminator would result in decreased power consumption. A manufacturer has indicated that the horsepower savings can be as much as 35 percent when a herringbone drift eliminator is replaced with the most efficient cellular drift eliminator in a counterflow tower. The savings in a crossflow tower would not be as great.³

9.3 REFERENCES FOR CHAPTER 9

1. Memorandum from R. Myers, EPA:ISB, to Comfort Cooling Tower Project Files. October 16, 1986. Summary of telephone conversation with B. Davis, Center for Disease Control, concerning Legionnaire's disease.
2. Memorandum from D. Randall, MRI, to D. Stackhouse, EPA:SDB. September 3, 1987. Calculations of phosphorus discharges from model CCT's and nationwide discharges of phosphorus to sewage treatment plants.
3. Kelly, G. M. A System-Efficient Approach to Cooling Tower Energy Modifications. Cooling Tower Institute Technical Paper No. TP-85-18. New Orleans, Louisiana. January 1985.



APPENDIX A.
EVOLUTION OF THE BACKGROUND INFORMATION DOCUMENT

The purpose of this study was to develop a basis for supporting proposed chromium emission standards for CCT's. To accomplish the objectives of this program, technical data were acquired on the following aspects of chemical treatment programs and CCT's: (1) formulations, effects, and costs of water chemical treatments; (2) the release of hexavalent chromium emissions into the atmosphere by CCT's; and (3) the types and costs of demonstrated control technologies. The bulk of the information was gathered from the following sources:

1. Technical literature;
2. State, regional, and local air pollution control agencies;
3. Site visits and case studies;
4. Industry representatives; and
5. Equipment vendors.

Significant events relating to the evolution of the background information document are itemized in Table A-1.

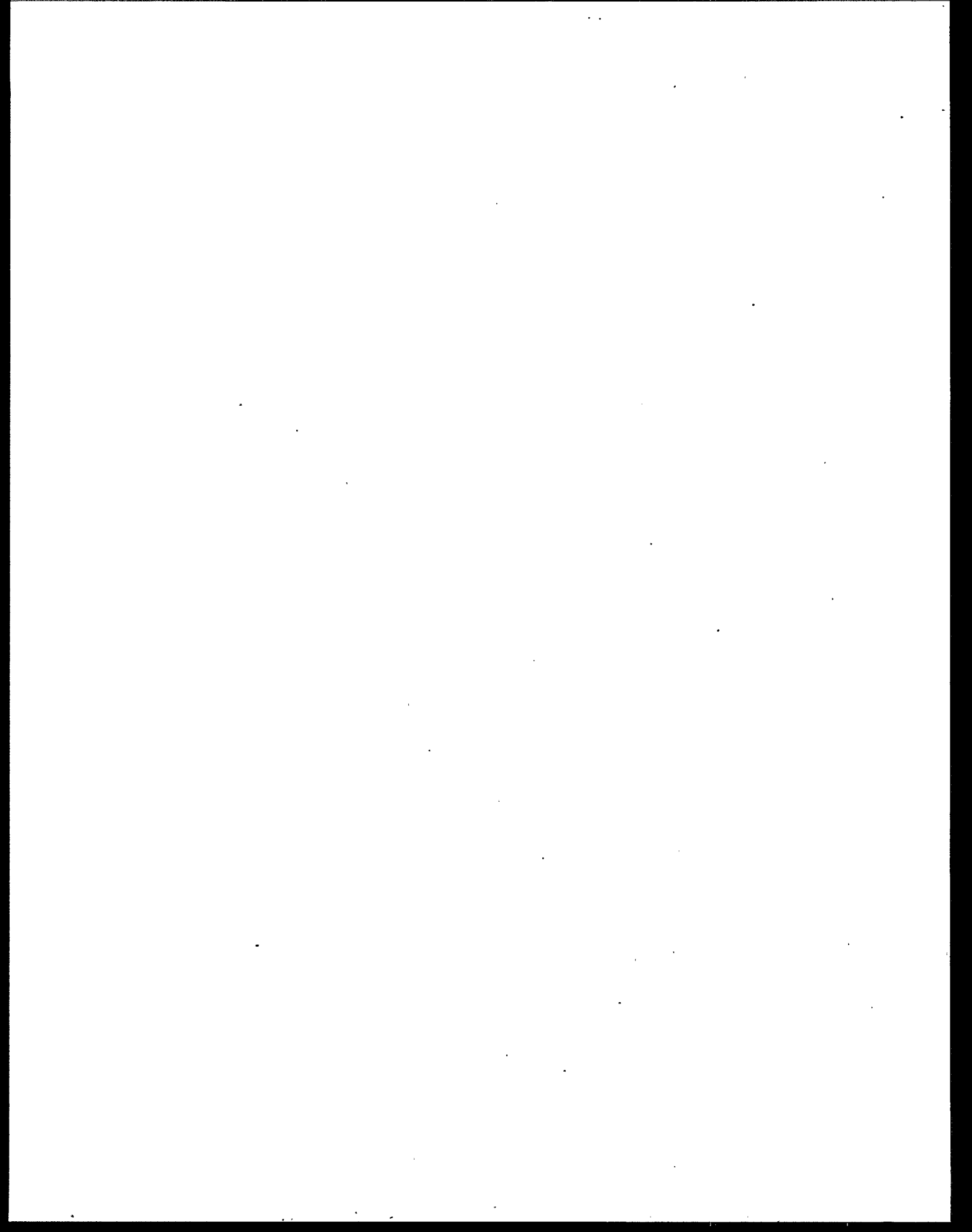
TABLE A-1. EVOLUTION OF THE BACKGROUND INFORMATION DOCUMENT

Date	Company, consultant, or agency/location	Nature of action
02/07/85	Mogul Division, Dexter Corp., Chagrin Falls, Ohio	Visit to water chemicals vendor.
02/21/85	Harley Cooling Tower Company, Mission, Kans.	Visit to cooling tower manufacturer.
04/16/85	Mobil Oil Corp., Torrance, Calif.	Visit to petroleum refinery.
04/16/85	ARCO Petroleum Refinery, Carson, Calif.	Visit to petroleum refinery.
04/17/85	Chevron U.S.A., Richmond, Calif.	Visit to petroleum refinery.
04/18/85	Amoco Oil Company, Chicago, Ill. Atlantic Richfield Company, Los Angeles, Calif. Chevron U.S.A., Inc., San Francisco, Calif. Exxon Company, U.S.A., Houston, Tex. Gulf Oil Products Company, Houston, Tex. Mobil Oil Corp., Fairfax, Va. Phillips Petroleum Company, Bartlesville, Okla. Shell Oil Company, Houston, Tex. Texaco, Inc., Houston, Tex.	Section 114 information request.
04/23/85	Armco, Inc., Middletown, Ohio Bethlehem Steel Company, Bethlehem, Pa. Inland Steel Corp., East Chicago, Ind. LTV Steel Company, Cleveland, Ohio Lone Star Steel Company, Lone Star, Tex. McLouth Steel Products Corp., Trenton, Mich. National Steel Corp., Pittsburgh, Pa. U.S. Steel Corp., Pittsburgh, Pa. Wheeling-Pittsburgh Steel Corp., Wheeling, W. Va.	Section 114 information request
05/08/85	Chemical Manufacturers Association, Washington, D.C.	Request for information about cooling water and corrosion inhibitor use from member chemical manufacturing plants.
09/01/85	U. S. Environmental Protection Agency	Technical Report--Cooling Towers
01/15/86	Association of Building Owners and Management	Requesting ABOM participation in cooling towers study.
05/13/86	U. S. Environmental Protection Agency	Start Action Request for Development of Accelerated NESHAP--Chromium Emissions From Cooling Towers
05/22/86	National Bureau of Standards, Gaithersburg, Md.	Site visit.
06/04/86	Union Oil Company, Los Angeles, Calif.	Section 114 information request.
06/12/86	Chevron U.S.A., San Francisco, Calif. Shell Oil Company, Houston, Tex.	Section 114 information request.
06/16/86	Hooker Industrial and Specialty Chemicals, Niagara Falls, N.Y. Inmont Corp., Clifton, N.J.	Section 114 information request.
06/17/86	North Carolina State University, Raleigh, N.C.	Case study.
06/20/86	Interlake, Inc., Oak Brook, Ill. Kaiser Aluminum & Chemical Corp., Oakland, Calif. LTV Corp., Cleveland, Ohio	Section 114 information request.
06/23/86- 06/27/86	U. S. Environmental Protection Agency	Emission tests at Department of Energy Gaseous Diffusion Plant, Paducah, Ky.
07/02/86	University of North Carolina at Chapel Hill, Chapel Hill, N.C.	Case study.
07/03/86	Duke University, Durham, N.C.	Case study.
07/08/86	Wake Medical Center, Raleigh, N.C.	Case study.
	Peoples Security Insurance, Durham, N.C.	Case study.
07/10/86	Crabtree Valley Mall, Raleigh, N.C.	Case study.
07/15/86	Greenbrier Mall, Norfolk, Va. Sovran Bank, Norfolk, Va.	Case study.
07/16/86	Gani International Hotel, Norfolk, Va. Old Dominion University, Norfolk, Va.	Case study.
07/17/86	Humana Bayside Hospital, Norfolk, Va.	Case study.

(continued)

TABLE A-1. (continued)

Date	Company, consultant, or agency/location	Nature of action
07/22/86	North Carolina State University, Raleigh, N.C.	Followup to case study.
07/29/86	North Carolina State Department of Administration, Raleigh, N.C.	Visit to State water treatment chemicals purchasing agency.
08/12/86	Industry representatives, Associations, and Concerned Individuals	Notice of September 17-19, 1986, meeting of National Air Pollution Control Techniques Advisory Committee and draft of <u>Federal Register</u> Notice of Solicitation of Information.
08/21/86	ARCHEM, Inc., Virginia Beach, Va. Anderson Chemical Company, Litchfield, Minn. Anderson Chemical Company, Macon, Ga. Aqua-Chem, Inc., Raleigh, N.C. Betz Laboratories, Treviso, Pa. Calgon Corp., Pittsburgh, Pa. Chemtreat, Inc., Ashland, Va. Dearborn Chemical Division--CHEMED Corp. Drew Chemical Company, Boonton, N.J. Dubois Chemical Division--CHEMED Corp., Hercules, Inc., Wilmington, Del. Industrial Maintenance Corp., Raleigh, N.C. Mogul Division--Dexter Corp., Charlotte, N.C. Nalco Chemical Company, Oak Brook, Ill. Olin Water Services, Inc., Overland Park, Kans. Unichem International, Inc., Hobbs, N. Mex. Water Chemist, Inc., Los Angeles, Calif. Water Chemistry, Inc., Norfolk, Va. Water Services, Inc., Knoxville, Tenn.	Requesting information on comfort cooling tower population and chemical treatment program technical and cost data.
08/18/86- 08/22/86	U. S. Environmental Protection Agency	Emission tests at National Bureau of Standards, Gaithersburg, Md.
09/01/86- 09/05/86	U. S. Environmental Protection Agency	Emission tests at Exxon Company Petroleum Refinery, Baytown, Tex.
09/15/86	<u>Federal Register</u>	Notice of Solicitation of Information.
09/17/86	National Air Pollution Control Techniques Advisory Committee	Meeting.
09/22/86	U. S. Environmental Protection Agency	Press release concerning comfort cooling tower study and soliciting information on aspects of regulating chromium use in cooling towers.
10/03/86	Working Group	Meeting to discuss status of project and appropriate authority.
12/08/86	Working Group	Meeting to discuss draft Regulatory Impacts Analysis, Preamble, and Regulation
02/02/87	Working Group	Mailout of draft Regulatory Impacts Analysis, Preamble, and Regulation.
02/23/87	U. S. Environmental Protection Agency	Document title changed from Regulatory Impacts Analysis to Background Information Document.
04/28/87	Steering Committee	Mailout of draft Background Information Document



APPENDIX B. PUBLIC CANCER RISKS FROM THE EMISSIONS OF HEXAVALENT CHROMIUM FROM COMFORT COOLING TOWERS

B.1 INTRODUCTION

B.1.1. Overview

The quantitative expressions of public cancer risks presented in this appendix are based on (1) a dose-response model that numerically relates the degree of exposure to airborne hexavalent chromium (Cr^{+6}) to the risk of getting lung cancer and (2) numerical expressions of public exposure to ambient air concentrations of Cr^{+6} estimated to be caused by emissions from comfort cooling towers (CCT's). Each of these factors is discussed briefly below, and details are provided in the following sections of this appendix.

B.1.2 The Relationship of Exposure to Cancer Risk

The relationship of exposure to the risk of getting lung cancer is derived from epidemiological studies in occupational settings rather than from studies of excess cancer incidence among the public. The epidemiological methods that have successfully revealed associations between occupational exposure and cancer for substances such as asbestos, benzene, vinyl chloride, and ionizing radiation as well as for chromium are not easily applied to the public sector with its increased number of confounding variables, much more diverse and mobile exposed population, lack of consolidated medical records, and almost total absence of historical exposure data. Given such uncertainties, EPA considers it improbable that any association, short of very large increases in cancer, can be verified in the general population with any reasonable certainty by an epidemiological study. Furthermore, as noted by the National Academy of Sciences (NAS), ". . . when there is exposure to a material, we are not starting at an origin of zero cancers. Nor are we starting at an origin

of zero carcinogenic agents in our environment. Thus, it is likely that any carcinogenic agent added to the environment will act by a particular mechanism on a particular cell population that is already being acted on by the same mechanism to induce cancers."¹ In discussing experimental dose-response curves, NAS observed that most information on carcinogenesis is derived from studies of ionizing radiation with experimental animals and with humans which indicate a linear no-threshold dose-response relationship at low doses. They added that although some evidence exists for thresholds in some animal tissues, by and large, thresholds have not been established for most tissues. The NAS concluded that establishing such low-dose thresholds ". . . would require massive, expensive, and impractical experiments . . ." and recognized that the U.S. population ". . . is a large, diverse, and genetically heterogeneous group exposed to a large variety of toxic agents." This fact, coupled with the known genetic variability to carcinogenesis and the predisposition of some individuals to some form of cancer, makes it extremely difficult, if not impossible, to identify a threshold.

For these reasons, EPA has taken the position, which is shared by other Federal regulatory agencies, that in the absence of sound scientific evidence to the contrary, carcinogens should be considered to pose some cancer risk at any exposure level. This no-threshold presumption is based on the view that as little as one molecule of a carcinogenic substance may be sufficient to transform a normal cell into a cancer cell. Evidence is available from both the human and animal health literature that cancers may arise from a single transformed cell. Mutation research with ionizing radiation in cell cultures indicates that such a transformation can occur as the result of interaction with as little as a single cluster of ion pairs. In reviewing the available data regarding carcinogenicity, EPA found no compelling scientific reason to abandon the no-threshold presumption for Cr^{+6} .

In developing the exposure-risk relationship for Cr^{+6} , EPA has assumed that a linear no-threshold relationship exists at and below the levels of exposure reported in the epidemiological studies of occupational exposure. This means that any exposure to Cr^{+6} is assumed to pose some risk of lung cancer and that the linear relationship between cancer risks

and levels of public exposure is the same as that between cancer risks and levels of occupational exposure. The EPA believes that this assumption is reasonable for public health protection in light of presently available information. The exposure-risk relationship used by EPA represents a plausible upper-limit risk estimate in the sense that the risk is probably not higher than the calculated level but could be lower.

The numerical constant that defines the exposure-risk relationship used by EPA in its analysis of carcinogens is called the unit risk estimate. The unit risk estimate for an air pollutant is defined as the lifetime cancer risk occurring in a hypothetical population in which all individuals are exposed continuously from birth throughout their lifetimes (about 70 years) to a concentration of one $\mu\text{g}/\text{m}^3$ of the agent in the air which they breathe. Unit risk estimates are used for two purposes: (1) to compare the carcinogenic potency of several agents with each other and (2) to give a crude indication of the public health risk which might be associated with estimated air exposure to these agents. The comparative potency of different agents is more reliable when the comparison is based on studies of like populations and on the same route of exposure, preferably inhalation.

The Health Assessment Document for Chromium (HAD) (EPA 600/8-83-014F) contains the derivation of the unit risk number.² The HAD notes that although there are many epidemiologic studies demonstrating that chromium is a potential human carcinogen, few provide adequate exposure data for use in risk estimation purposes. It is not clear from the epidemiological studies whether only hexavalent or both trivalent and Cr^{+6} are responsible for the increased cancer risk. Because Cr^{+6} compounds have generally yielded positive results in animal bioassays and mutagenicity studies and trivalent (Cr^{+3}) generally have not, EPA has taken the position that Cr^{+6} is the form responsible for the carcinogenic response. However, this position may change pending results of research currently underway.

B.1.3 Public Exposure

The unit risk estimate is only one of the factors needed to produce quantitative expressions of public health risks. Another factor needed is a numerical expression of public exposure, i.e., the numbers of people exposed to the various concentrations of Cr^{+6} . The difficulty of defining

public exposure was noted by the National Task Force on Environmental Cancer and Health and Lung Disease in its 5th Annual Report to Congress in 1982.³ The Task Force reported that ". . . a large proportion of the American population works some distance away from their homes and experience different types of pollution in their homes, on the way to and from work, and in the workplace. Also, the American population is quite mobile, and many people move every few years." They also noted the necessity and difficulty of dealing with long-term exposures because of ". . . the long latent period required for the development and expression of neoplasia [cancer]"

The EPA's numerical expression of public exposure is based on two estimates. The first is an estimate of the magnitude and location of long-term average ambient air concentrations of Cr^{+6} in the vicinity of emitting sources, which is based on dispersion modeling using long-term estimates of source emissions and meteorological conditions. The second is an estimate of the number and distribution of people living in the vicinity of emitting sources based on Bureau of Census data which "locates" people by population centroids in block group or enumeration district (BG/ED) areas. The people and concentrations are combined to produce numerical expressions of public exposure by an approximating technique contained in a computerized model. The methodology is described in B.3 below.

B.1.4 Public Cancer Risks

By combining numerical expressions of public exposure with the unit risk estimate, two types of numerical expressions of public cancer risks are produced. The first, called individual risk, relates to the person or persons estimated to live in the area of highest concentration as estimated by the dispersion model. Individual risk is expressed as "maximum lifetime risk." As used here, the word "maximum" does not mean the greatest possible risk of cancer to the public. It is based only on the maximum exposure estimated by the procedure used. The second, called aggregate risk, is a summation of all the risks to people estimated to be living within the vicinity (usually within 50 kilometers) of a source and is customarily summed for all the sources in a particular category. The aggregate risk is expressed as incidence of cancer among all of the

exposed population after 70 years of exposure; for statistical convenience, it is often divided by 70 and expressed as annual cancer incidence. These calculations are described in more detail in B.4 below.

B.2 THE UNIT RISK ESTIMATE FOR HEXAVALENT CHROMIUM

The following discussion is summarized from a more detailed description of the Agency's Cr^{+6} unit risk estimate in the HAD mentioned above.² The model used to estimate risk is linear with age-specific incidence being a function of the background incidence, age of the individual, and dose to which the person is exposed. The theory relating the maximum likelihood and nonlinear least square estimation was used to estimate the key parameters in the model. Calculating the unit risk also required estimating the probability of surviving and relied upon U.S. vital statistics.

The unit risk estimate for Cr^{+6} was based on the Mancuso (1975) data in which a cohort of 332 white male workers who were employed in a chromate plant between 1931 and 1937 were followed to 1974.⁴ In his study, Mancuso reported lung cancer death rates by levels of exposure to soluble, insoluble, and total chromium concentrations. Because only lung cancer mortality for total chromium exposure was reported by age group, EPA's Carcinogen Assessment Group used only the dose-response data for total chromium to estimate the carcinogenic potency of Cr^{+6} . Although the use of dose-response data for total chromium results in an underestimation of the potency of Cr^{+6} , the effect of this underestimation is approximately compensated for by other factors that may overestimate the risk such as the failure of the author to correct for smoking.

The unit risk estimate calculated for Cr^{+6} based on the Mancuso study is 1.2×10^{-2} . This means that if a person is continuously exposed for 70 years to $1 \mu\text{g}/\text{m}^3$, the probability of getting lung cancer would not likely exceed 1.2 chances in 100. There are numerous uncertainties concerning this estimate. The effects of age, sex, race, and general health of the sensitivity of responses to Cr^{+6} exposure are unknown. Because of the unavailability of sufficient data to correct for these factors, the impact of these factors cannot be addressed in this assessment.

B.3 QUANTITATIVE EXPRESSIONS OF PUBLIC EXPOSURE

The EPA's Human Exposure Model (HEM) is a general model capable of producing quantitative expressions of public exposure to ambient air concentrations of pollutants emitted from stationary sources. The HEM contains (1) an atmospheric dispersion model, which included meteorological data, and (2) a population distribution estimate based on Bureau of Census data. The only input data needed to operate this model are source data, e.g., plant location, height of the emission release point, and temperature of the off-gases. Based on the source data, the model estimates the magnitude and distribution of ambient air concentrations of the pollutant in the vicinity of the source. The model is programmed to estimate these concentrations within a radial distance of 50 kilometers from the source. If other radial distances are preferred, an override feature allows the user to select the distance desired. The selection of 50 kilometers as the programmed distance is based on modeling considerations, not on health effects criteria or EPA policy. The dispersion model contained in HEM is reasonably accurate within 50 kilometers. If the user wishes to use a dispersion model other than the one contained in HEM to estimate ambient air concentrations in the vicinity of a source, HEM can accept the concentrations if they are put into an appropriate format. It also is possible to evaluate the effect particle deposition near the stack has on the ambient air concentrations of the pollutant. A detailed description of the HEM can be found in Reference 5.

Based on the radial distance specified, HEM combines numerically the distributions of pollutant concentrations and people to produce quantitative expressions of public exposure to the pollutant. The HEM allows for estimates to be made for both point sources and area sources.

B.3.1 Model Selection and Description

The area source model that is contained in HEM was selected to assess the carcinogenic risks from CCT's for several reasons: (1) the nationwide population of CCT's is estimated to be about 250,000; of these, about 37,500 are estimated to use chromium-based water treatment chemicals, (2) the specific locations of CCT's are largely unknown, (3) CCT's are most likely to be located in urban areas, which the area source model is

well suited to address, and (4) the majority of Cr^{+6} emitted from the CCT's is expected to remain airborne and be dispersed over a large area. As discussed in Section 5.1.2.1, the majority of the droplets in the plume are expected to evaporate rapidly because they are smaller than 30 μm . Thus, it was not necessary to include deposition in the modeling effort.

The area source model is used for those sources which cannot be specified in detail. The allocation of emissions from such sources must be inferred by relating the source to a correlated parameter such as population, motor vehicles, etc. For these sources, the dispersion of emissions is then modeled by a simplified dispersion algorithm to estimate concentration patterns. The Gifford urban area dispersion algorithm (Hanna and Gifford, 1973) has proved to be a simple but physically realistic model capable of estimating atmospheric pollutant concentrations caused by area source emissions in cities. The basic Hanna-Gifford equation is given as:

$$X = CQ_0/U \quad (1)$$

where X is air pollutant concentration, Q_0 is the effective emissions rate per unit area, and U is the wind speed. The parameter C , generally referred to as the Gifford coefficient, is a weak function of the city size; it may be taken to be approximately constant. Theoretically, the parameter C is given by:

$$C = (2)^{1/2} \cdot X^{1-b} / [a(1-b)]^{-1} \quad (2)$$

where X is the distance from a receptor point to the upwind edge of the area source. The constants a and b are defined by the vertical atmospheric diffusion length, $\sigma_z = ax^b$. Values of a and b for different atmospheric dispersion conditions have been discussed by Pasquill (1970, 1971). The parameter C can be estimated for various combinations of the stability factors a and b and by assuming that X equals half the city size (Hanna, 1978). For example, 213 would be an appropriate value of C for a city with a land area of 400 km^2 under Pasquill Class D stability (where $a = 0.15$ and $b = 0.75$). Specific values of the parameter C have been

empirically estimated by Hanna and Gifford for a large number of U.S. cities based on a large quantity of air quality data, average annual emissions, and meteorological conditions. The mean value of C has been found to equal 225, with a standard deviation roughly half that magnitude. This value of the parameter C has been recommended for use in evaluating an area source by EPA if removal and decay processes may be neglected. Estimates of the parameter C were calculated by using Equation 2 and by assuming Pasquill Class D stability as the average long-term meteorological condition.

The application of the Gifford approach within HEM has been modified to provide variation of atmospheric concentration across a modeling region in proportion to the local emission rate per unit area. This approach provides a higher degree of resolution of concentration patterns than does the single urban box approach but does not address the details of pollutant advection and dispersion that are treated by grid dispersion models.

In the present approach, box model (Gifford model) dispersion results are simply scaled at each BG/ED by the ratio of the density of emissions per surface area at the BG/ED to the regional mean emission density.

Options in the AREA code provide for varying or nonvarying (from district to district) emission rates. Emissions that vary with BG/ED, which was used for CCT's, are scaled by the population density of the BG/ED. This is to address pollutant-emitting activities that uniform fractions of the population are expected to be engaged in at any given time. Examples of such activities are motor vehicle usage and operation of home furnaces.

The basic Hanna-Gifford equation (1) shows that the concentration is inversely proportional to the wind speed. In HEM, each wind speed in the stability array (STAR) set is used.^a The STAR matrix is summed over wind direction and stability class to give the frequency of occurrence of each

^aStability array refers to meteorological data usually collected at airports. These data consist of frequency distributions of wind speed and direction and atmospheric stability.

speed. The concentration is computed as the sum of the frequency-weighted concentrations for each wind speed.

The population data in the area model require estimates of population data density. This information was not available when the model was developed. The only data taken from Bureau of Census were the location (UTM coordinates of centroid) and population of each BG/ED. In the absence of information on the area of each BG/ED, arbitrary estimates are made for each BG/ED.

Estimates of BG/ED areas require dividing the analysis region into a grid of Cartesian cells. The size and number of cells are chosen to produce a grid mesh that is as fine as resources permit. Ideally, grid cells should be much smaller than the distance between the closest BG/ED centroids, but much coarser resolution may be acceptable, depending on analysis goals.

The "best guess" area of any BG/ED is defined here to be the sum of the areas of grid cells for which the centroid of the BG/ED in question is the closest centroid. If more than one BG/ED centroid falls within a grid cell, the cell area is divided among the districts so identified. The cells are scanned in square "spirals" about each centroid, with cells "belonging" to their centroid of origin until spirals overlap. Specific radius tests resolve the "ownership" of cells in overlapped portions of spirals.

B.3.2 Input Data and Results

To facilitate area source modeling and conserve computer resources, given that population exposure and cancer risks are proportional to the chemical's carcinogenic potency and emissions, the area source model was previously run for each U.S. county and aggregated to the State level for a unit emission rate of 1 kilogram per person and a cancer potency of 1.00×10^{-1} (lifetime probability of cancer per $\mu\text{g}/\text{m}^3$ of the modeled pollutant). This run provides for each county and State an estimated unit annual cancer incidence that may be scaled by the actual potency factor for Cr^{+6} and the Cr^{+6} emission rate by State to obtain specific area source estimates of risk for the CCT category.

$$\text{cancer incidence (State-CCT's)} = \frac{\text{cancer incidence (State-model run)}}{\text{0.1}} \times \frac{\text{Cr}^{+6} \text{ potency}}{\text{1 kg}} \times \frac{\text{emission rate/person (State)}}{\text{1 kg}}$$

Table B-1 lists population, annual incidence (prescaling), the emission rate (person x 10⁻⁵ grams), and estimated annual incidence for each State. (Chapter 4 provides a discussion of the emission rate calculations). Alaska was assumed to have no CCT's that emit Cr⁺⁶. The total nationwide annual incidence for Cr⁺⁶ was estimated to range from 4 to 112 per year. This range reflects lower- and upper-bound emissions estimates. (For more detail, see Chapter 4.)

To estimate maximum lifetime risk, the largest model plant was assumed to release all the Cr⁺⁶ at ground level (1.5 m) (see Table B-3). Ground-level release was specified since concentrations are inversely proportional to release height. This plant was then placed in 50 large cities, one in each State plus Washington, D.C. (Alaska was excluded from the analysis). The highest maximum lifetime risk ranged from 2.3 x 10⁻⁶ to 6.6 x 10⁻⁵. Table B-2 shows the cities used to estimate maximum lifetime risk. The maximum lifetime risk is calculated by multiplying the Cr⁺⁶ unit risk factor (1.2 x 10⁻²) by the highest concentration to which any person is predicted to be exposed (1.9 x 10⁻⁴ to 5.5 x 10⁻³ µg/m³ annual average by State). Table B-3 shows the model CCT emission parameters. Table B-4 shows the range of maximum concentrations to which people are predicted to be exposed by State.

B.4 ANALYTICAL UNCERTAINTIES APPLICABLE TO THE CALCULATIONS OF PUBLIC HEALTH RISKS CONTAINED IN THIS APPENDIX

B.4.1 The Unit Risk Estimate

The procedure used to develop the unit risk estimate is described in Reference 2. The model used and its application to epidemiological data have been the subjects of substantial comment by health scientists. The uncertainties are too complex to be summarized in this appendix.

The unit risk estimate used in this analysis applies only to lung cancer. Other health effects are possible; these include respiratory tract irritation and hypersensitivity, i.e., asthmatic-like symptoms. No numerical expressions of risks relevant to these health effects is included in this analysis.

TABLE B-1. HEXAVALENT CHROMIUM EMISSION RATE PER PERSON AND ANNUAL INCIDENCE BY STATE

Area source analysis (by county)

Emission rate = 1 kg/person/yr

Unit potency = 0.1

Cr⁺⁶ potency = 0.012

State	Population	Unit annual incidence	Annual Cr ⁺⁶ emissions per person, kgx10 ³ /yr	Cr ⁺⁶ annual incidence
Alabama	4,030,000	7,800	4.01-113.8	0.038-1.1
Alaska	448,000	73	0.0-0.0	0
Arizona	3,010,000	12,000	3.74-106.1	0.054-1.5
Arkansas	2,400,000	23,000	3.80-108.0	0.11-3.0
California	24,800,000	160,000	3.67-104.1	0.70-20
Colorado	3,110,000	14,000	1.97-55.9	0.033-0.94
Connecticut	3,130,000	11,000	2.24-63.6	0.030-0.84
Delaware	610,000	13,000	2.24-63.6	0.035-0.99
D.C.	608,000	15,000	6.04-171.6	0.30-8.4
Florida	10,600,000	41,000	4.01-113.8	0.053-1.5
Georgia	5,710,000	11,000	6.79-192.8	0.026-0.74
Hawaii	1,020,000	3,200	1.43-40.5	0.002-0.063
Idaho	1,020,000	1,300	2.85-81.0	0.28-8.0
Illinois	11,500,000	82,000	2.85-81.0	0.038-1.1
Indiana	5,570,000	11,000	2.58-73.3	0.009-0.25
Iowa	2,940,000	2,800	2.85-81.0	0.015-0.42
Kansas	2,410,000	4,300	2.85-81.0	0.018-0.51
Kentucky	3,790,000	5,200	4.41-125.3	0.090-2.6
Louisiana	436,000	17,000	1.43-40.5	0.001-0.036
Maine	1,170,000	750	3.12-88.7	0.13-3.6
Maryland	4,330,000	34,000	2.24-63.6	0.070-2.0
Massachusetts	5,780,000	26,000	2.24-63.6	0.078-2.2
Michigan	9,400,000	29,000	1.97-55.9	0.021-0.59
Minnesota	4,160,000	8,800	4.01-113.8	0.014-0.38
Mississippi	2,600,000	2,800	2.85-81.0	0.041-1.2
Missouri	5,010,000	12,000	1.70-48.2	0.001-0.041
Montana	826,000	700	2.58-73.3	0.012-0.34
Nebraska	1,600,000	3,900	2.65-75.2	0.016-0.45
Nevada	891,000	5,000	1.83-52.1	0.002-0.060
New Hampshire	981,000	960	2.85-81.0	0.18-5.1
New Jersey	7,450,000	52,000	2.65-75.2	0.009-0.25
New Mexico	1,390,000	2,800	2.24-63.6	0.78-22
New York	17,400,000	290,000	3.60-102.2	0.048-1.3
North Carolina	6,110,000	11,000	1.70-48.2	0.001-0.025
North Dakota	667,000	430	2.65-75.2	0.080-2.3
Ohio	10,800,000	25,000	3.67-104.1	0.023-0.66
Oklahoma	3,170,000	5,300	1.56-44.3	0.015-0.44
Oregon	2,800,000	8,200	2.65-75.2	0.19-5.4
Pennsylvania	11,800,000	60,000	2.24-63.6	0.007-0.19
Rhode Island	953,000	2,500	4.01-113.8	0.026-0.75
South Carolina	3,280,000	5,500	2.24-63.6	0.001-0.029
South Dakota	700,000	380	3.40-96.4	0.036-1.0
Tennessee	4,790,000	8,800	4.28-121.5	0.14-4.1
Texas	15,100,000	28,000	2.11-59.8	0.015-0.42
Utah	1,580,000	5,900	1.70-48.2	0.001-0.015
Vermont	530,000	250	2.85-81.0	0.065-1.8
Virginia	5,590,000	19,000	1.36-38.6	0.023-0.63
Washington	4,310,000	14,000	2.85-81.0	0.007-0.18
West Virginia	2,000,000	1,900	2.11-59.8	0.021-0.59
Wisconsin	4,820,000	8,200	1.70-48.2	0.001-0.024
Wyoming	514,000	410	3.40-96.4	0.061-1.7
Total annual incidence				4-112

TABLE B-2. LOCATIONS USED IN ESTIMATING INDIVIDUAL RISK

Location	Latitude		Longitude	
	Degrees	Minutes	Degrees	Minutes
Alabama, Birmingham	33	31	86	50
Arizona, Phoenix	33	27	112	05
Arkansas, Little Rock	34	44	92	15
California, Los Angeles	34	03	118	15
Colorado, Denver	39	43	105	01
Connecticut, Hartford	41	46	72	41
Delaware, Dover	39	10	75	32
Washington, D.C.	38	54	77	01
Florida, Miami	25	46	80	12
Georgia, Savannah	32	04	81	05
Hawaii, Honolulu	21	19	157	52
Idaho, Boise	43	37	116	13
Illinois, Chicago	41	53	87	38
Indiana, Indianapolis	39	46	86	09
Iowa, Des Moines	40	22	91	26
Kansas, Kansas City	39	07	94	36
Kentucky, Louisville	38	16	85	45
Louisiana, Baton Rouge	30	23	91	11
Maine, Augusta	44	19	69	47
Maryland, Baltimore	39	17	76	36
Massachusetts, Boston	42	21	71	04
Michigan, Detroit	42	20	83	03
Minnesota, Duluth	46	47	92	06
Mississippi, Jackson	32	18	90	12
Missouri, Kansas City	39	05	94	35
Montana, Helena	46	36	112	01
Nebraska, Omaha	41	16	95	57
Nevada, Las Vegas	36	11	115	08
New Hampshire, Concord	43	12	71	32
New Jersey, Trenton	40	13	74	45
New Mexico, Albuquerque	35	05	106	40
New York, New York City	40	43	24	01
North Carolina, Charlotte	35	14	80	50
North Dakota, Bismarck	46	48	100	47
Ohio, Cincinnati	39	06	92	56

(continued)

TABLE B-2. (continued)

Location	Latitude		Longitude	
	Degrees	Minutes	Degrees	Minutes
Oklahoma, Oklahoma City	35	28	97	32
Oregon, Portland	43	39	70	17
Pennsylvania, Philadelphia	39	57	75	07
Rhode Island, Providence	41	50	71	25
South Carolina, Columbia	34	00	81	03
South Dakota, Sioux Falls	43	32	96	44
Tennessee, Nashville	36	09	86	48
Texas, Houston	29	46	95	22
Utah, Salt Lake City	40	46	111	53
Vermont, Montpelier	44	16	72	35
Virginia, Richmond	37	32	77	28
Washington, Seattle	47	36	122	20
West Virginia, Charleston	38	21	81	38
Wisconsin, Milwaukee	43	02	87	54
Wyoming, Cheyenne	41	08	104	49

TABLE B-3. MODEL PLANT PARAMETERS^a

Emission rate, kg/yr	Release height, m	Dia- meter, m	Exit velocity, m/s	Exit temp., °K	Building cross sectional area, m ^{2b}
2.13-60.6	7.5	4.6	8.2	300	2,240

^aThe area source model was used to estimate annual incidence.

^bThe building cross-sectional area was used to calculate the maximum individual risk.

TABLE B-4. MAXIMUM CONCENTRATIONS PREDICTED

State	Concentration, $\mu\text{g}/\text{m}^3 \times 10^{-3}$
Oklahoma	0.19-5.5
Vermont	0.16-4.6
California	0.16-4.5
Missouri	0.15-4.1
Kansas	0.15-4.1
North Dakota	0.13-3.8
Tennessee	0.13-3.8
Idaho	0.13-3.8
Florida	0.13-3.8
Utah	0.13-3.7
Nebraska	0.12-3.4
Colorado	0.12-3.4
Massachusetts	0.11-3.2
South Dakota	0.11-3.2
Minnesota	0.11-3.0
Texas	0.11-3.0
New Mexico	0.11-3.0
Wyoming	0.10-2.9
Maryland	0.10-2.8
Arizona	0.10-2.8
Washington, D.C.	0.10-2.8
New Hampshire	0.09-2.6
Nevada	0.09-2.5
Michigan	0.09-2.5
Kentucky	0.09-2.5
Washington	0.09-2.5
Illinois	0.08-2.3
Montana	0.08-2.3
Iowa	0.08-2.3
West Virginia	0.08-2.2
Wisconsin	0.07-2.1
New York	0.07-2.0
Pennsylvania	0.07-2.0
Rhode Island	0.07-2.0
Oregon	0.07-1.9

(continued)

TABLE B-4. (continued)

State	Concentration, $\mu\text{g}/\text{m}^3 \times 10^{-3}$
New Jersey	0.8-22.7
Arkansas	0.8-22.7
New Mexico	0.8-22.7
Pennsylvania	0.8-22.7
Louisiana	0.7-20.6
Rhode Island	0.7-20.6
Ohio	0.7-20.6
Indiana	0.7-20.6
Alabama	0.7-20.6
Massachusetts	0.7-20.6
Georgia	0.7-18.6
North Carolina	0.7-18.6
Delaware	0.7-18.6
South Carolina	0.7-18.6
Mississippi	0.6-16.5

B.4.2 Public Exposure

B.4.2.1 General. The basic assumptions implicit in the methodology are that all exposure occurs at people's residences, that people stay at the same location for 70 years, that the ambient air concentrations and the emissions which cause these concentrations persist for 70 years, and that the concentrations are the same inside and outside the residences. From this, it can be seen that public exposure is based on a hypothetical rather than a realistic premise. It is not known whether this results in an overestimation or an underestimation of public exposure.

B.4.2.2 The Public. The following are relevant to the public as dealt with in this analysis:

1. Studies show that all people are not equally susceptible to cancer. There is no numerical recognition of the "most susceptible" subset of the population exposed.
2. Studies indicate that whether or not exposure to a particular carcinogen results in cancer may be affected by the person's exposure to other substances. The public's exposure to other substances is not numerically considered.
3. Some members of the public included in this analysis are likely to be exposed to Cr^{+6} in the air in the workplace, and workplace air concentrations of a pollutant are customarily much higher than the concentrations found in the ambient, or public air. Workplace exposures are not numerically approximated.
4. Studies show that there is normally a long latent period between exposure and the onset of lung cancer. This has not been numerically recognized.
5. The people dealt with in the analysis are not located by actual residences. As explained previously, they are "located" in the Bureau of Census data for 1980 by population centroids of census districts. Further, the locations of these centroids have not been changed to reflect the 1980 census. The effect is that the actual locations of residences with respect to the estimated ambient air concentrations is not known and that the relative locations used in the exposure model have changed since the 1970 census.

6. Many people dealt with in this analysis are subject to exposure to ambient air concentrations of Cr^{+6} where they travel and shop (as in downtown areas and suburban shopping centers), where they congregate (as in public parks, sports stadiums, and schoolyards), and where they work outside (as mailmen, milkmen, and construction workers). These types of exposures are not numerically dealt with.

B.4.2.3 The Ambient Air Concentrations. The following are relevant to the estimated ambient air concentrations of Cr^{+6} used in this analysis:

1. Flat terrain was assumed in the dispersion model. Concentrations much higher than those estimated would result if emissions impact on elevated terrain or tall buildings near a plant.

2. The estimated concentrations do not account for the additive impact of emissions from plants located close to one another.

3. The increase in concentrations that could result from reentrainment of Cr^{+6} -bearing dust from areas such as city streets, dirt roads, and vacant lots is not considered.

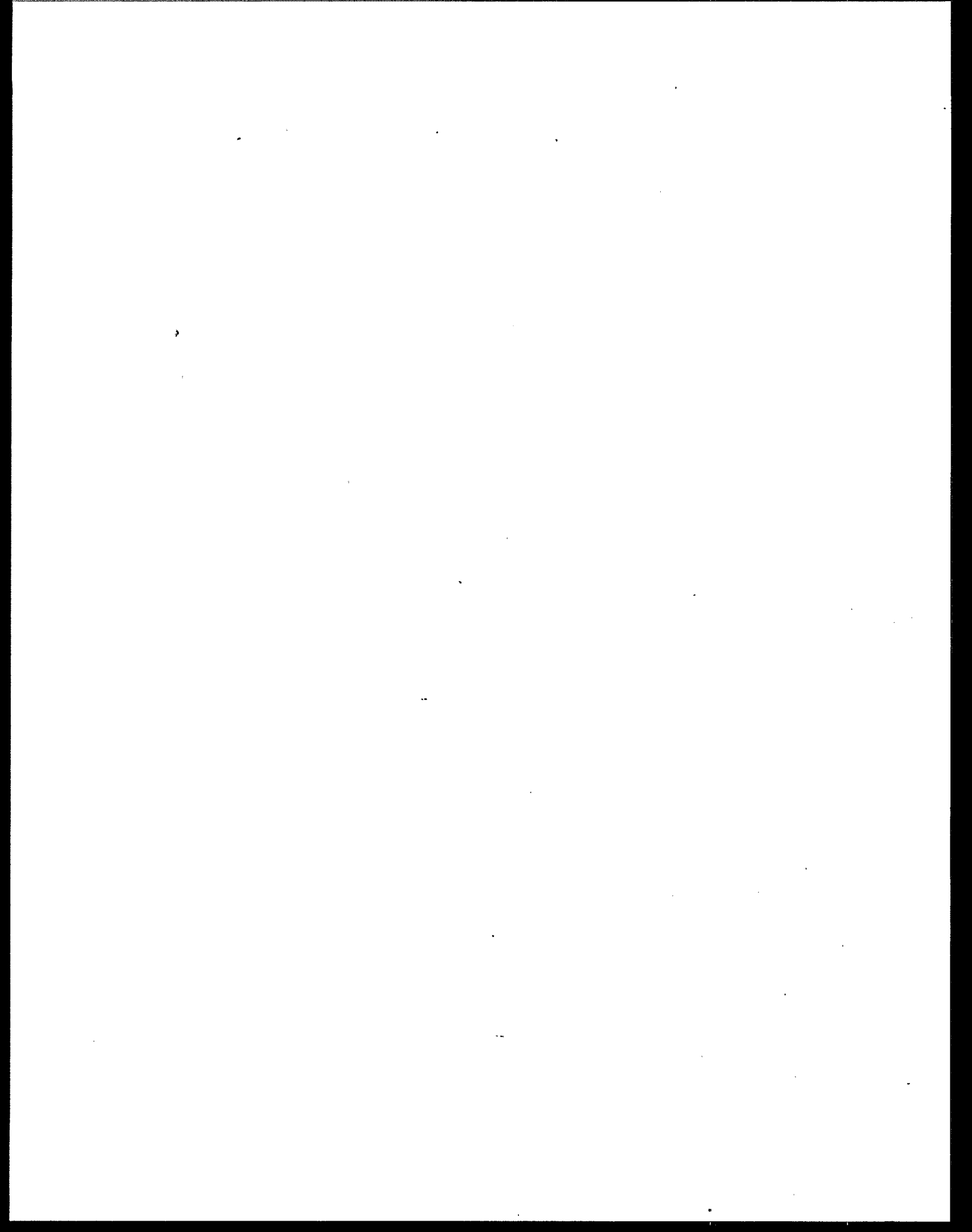
4. Meteorological data specific to plant sites are not used in the dispersion model. As explained, HEM uses the meteorological data from the STAR station nearest the plant site. Site-specific meteorological data could result in significantly different estimates, e.g., the estimates of where the higher concentrations occur.

5. With few exceptions, the Cr^{+6} emission rates are based on engineering estimates rather than on emission tests. See Chapter 4 for details.

B.5 REFERENCES FOR APPENDIX B

1. National Academy of Sciences. "Arsenic" Committee on Medical and Biological Effects of Environmental Pollutants, Washington, D.C. 1977. Docket No. OAQPS 79-8 II-A-3.
2. Health Assessment Document for Chromium. Publication No. EPA-600/8-83-014F. August 1984.
3. Environmental Cancer and Heart and Lung Disease. Fifth Annual Report to Congress by the Task Force on Environmental Cancer and Health and Lung Disease. August 1982.

4. Mancuso, T. F. Consideration of Chromium As An Industrial Carcinogen. Proceedings of the International Conference on Heavy Metals in the Environment. Hutchinson, T. C., ed. Institute for Environmental Studies. Toronto, 1975. pp. 343-356.
5. User's Manual for the Human Exposure Model (HEM). Publication No. EPA-450/5-86-001. June 1986.



APPENDIX C. SUMMARY OF TEST DATA

This appendix presents the results of three EPA-conducted tests for hexavalent chromium (Cr^{+6}) emissions from industrial process cooling towers (IPCT's) and one EPA-conducted test of Cr^{+6} emissions from a comfort cooling tower (CCT). Emission data from IPCT's can be used to represent emissions from CCT's because design parameters that affect the emission rate are similar for both tower types. The test data were considered in developing emission factors and in quantifying the performance of high-efficiency drift eliminators (HEDE's) versus low-efficiency drift eliminators (LEDE's) in Chapter 4. The emission data include mass emissions and particle size distributions. For each test series, Section C.1 presents descriptions of the physical and operating parameters of the cooling tower and of the water treatment program. The test results are tabulated in Section C.2.

Three test methods were used to quantify emissions of Cr^{+6} from cooling towers, one isokinetic method and two methods that rely on water droplet impaction. The EPA isokinetic test method utilizes a Method 13 sampling train with the exception that the filter is made of Teflon® and a propeller anemometer is used in place of the pitot tube. The collected samples were analyzed for total chromium by Neutron Activation Analysis or graphite furnace atomic adsorption after concentrating the liquid to 25 milliliters. Because the isokinetic sampling probe does not alter the airflow approaching the probe nozzle, all emissions are collected by this method. The total chromium in the cooling water was 99 percent Cr^{+6} ; therefore, it was assumed that the total emissions are Cr^{+6} .

The sensitive paper test method utilizes the collection of water droplets by inertial impaction onto a chemically treated paper. The water droplets, which turn the paper blue, are examined optically with a

microscope to quantify the number of each size water droplet impacting the paper. The results of these counts are totaled to quantify the emissions of water droplets from the cooling tower.

The absorbent test method uses the same collection method as the sensitive test method except that absorbent paper (Whatman 541 filter paper) replaces the chemically treated sensitive paper. The absorbent papers were analyzed for chromium by Neutron Activation Analysis or graphite furnace atomic adsorption to quantify emissions.

Both the sensitive paper method and the absorbent paper method alter the airflow approaching the collection media. Although the inertia of the larger droplets approaching these devices would cause the droplets to continue in a straight line and, therefore, impact on the surface of the paper, the smaller droplets tend to follow the streamlines around the sampling device. Given the typical air velocities of the cooling tower stack and the size of the collection device, less than 50 percent of the droplets smaller than 30 micrometers in diameter would impact the surface of the paper. Because of this phenomenon, the sensitive paper analyses include a correction factor for different size droplets.

C.1 DESCRIPTION OF TESTS

C.1.1 Department of Energy, Gaseous Diffusion Plant, Paducah, Kentucky

C.1.1.1 Process Description. The Department of Energy facility at Paducah, Kentucky, is operated by Martin Marietta Energy Systems, Inc. This facility enriches uranium in the U^{235} isotope using a gaseous diffusion (cascade) process. The diffusion process involves pressure-induced flow of the uranium hexafluoride (UF_6) process gas through microporous barriers. The heat of compression is removed from the process gas by thermosyphon refrigerant systems to control the operating temperature. The refrigerant is vaporized in process gas coolers and is transferred to water-cooled heat exchangers where it is condensed before it returns to the gas coolers. Recirculating cooling water is pumped from a basin to the process condensers and returned to the cooling towers where waste process heat is rejected to the atmosphere. Indirect cooling of the UF_6 is used for safety and reliability considerations.

The process cooling tower system consists of two towers that are designated C-637-2A and C-637-2B. A sketch of the C-637-2A and C-637-2B

system is shown in Figure C-1. The C-637-2A tower was selected for source testing; this tower is a seven-cell Marley crossflow design with two fans per riser cell and is equipped with both LEDE's (herringbone) and HEDE's (Thermatec Spectra). Riser cell Nos. 1 through 5 are equipped with LEDE's and redwood splash fill. The HEDE riser cell Nos. 6 and 7 contain polyvinyl chloride (PVC) splash fill.

The tower was originally constructed in the early 1950's with redwood splash fill and herringbone drift eliminators in all the riser cells. Riser cell Nos. 6 and 7 were recently modified by the installation of the PVC splash fill and Thermatec Spectra drift eliminators. The water systems of towers C-637-2A and C-637-2B are served by a common pumphouse that has a total nominal capacity of 605,670 liters per minute (ℓ/min) (160,000 gallons per minute [gal/min]): six pumps rated for 75,709 ℓ/min (20,000 gal/min) each and four pumps rated for 37,854 ℓ/min (10,000 gal/min) each. Each of the tower systems is constructed with a water basin having a capacity of 15.9 million liters (4.2 million gallons). Makeup water from the Ohio River is softened and clarified and then supplied through a 76.2-centimeter (30-inch) pipeline to the pumphouse.

Two 152.4-centimeter (60-inch) cooling water supply and return loops ("G" and "H" on Figure C-1) are used to recirculate the tower water through the process building. The return lines of each loop are connected by a "crossover" pipeline that allows water to be directed to either the C-637-2A or 2B tower for cooling. Another "crossover" pipeline interconnects the process cooling water supply lines. The recirculating water enters the tower after the flow is split into seven branches (riser pipes) that serve each of the seven riser cells. The flow from each of the riser pipes is split and conveyed into the water distribution decks of each of the two fan cells.

The water distribution decks are located directly above the splash fill sections of the fan cells and equipped with gravity flow nozzles for even distribution of the recirculating water in a cascade over the fill material. Propeller fans measuring 6.7 meters (m) (22 feet [ft]) in diameter that are located in the stack of each cell provide 17,273 cubic meters per min (m^3/min) (610,000 cubic feet per min [ft^3/min]) of induced horizontal airflow through the fill sections.

Sodium bichromate with a target concentration of 18 to 20 parts per million (ppm) is added to the recirculating cooling water to inhibit corrosion in the heat exchangers. Chromate additions are made manually, and the chromate levels are measured daily. A chlorine residual of 0.5 ppm is the target concentration for providing control of biological organism levels in the recirculating water. Chlorine is continuously injected into the system at a constant flow rate. The pH of the water is monitored continuously by a pH probe and meter. Additions of sulfuric acid are controlled manually to maintain the 6.0 to 6.1 target pH range. The calcium hardness is maintained at concentrations between 350 and 500 ppm in the recirculating water by controlling the blowdown rate.

C.1.1.2 Operating Conditions During Testing. The C-637-2A cooling tower operating parameters that were monitored throughout the test period were the fan motor amperage, pump outlet pressures, total water flow, basin water temperature, return water temperature, chlorine addition rate, makeup water flow rate, pH, wet well temperature, and blowdown rate. Meteorological data were obtained from the National Weather Service (NWS) at the Paducah Airport for each day that tests were performed and included hourly observations of dry bulb temperature, dew point, wind speed, and wind direction. Table C-1 is a summary of the cooling tower operating parameters and meteorological data recorded and obtained during the test period.

The cooling tower was not operating at the recirculating water design capacity during the tests due to low process cooling demands. It was necessary to increase the water flow rates of the riser cells being tested to between 90 and 100 percent of design capacity (30,564 to 33,959 L/min [8,074 to 8,971 gal/min], respectively) by directing some of the recirculating water in the riser cells not being tested to the riser cells that were being tested. This was accomplished by partially closing the isolation valve for the riser cells not being tested. Additionally, the distribution of the riser cell water to each of the fan cells was balanced by adjusting the individual flow control valves on each fan cell until the depth of water appeared to be equal in the distribution decks. The blowdown rate was maintained at zero throughout the test period to minimize the loss of sodium bromide that was added to the recirculating water as a tracer chemical.

On the day prior to the first test series, the recirculating water flow rates on riser cell Nos. 4 and 7 were adjusted while the waterflow rates were measured. Waterflow rates were established at 32,176 ℓ /min (8,500 gal/min) and 32,555 ℓ /min (8,600 gal/min) for riser cell Nos. 4 and 7, respectively. A waterflow measurement on riser pipe No. 7 concurrent with the first test series indicated that the flow was at 85 percent of capacity or 28,390 ℓ /min (7,500 gal/min). The reason for this variation is not known, but there may have been a leak in the pitot tube during the pretest flow rate measurement. Inspection of the drift eliminator in fan cell No. 13 indicated the presence of a significant water leak from the distribution deck into the tower on the fan side of the drift eliminator section. The first test on riser cell No. 7 was invalidated because the waterflow rate was less than 90 percent of the design flow rate and because of the water leak into the tower on the fan side of the drift eliminator. The tests on riser cell No. 7 were successfully repeated after the pitot tube was repaired and a broken redwood plank in the side of the water distribution deck was replaced. The remaining tests on riser cell Nos. 4, 5, and 6 were completed under acceptable conditions with respect to the test plan and Cooling Tower Institute guidelines.

C.1.2 National Bureau of Standards, Gaithersburg, Maryland

C.1.2.1 Process Description

The National Bureau of Standards (NBS) is a Federal government research facility near Gaithersburg, Maryland. On the grounds are seven laboratory/office buildings with a total floor area of 58,066 square meters (m^2) (625,000 square feet [ft^2]) and a number of support buildings with a floor area of 62,711 m^2 (675,000 ft^2). Comfort cooling and cooling for laboratory processes (lasers, ovens, etc.) are both provided by a four-cell Marley tower located near the western boundary of the facility. The tower was installed in the early 1960's.

A sketch of the cooling tower system is provided in Figure C-2. The tower is a crossflow design with redwood splash fill and one fan per cell. Propeller fans measuring 6.7 m (22 ft) in diameter are located in the stack of each cell. In 1985, the tower was retrofitted with high-efficiency Munters D-15 drift eliminators.

The capacity of the water basin is about 1.893×10^6 ℓ (500,000 gal). Four pumps each rated for 33,312 ℓ /min (8,800 gal/min) circulate the water to the chillers. The water from the chillers is combined and returned to the tower through a 106.7-centimeter (42-inch) riser pipe. Above the tower, the flow is split into four branches and distributed to each of the cells. The water distribution decks are located directly above the fill and are equipped with gravity flow nozzles. In winter, heated water is sprayed up into the rear of the tower to prevent icing conditions.

A solution of molybdate and polyacrylate is used to inhibit corrosion in the heat exchangers. The target concentration of molybdate in the recirculating water is about 15 ppm. Conductivity and pH are monitored continuously, and blowdown occurs automatically when the conductivity reaches 1,800 micromhos (μ mhos). Blowdown averages about 227,126 liters per day (ℓ /d) (60,000 gallons per day [gal/d]) in summer and about 7,571 ℓ /d (2,000 gal/d) in winter.

Makeup water is provided by the City of Gaithersburg. The conductivity is generally about 300 μ mhos, but after heavy rains and after salt has been applied to the roads in the winter, the conductivity increases. Makeup requirements average about 1.136×10^6 ℓ /d (300,000 gal/d) in summer and about 208,200 ℓ /d (55,000 gal/d) in winter. Most of the water has first been used for once-through cooling of oil and air compressors.

Biological growth is controlled by manually adding 24.6 ℓ (6.5 gal) of a solution containing disodium cyanodithiocarbamate (7.35 percent) and potassium methyldithiocarbamate (10.15 percent) once a week.

C.1.2.2 Operating Conditions During Testing. Eight test series were conducted. The cooling tower operating parameters that were monitored during each test series included the recirculating water temperatures into and out of the chiller, recirculating water flow rate, daily blowdown and water makeup, wind speed, and wind direction. Meteorological data were also obtained from the NWS at Washington National Airport.

The design water flow was achieved on each of the test days, but one chiller was not operated; water simply circulated through it. The low ambient temperature and low demand during test series 5, 6, and 7 necessitated turning off a second chiller and one fan. Table C-2 is a

summary of the cooling tower operating parameters and meteorological data recorded during the test period.

It was determined from the estimated system volume that the addition of about 90.7 kilograms (kg) (200 pounds [lb]) of crystalline sodium dichromate would result in a Cr^{+6} concentration of slightly over 15 ppm in the recirculating water. This amount of sodium dichromate was added on the day before the first test, and lesser amounts were added on following days to replenish the estimated losses via blowdown and drift. To determine the actual Cr^{+6} concentration, water samples were taken during each test series and later analyzed for Cr^{+6} . Sodium bromide also was added to the recirculating water for evaluation of bromide as a surrogate for chromium in drift emissions testing.

A pretest walk-through of the tower was conducted on Tuesday, August 19. Inspection of the drift eliminators revealed a number of water leaks into the fan side of the eliminator sections. This was most significant in the first cell, but in no case did the airflow appear to be shearing droplets away from the water stream. Inspection of the water flow along the outside of the tower revealed an unequal distribution that was most pronounced on the windiest days. The strongest winds were evident on Wednesday, August 20, when the anemometer mounted atop a nearby building indicated gusts of up to 22.5 kilometers per hour (km/h) (14 miles per hour [mph]). On the tower itself, an anemometer indicated 22.5 km/h (14 mph), and the NWS reported winds of 16.1 to 24.1 km/h (10 to 15 mph) for that day. In no instance, however, was drift observed from the sides of the tower. All tests were completed under acceptable conditions with respect to the test plan and Cooling Tower Institute guidelines.

C.1.3 Exxon Refinery, Ethylene Production, Baytown, Texas

C.1.3.1 Process Description. Tower No. 68 provides cooling for the catalytic light end units, which recover ethylene and other light end products. The tower handles a constant heat load 24 hours per day. Figure C-3 is a sketch of tower No. 68. This tower consists of four counterflow cells and one Marley crossflow cell. Each cell has one single-speed fan and redwood herringbone drift eliminators. The counterflow section has redwood splash fill and is served by two risers

that distribute the water over the fill through a manifold and pressure spray nozzles. The crossflow section has plastic splash fill and is served by one riser that supplies a water distribution deck equipped with gravity flow nozzles. Two pumps circulate water from the northern end of the common basin to the process heat exchangers, and a third pump is on standby. Blowdown is withdrawn from the system before the water is returned to the tower. Makeup water from the San Jacinto River is supplied through a 10.2-centimeter (4-inch) pipeline to the basin. The fans are 5.5 m (18 ft) in diameter in the counterflow cells and 7.3 m (24 ft) in diameter in the crossflow cell.

The corrosion inhibitor is a chromate/zinc formulation that is supplied by Betz. The target concentration of chromate in the recirculating water is 10 to 15 ppm. The solution is added automatically at a rate that is set manually. Dispersant is added in the same manner. A free chlorine residual of 0.2 to 0.5 ppm is the target for control of microbiological growth. Chlorine gas is injected into a side stream of the makeup water and added to the southern end of the basin. The pH of the water is monitored continuously, but it is not used as an automatic controller. When pH exceeds the critical control range of 6.0 to 9.0, it must be corrected by manually adding acid or caustic soda. Blowdown is dictated by the conductivity, which should not exceed 1,500 μ mhos.

C.1.3.2 Operating Conditions During Testing. The operating parameters that were monitored throughout the test period included fan motor amperage, pump outlet pressure, hot water line pressure, water flow in each riser, temperature in each riser, basin water temperature, pH, conductivity, wind speed and direction, wet bulb temperature, and dry bulb temperature. In addition, the makeup flow rate was measured and the blowdown was estimated concurrently with the fourth test series. Table C-3 is a summary of the cooling tower operating parameters and meteorological data recorded during the test period.

On the day prior to the first test, the recirculating water flow rates were measured. The flow in the crossflow cell was about 20 percent greater than the flow in each of the counterflow cells. However, because the pump outlet pressures and fan amperages were constant and within design specifications, no changes were made to the air or water flow rates for the test.

The drift eliminator on one side of the crossflow cell was determined to be in good condition based on the visual inspection. The drift eliminators in the counterflow cells could not be inspected. However, it appeared that a similar quantity of drift was emitted from each stack although the amount may have been slightly less from cell No. 1. The quantity of steam rising from cell No. 1 also appeared to be slightly less than that from the other cells. Some of the nozzles in the distribution deck on cell No. 5 were plugged, and a few of the redwood slats in the lower sections of the counterflow cells were broken; but the overall condition of the tower was reasonably good.

Water meters are not installed on the makeup and total blowdown lines. To estimate these flows, alternative methods were attempted. During the fourth test series, a meter was connected to the pressure taps on an existing orifice plate in the makeup line. This indicated an average flow of about 1,060 L/min (280 gal/min) over the 6 hours of monitoring (greater in the afternoon than in the morning) but did not include the 56.8 to 75.1 L/min (15 to 20 gal/min) diverted for chlorine injection or the amount leaking through a valve into the system from a nearby tower (No. 58), which is treated with a phosphate inhibitor from Calgon. The Betz representative used the phosphate concentration in the recirculating water of tower No. 68 to calculate a gain of about 94.6 L/min (25 gal/min). Later work by Exxon confirmed that this estimate was correct.

To estimate the tower No. 68 blowdown, the flow was diverted to a 208-liter (55-gallon) drum. The amount of time required to fill the drum a couple of times was recorded. This estimated flow rate was within 20 percent of the estimate calculated by the Betz representative based on cycles of concentration and an estimate of evaporation.

Water temperatures also are not monitored by online equipment. Therefore, fittings were attached to taps on the three risers and the hot water return line itself. Mercury-in-glass thermometers were used to record the temperature. The basin temperature was determined about 5 feet from the basin wall below cell Nos. 1, 2, and 5. A mercury-in-glass thermometer was placed in a perforated can that was attached to a length of conduit. With this method, it was not possible to determine the actual

temperature drop in each cell, but the average basin temperature in all three locations was the same.

Two sources of meteorological data were available: one station set up at the tower and one maintained by Exxon refinery personnel less than a mile from the tower. Both stations indicated that the wind direction was from the southeast, and very few directional changes deviated more than 45 degrees from the southeast. Both average and peak wind speeds, however, were considerably higher at the tower station. The differences may have been the result of instrument calibration differences or they may have been caused by a slight tunneling effect created at the tower station where the wind had to pass between the cooling tower and a cryogenic process column (and other shorter equipment) 27.4 to 36.6 m (30 to 40 yards) downwind of the station. Gusts rarely exceeded 24.1 km/h (15 mph), and drift was never visible from the sides of the crossflow tower. The ambient temperature also varied between the stations. The actual temperature is probably that obtained at the tower site since the several thermometers that were used recorded the same levels.

Three days prior to the first test, the Exxon process personnel responsible for the tower disconnected the chlorine injection line to preclude any possible adverse health effects on test personnel. Chlorine will also react with most hydrocarbons. Thus, a decrease in the free chlorine residual concentration (normally determined once per shift) is the best indicator of a process fluid leak into the water. Alternatively, gas traps on the hot water return line, visual inspection of the surface of the water in the basin and the distribution deck of cell No. 5, and the chromate concentration were used to confirm that the process heat exchangers were not leaking. The chromate concentration, as determined by the operators each shift, was essentially constant and within the desired control range during the testing period. The Betz analysis on Tuesday agreed with that of the operators. The pH and conductivity were also within control ranges.

C.1.4 Exxon Refinery, Lube Oil Production, Baytown, Texas

C.1.4.1 Process Description. Cooling for the vacuum distillation unit for lube oil is provided by tower No. 84. Although the tower is operating at less than design capacity, it handles a constant heat load

24 hours per day. Figure C-4 is a sketch of tower No. 84. The tower is a Marley counterflow design with four riser cells and four fan cells. Each fan cell has one 6.7-m (22-ft) diameter constant-speed fan. The average measured airflow per fan ranged from 222 to 287 dry standard cubic meters per minute (dsm^3/min) (470,000 to 609,000 dry standard cubic feet per minute [dscfm]). Each cell is equipped with PVC film fill and a high-efficiency Marley XCEL-15 drift eliminator. Water is distributed over the fill through a manifold and spray nozzles. Two pumps circulate the water from the basin extension at the south end of the tower through the process heat exchangers. A recent potassium retention time study determined that the system volume was about 2.082×10^6 l (550,000 gal) of water.

Blowdown is designed to be controlled by the conductivity of the recirculating water. At certain set points, a valve is actuated in a line off the main hot water return. Most of the makeup water is supplied through a 15.2-centimeter (6-inch) pipe to the basin extension, but part of it is diverted continuously into five smaller lines. The inhibitor, dispersant, chlorine, sulfuric acid, and caustic soda are injected into the smaller lines automatically.

The corrosion inhibitor is a chromate/zinc formulation in a 7:1 ratio that is supplied by Nalco. The target chromate concentration in the recirculating water is 8 to 12 ppm. The solution is injected into one of the small makeup lines for a specific fraction of every 10-minute interval. The on/off time fraction can be changed by entering new values into the computer memory. The dispersant is injected into another makeup line in an identical manner. Acid and caustic are injected based on pH set points within the control range of 6.8 to 7.5. Chlorine gas is injected continuously at a rate controlled by a free chlorine residual monitor that is generally set to keep the concentration in the range of 0.3 to 0.5 ppm. The conductivity of the makeup water is about 150 μmhos , and the control range for the number of cycles is 6 to 8.

C.1.4.2 Operating Conditions During Testing. The operating parameters monitored throughout the test period were fan motor amperage, pump outlet pressures, cold water line pressure, water flow in each riser, temperature in three of the risers, basin temperature, temperature in pump inlet lines, pH, conductivity, wind speed and direction, and dry bulb

temperature. The computerized system that monitors inlet and outlet temperatures and the makeup, blowdown, and recirculating water flow rates was not calibrated correctly at the start of the test. With the exception of the blowdown, attempts at calibration were not successful. These problems are not considered to affect the amount of drift, and only the makeup and blowdown could not be monitored directly by the test personnel. Table C-4 is a summary of the cooling tower operating parameters and meteorological data recorded during the test period.

On the day prior to the first test series, the water flow rates in each riser were measured. The flows in Risers A and B were about 15 percent less than the flows in Risers C and D. The total flow was 25 percent greater than the tower design and 20 percent greater than the pump ratings. From the pump head pressure and the manufacturer's pump curves, it was calculated that the flow should be about 77,980 L/min (20,600 gal/min). The measured rate was about 10 percent greater than this calculated rate. As scale and fouling increase, and with additional process heat loads, the head pressure will increase slightly and cause a decrease in the flow rate. The conditions as measured (and with all the fans running) represented normal operation. Therefore, no attempt was made to equalize the flow in the risers or to reduce the overall flow to the design rate.

The drift eliminators could be inspected through a porthole in the fan stack below the fan. The drift eliminator in Cell A is assumed to have at least one defect because entrained droplets were observed periodically in the same area of the stack. The other drift eliminators appeared to be in good condition. The water distribution through the fill was even although it did cascade along some vertical beams at a greater rate than along others.

The quantity of blowdown was not easily determined because the conductivity control was not working and the valves in the line were closed. Also, recirculating water can be withdrawn from the system in the process area for general ground cleaning purposes. The operators, however, indicated that they had not been using any of this water on the test days. Finally, a water balance on the process side of the overhead vacuum condensers indicated an excess of about 189 L/min (50 gal/min).

This is approximately the amount that the Nalco representative calculated for the blowdown based on the cycles of concentration and an estimate of the evaporation loss.

The recirculating water temperature was measured with mercury-in-glass thermometers in fittings attached to taps in three of the risers. The basin temperature was determined with a mercury-in-glass thermometer at the intersection of the main basin and the basin extension. The temperatures indicated by gauges on the lines to the pumps were also recorded; they were always 2 degrees lower than the thermometer reading.

Meteorological data were available both at the tower site and from the Exxon meteorological station almost a mile away. The wind direction continued to be steady from the southeast, and the wind speeds were higher on the chart recorder at the tower station. At this site, there were no obstructions around the station except for the tower itself.

The operator log of the chromate concentration in the recirculating water was constant at the upper limit of the control range over the 2-day test period. The concentration agreed with that obtained by the Nalco representative on August 29. The pH, conductivity, and free chlorine residual were also within the control ranges.

C.2 SUMMARY OF TEST DATA

The results of the EPA isokinetic and the absorbent paper emission tests at the Department of Energy, Gaseous Diffusion Plant in Paducah, Kentucky, are summarized in Table C-5. For the tower tested, each riser supplies water to two fan cells. Stack emissions were sampled from fan cell Nos. 7 through 14 (riser cell Nos. 4 through 7). For most tests, half of the sample was collected from each of the fan stacks corresponding to a riser cell. All data for the isokinetic emission tests are reported in Table C-5 as being greater than the value presented because only about one third of the chromium was transferred with the liquid to the vial used for analysis after the concentration of the sample. The balance of the chromium remained in the beaker used to evaporate the water from the sample and required rinsing with aqua regia to solubilize the chromium for analysis. This method of rinsing was not accomplished with the beakers used to concentrate samples collected at the Department of Energy, Gaseous Diffusion Plant in Paducah, Kentucky.

The results of the Method 13 and absorbent paper emission tests at NBS in Gaithersburg, Maryland, are summarized in Table C-6.

The results of the Method 13 and absorbent paper emission tests at Tower 68 at the Exxon refinery in Baytown, Texas, are summarized in Table C-7. Although there are three riser cells and five fan stacks, individual tests were conducted on each fan stack.

The results of the Method 13, absorbent paper, and ion exchange emission tests at Tower 84 at the Exxon refinery in Baytown, Texas, are summarized in Table C-8.

Sensitive paper drift measurements at all four test sites are summarized in Table C-9.

SYSTEM DATA

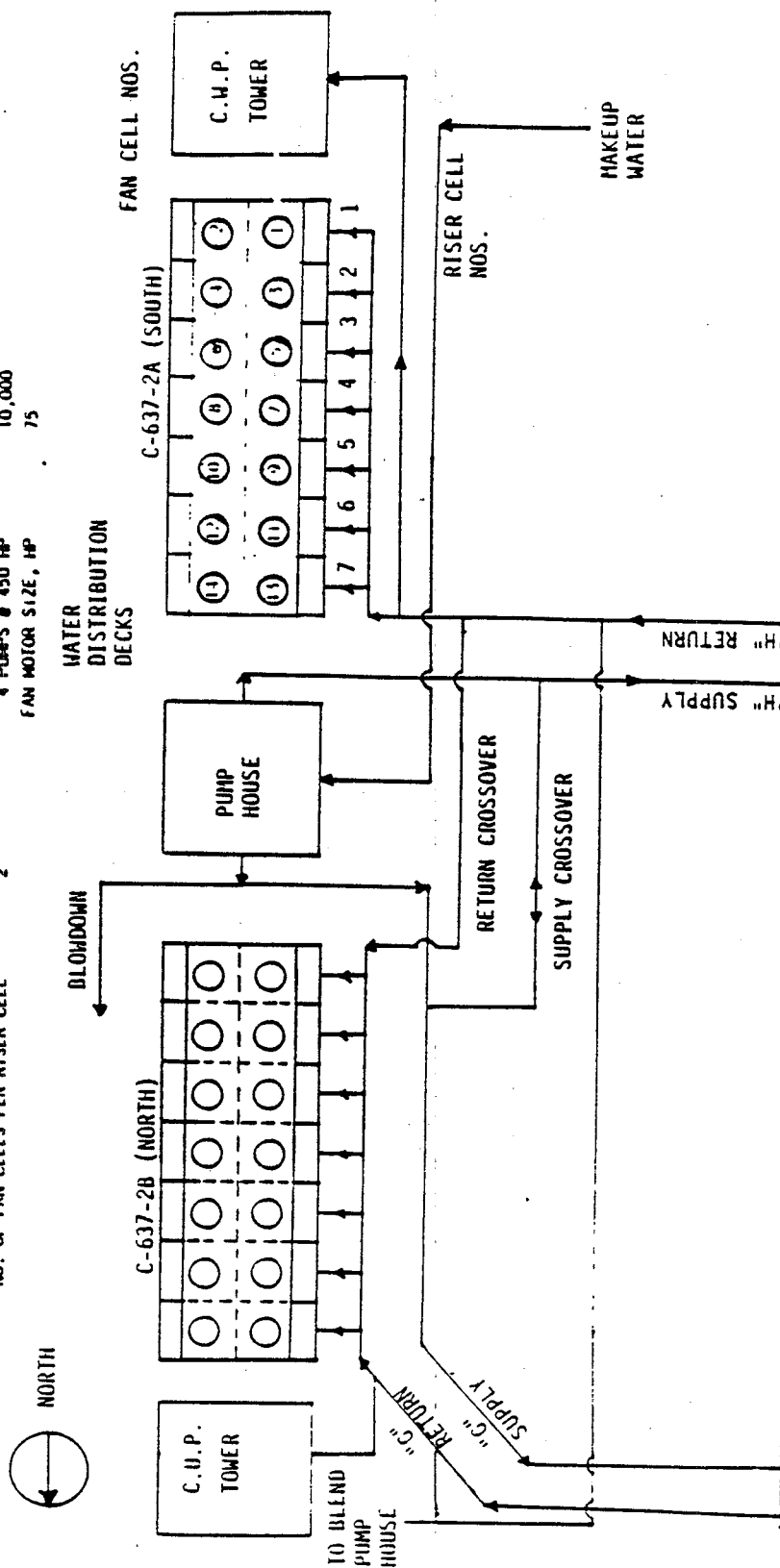
PARAMETER

VALUE

PARAMETER

VALUE

TOWER AGE, YEARS	31	DIAMETER OF FAN STACKS, 11"	22
AIRFLOW CAPACITY OF EACH FAN, FT ³ /MIN	478,000	BASIN CAPACITY--NORTH AND SOUTH, GALLONS EACH	4.2 x 10 ⁶
TOTAL AIRFLOW RATE, FT ³ /MIN	6.69 x 10 ⁶	PUMP SIZE, GAL/MIN	20,000
RECIRCULATING WATER FLOW RATE, GAL/D	101.6 x 10 ⁶	6 PUMPS @ 1,250 HP	10,000
NO. OF RISER CELLS	7	4 PUMPS @ 450 HP	75
NO. OF FAN CELLS PER RISER CELL	2	FAN MOTOR SIZE, HP	



PROCESS BUILDING

Figure C-1. Tower C-637-2A at Department of Energy Gaseous Diffusion Plant.

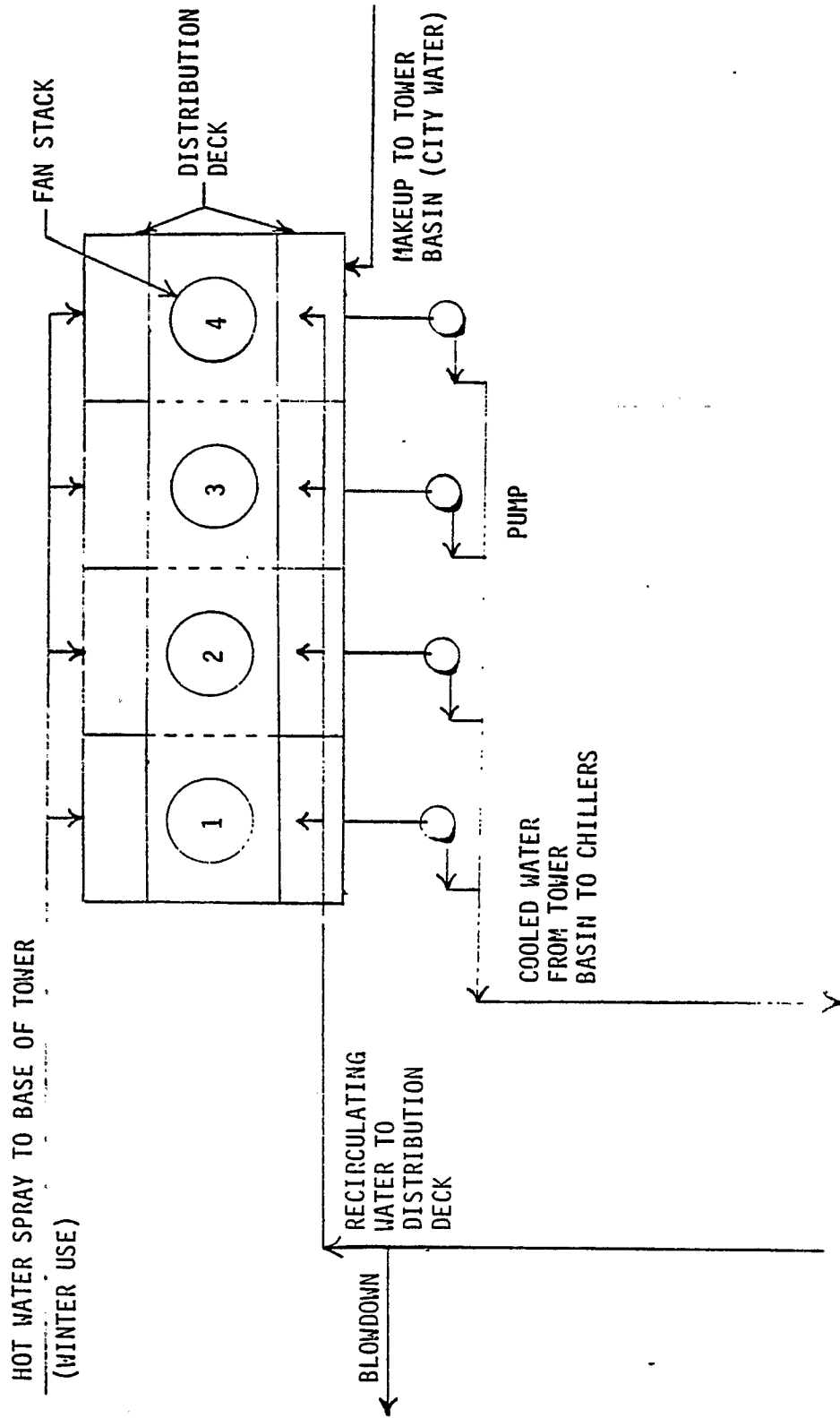


Figure C-2. Cooling tower at NBS facility in Gaithersburg, Maryland.

SYSTEM DATA

<u>PARAMETER</u>	<u>VALUE</u>	<u>PARAMETER</u>	<u>VALUE</u>
TOWER AGE (ORIGINAL SECTION) YEARS	31	NO. OF RISERS	3
NO. OF FAN CELLS	5	RECIRCULATING WATER FLOW RATE, gal/min	7,300
AIRFLOW, dry scfm		RISERS 1 AND 2, EACH	8,800
CELLS 1-4, AVERAGE PER CELL	3.0×10^{-5}	RISER 3 FOR CELL 5	
CELL 5	8.9×10^{-5}		
DIAMETER OF FAN STACKS, ft	18		
CELLS 1-4	24		
CELL 5			

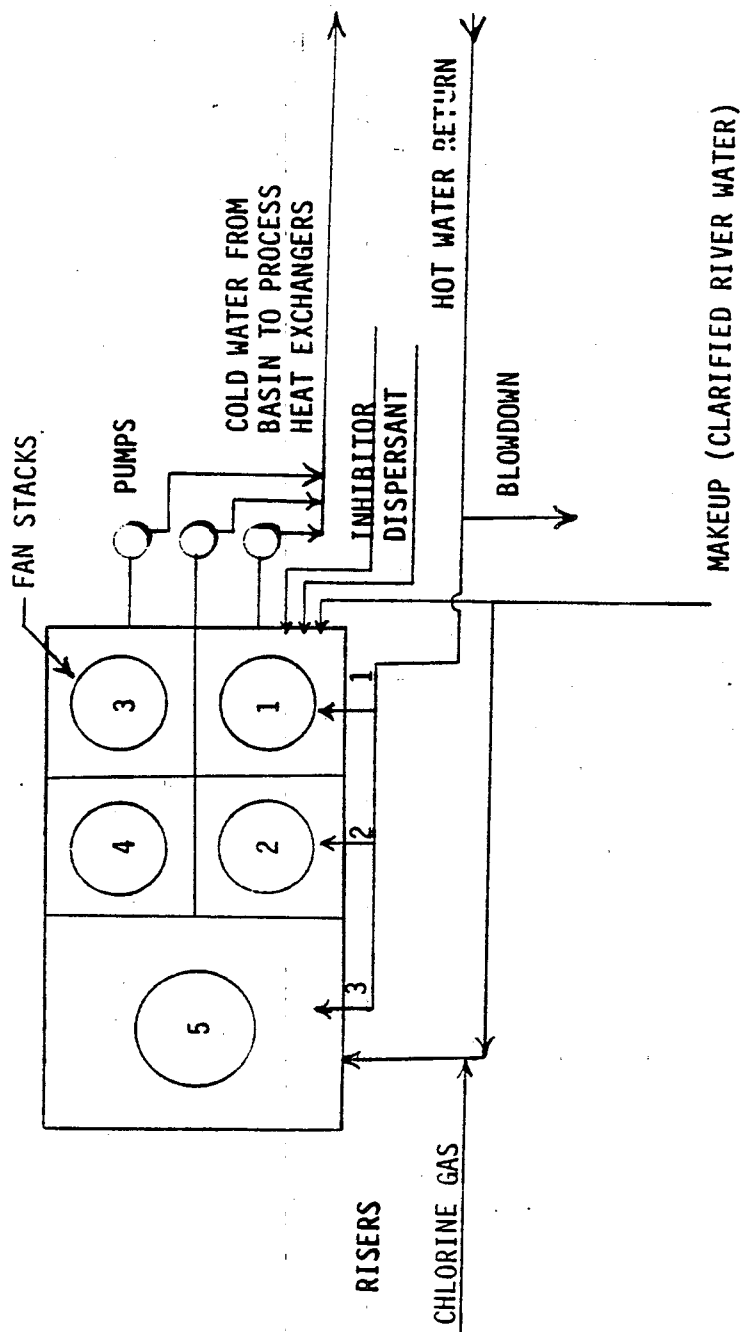
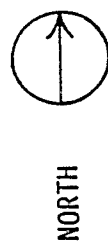


Figure C-3. Tower 68 at Exxon-Baytown refinery.



SYSTEM DATA

PARAMETER	VALUE
TOWER AGE, YEARS	<1
RECIRCULATING WATER FLOW RATE, gal/min	22,700
AVERAGE AIR FLOW RATE PER FAN, dry scfm	550,000
DIAMETER OF FAN STACKS, ft	22
NO. OF RISERS	4
NO. OF FAN CELLS	4

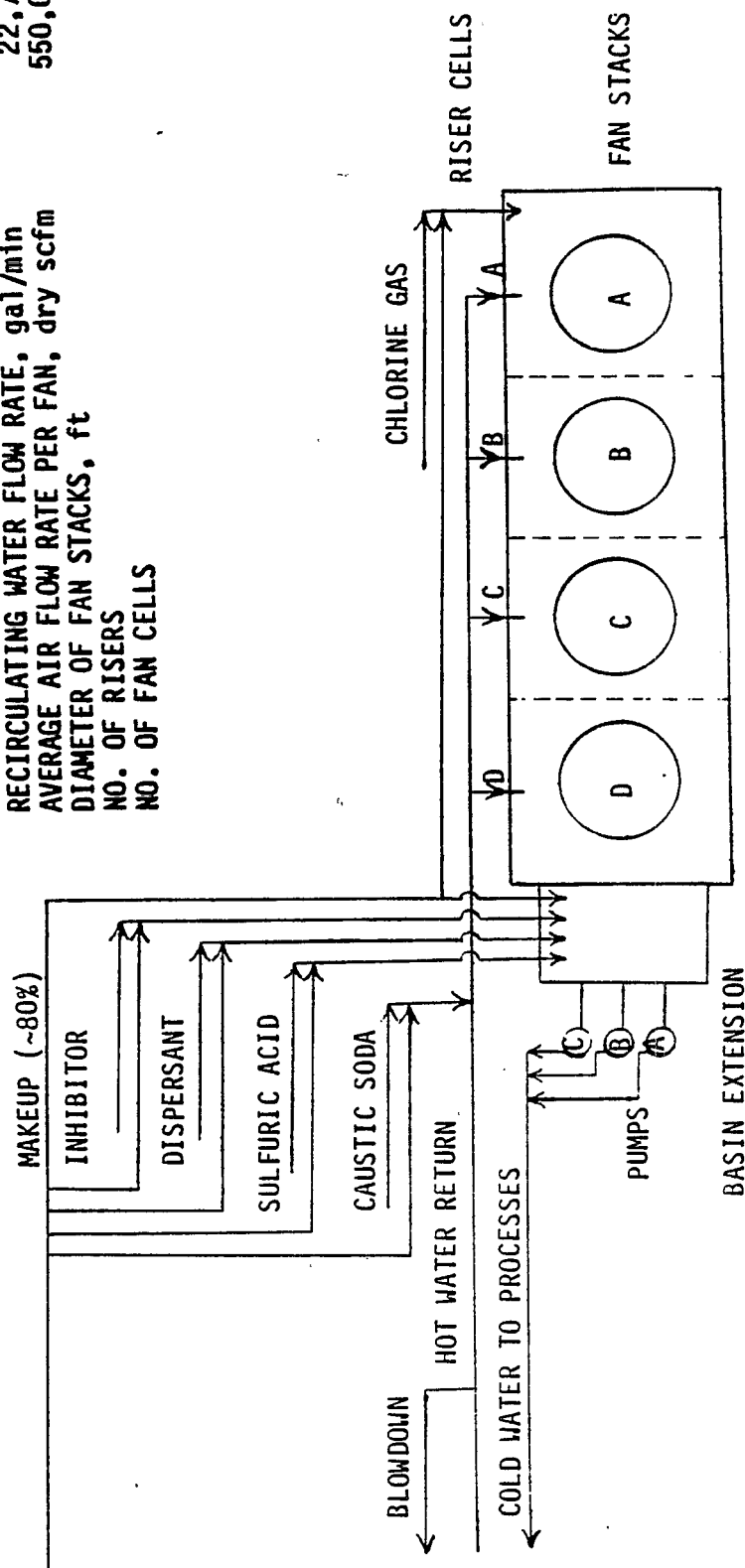


Figure C-4. Tower 84 at Exxon-Baytown refinery.

TABLE C-1. SUMMARY OF OPERATING PARAMETERS AND METEOROLOGICAL DATA DURING TESTS AT
DEPARTMENT OF ENERGY, GASEOUS DIFFUSION PLANT, PADUCAH, KENTUCKY

Parameter	Test series No. 1	Test series No. 2	Test series No. 3	Test series No. 4	Test series No. 5	Test series No. 6	Test series No. 7	Test series No. 8
Date	6/24/86	6/24/86	6/25/86	6/25/86	6/26/86	6/26/86	6/27/86	6/27/86
Run Nos.	4-(8,7)-1 7-(13,14)-1	4-(7,8)-2 7-(14,14)-2	5-(10,9)-3 6-(12,11)-3	5-(9,10)-4 6-(11,12)-4	5-(10,9)-5 6-(12,11)-5	4-(7,8)-6 7-(14,13)-6	7-(14,13)-7	7-(13,14)-8
Recirculating water flow, $\frac{\text{g}}{\text{min}}$ (gal/min)								
"G" Loop	74,337 (19,640)	73,429 ^a (19,400)	70,969 (18,750)	71,991 (19,020)	72,937 (19,270)	72,445 (19,140)	72,937 (19,270)	72,937 (19,270)
"H" Loop	53,860 (13,890)	52,574 (13,890)	53,217 (14,060)	53,861 (14,230)	53,861 (14,230)	53,861 (14,230)	53,861 (14,230)	53,861 (14,230)
Riser 4	30,742 (8,122)	30,741 (8,122)	--	--	--	32,407 (8,562)	--	--
Riser 5	--	31,809 (8,404)	31,048 (8,203)	31,048 (8,203)	31,268 (8,261)	--	--	--
Riser 6	--	33,607 (8,879)	32,665 (8,630)	32,665 (8,630)	32,638 (8,623)	--	--	--
Riser 7	27,419 (7,244)	27,419 (7,244)	--	--	--	31,302 (8,270)	31,529 (8,330)	31,529 (8,330)
Fan amperage, amps								
Cell 7	66-68	66-67	--	--	67-68	67-68	67-68	67-68
Cell 8	63-64	63-64	--	--	64	63-64	64	64-65
Cell 9	67-68	67	66-67	67	68	67-68	68-69	67-68
Cell 10	72-73	72-73	72-73	72-73	72-73	73-74	72-73	72-73
Cell 11	70	70	70-72	70-71	70-71	69-70	70-71	70-71
Cell 12	65-76	66	66	65-66	64-65	66-67	66-67	66-67
Cell 13	74	74	--	--	--	72-74	72-73	72-73
Cell 14	71-72	71-72	--	--	--	71-72	71-73	71-72
Makeup water flow, $\frac{\text{g}}{\text{min}}$								
	9,160 (2,420)	9,160 (2,420)	8,554 (2,260)	9,462 (2,500)	9,084 (2,400)	8,478-9,803 (2,240-2,590)	8,478-9,463 (2,240-2,500)	9,273 (2,450)
Total water pressure, psig								
	76	77-78	77-79	74-77	76	74-76	76	75-76
Water temperature, °C (°F)								
Basin								
• North	33.9-35.0 (93-95)	32.8-33.6 (91-92.5)	33.3-36.4 (92-97.5)	35.0-37.2 (95-99)	35.0-36.1 (95-97)	33.9 (93)	30.6-31.1 (87-88)	31.1 (88)
• South	29.4-30.0 (85-86)	29.4-30.0 (85-86)	30.6-31.7 (87-89)	31.7-32.2 (89-90)	28.3-29.4 (83-85)	31.1-32.2 (88-90)	30.6 (87)	30.6 (87)
"G" return	55.6 (132)	55.6 (132)	55.0-55.6 (131-132)	55.6 (132)	55.0 (131)	55.0 (131)	55.6 (132)	55.6 (132)
"H" return	52.2-52.8 (126-127)	51.7-52.2 (125-126)	51.7 (125)	51.7 (125)	51.1-52.2 (124-126)	51.7 (125)	51.1 (124)	51.1 (124)
Hot well	32.8-33.3 (91-92)	32.8 (91)	32.2-33.3 (90-92)	33.9-34.4 (93-94)	33.3 (92)	32.8-33.6 (91-92.5)	33.1-33.2 (91.5-91.8)	33.3-33.6 (92-92.5)

(cont inued)

TABLE C-1. (continued)

Parameter	Test series No. 1	Test series No. 2	Test series No. 3	Test series No. 4	Test series No. 5	Test series No. 6	Test series No. 7	Test series No. 8
Blowdown rate, g/min (gal/min)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Water chemistry								
Control/feed								
• pH	6.04	6.05	6.0-6.05	6.05-6.08	6.06-6.08	6.06-6.10	6.02-6.11	5.98-6.02
• Chlorine, kg/d (lb/d)	109 (240)	109 (240)	109 (240)	109 (240)	109 (240)	109 (240)	109 (240)	109 (240)
• Orcoel, g/d (gal/d)	17 (4.5)	17 (45)	34 (9.0)	34 (9.0)	0 (0)	0 (0)	34 (9.0)	34 (9.0)
Lab analysis (Daily)								
• pH	6.0	6.0	6.1	6.1	6.2	6.2	6.2	6.2
• Residual Cl_2 , ppm	--	--	0.54	0.54	--	--	0.82	0.82
• Ca hardness, ppm	431	431	422	422	422	422	426	426
• Chromate, CrO_4 , ppm	18.1	18.1	17.9	17.9	18.9	18.9	18.4	18.4
• Total dissolved solids, ppm	--	--	2,149	2,149	--	--	2,199	2,199
Meteorological data								
Wind speed, km/h (mph)	8.0-12.9 (5-8)	4.8-14.5 (3-9)	12.9-14.5 (8-9)	9.7-12.9 (6-8)	9.7-12.9 (6-8)	12.9-19.3 (8-12)	14.5-20.9 (9-13)	19.3-20.9 (12-13)
Wind direction (00-360)	320-060	340-060	060-090	050-090	140-180	160-190	210-230	190-210
Ambient temperature, $^{\circ}\text{C (}^{\circ}\text{F)}$	28.3-30.6 (83-87)	31.1-32.2 (88-90)	25.6-27.2 (78-81)	27.2-28.9 (81-84)	27.8-31.1 (82-88)	32.8-33.3 (91-92)	28.9-31.7 (84-89)	31.7-33.3 (89-92)
Dew point temperature, $^{\circ}\text{C (}^{\circ}\text{F)}$	19.4-21.1 (67-70)	18.3-21.1 (65-70)	13.9-15.0 (57-59)	15.0-15.6 (59-60)	17.8-18.3 (64-65)	21.1-22.8 (70-73)	22.2-22.8 (72-73)	22.2-22.8 (72-73)

"G" and "H" loop waterflows were taken from venturi readings, and the riser waterflows were taken with a pitot tube. In test No. 2, the total flows from the two methods differ by about 2 percent, probably due to the fact that the venturi readings were in the bottom 10 percent of their range.

TABLE C-2. SUMMARY OF OPERATING PARAMETERS AND METEOROLOGICAL DATA DURING TESTS AT
NATIONAL BUREAU OF STANDARDS, GAITHERSBURG, MARYLAND

Parameter	Test series No. 1	Test series No. 2	Test series No. 3	Test series No. 4	Test series No. 5	Test series No. 6	Test series No. 7	Test series No. 8
Date	8-19-86	8-19-86	8-20-86	8-20-86	8-21-86	8-21-86	8-22-86	8-22-86
Run Nos.	A-1	A-2	B-1	B-2	C-1	C-2	D-1	D-2
Recirculating water flow in riser, l/min (gal/min)	136,700 (36,108)	136,700 (36,108)	137,900 (36,428)	137,900 (36,428)	137,700 (36,383)	137,700 (36,383)	135,400 (35,761)	135,400 (35,761)
Fans	All 4 high	All 4 high	All 4 high	All 4 high	3 high, 1 off	3 high, 1 off	All 4 high	All 4 high
Blowdown, l/d (gal/d)	353,500 (93,400)	353,500 (93,400)	190,000 (50,200)	190,000 (50,200)	120,400 (31,800)	120,400 (31,800)	171,100 (45,200)	171,100 (45,200)
Makeup, l/d (gal/d)	1,274,000 (336,600)	1,274,000 (336,600)	963,000 (254,400)	963,000 (254,400)	761,000 (201,000)	761,000 (201,000)	616,000 (162,500)	616,000 (162,500)
Chillers	3 on, 1 off	3 on, 1 off	3 on, 1 off	3 on, 1 off	2 on, 2 off	2 on, 2 off	2 on, 2 off for 1 h 3 on, 1 off for 1 h	3 on, 1 off
Water temperature, °C (°F)								
Entering con- denser, avg.	23.9-25.6 (75-78)	26.1-26.7 (79-80)	25.0-25.6 (77-78)	25.6-26.1 (78-79)	23.9-25.0 (75-77)	25.0-25.6 (77-78)	22.8-23.9 (73-75)	23.9-24.4 (75-76)
Leaving con- denser, avg.	27.2-29.4 (81-85)	29.4-30.0 (85-86)	28.3-28.9 (83-84)	28.9-29.4 (84-85)	26.7-27.8 (80-82)	27.8-28.3 (82-83)	25.0-27.2 (77-81)	27.2-27.8 (81-82)
Water chemistry								
pH	--	--	--	--	--	--	8.5	8.6
Conductivity, umhos	1,700	1,700	1,700	1,700	1,700	1,700	1,750	1,750
Biocide addition, l (gal)	0 (0)	0 (0)	24.6 (6.5)	24.6 (6.5)	0 (0)	0 (0)	0 (0)	0 (0)
Meteorological data								
Wind speed, km/h (mph)	0-8.0 (0-5)	0-9.6 (0-6)	0-22.5 (0-14)	0-17.7 (0-11)	0-8.0 (0-5)	0-8.0 (0-5)	0-17.7 (0-11)	0-8.0 (0-5)
Wind direction (00-360)	0-75	15-90	45-90	90-105	0	0-90	270-360	270-360

TABLE C-3. SUMMARY OF OPERATING PARAMETERS AND METEOROLOGICAL DATA
DURING TESTING OF TOWER 68 AT EXXON REFINERY, BAYTOWN, TEXAS

Parameter	Pretest	Test series No. 1	Test series No. 2
Date	08/31/86	09/01/86	09/02/86
Run Nos.		CT-68-1-1 CT-68-2-1 CT-68-5-1 CT-68-5-2	CT-68-4-1 CT-68-5-3
Recirculating water flow, gal/min (gal/min)			
Riser 1	27,657 (7,307)		
Riser 2	27,479 (7,260)		
Riser 3	33,410 (8,827)		
Fan amperage, amps			
Cell 1		85	84-85
Cell 2		90	89-90
Cell 3		78	77-78
Cell 4		90	90
Cell 5		120	120
Pump outlet pressure, psig			
Pump 3		80	80
Pump 3B		80	80
Hot water line pressure, psig		28	28
Water temperature, °C (°F)			
Basin 1/3		27.8-29.7 (82-85.5)	28.3-29.4 (83-85)
Basin 2/4		29.4 (85)	28.3-29.2 (83-84.5)
Basin 5		28.3-29.7 (83-85.5)	28.3-29.4 (83-85)
Hot water line, °F		37.5-38.9 (99.5-102)	37.8-38.9 (100-102)
Riser 1		37.8-38.9 (100-102)	
Riser 2		≤39.4 (≤103) ^a	
Riser 3		37.8-38.9 (100-102)	38.3-38.9 (101-102)
Makeup water flow, gal/min (gal/min)			~1,230 (~325)
Blowdown, gal/min (gal/min)			~265 (~70)
Water chemistry on-line monitor			
pH		7.87-7.96	7.90-8.04
Conductivity, μmhos		1,029-1,056	1,026-1,038
Operator analysis			
pH		7.7	7.9-8.1
Conductivity, μmhos		1,000-1,057	1,022-1,035
Free chlorine, ppm		0.2	0-0.1
Chromate, ppm		12	13-14

(continued)

TABLE C-3. (continued)

Parameter	Pretest	Test series No. 1	Test series No. 2
Vendor analysis ^b			
pH			7.9
Conductivity, μ mhos			1,020
m-alkalinity, ppm			80
Chromate, ppm			14
Free chlorine, ppm			0
Calcium, ppm			226
Cycles			5.9
Chromate inhibitor feed rate, g/d (gal/d)			15.1 (4.0)
Meteorological data at tower			
Wind speed, km/h (mph)		6.4-40.2 (4-25)	1.6-32.2 (1-20)
Wind direction, 00-360		180-360	Unknown
Ambient temperature, $^{\circ}\text{C}$ ($^{\circ}\text{F}$)		≤ 31.7 (≤ 89) ^c	30.6-32.8 (87-91)
Meteorological data at Exxon station			
Wind speed, km/h (mph)		8.0-19.3 (5-12)	11.3-22.5 (7-14)
Wind direction, 00-360		90-180	90-180
Ambient temperature, $^{\circ}\text{C}$ ($^{\circ}\text{F}$)		25.4-30.2 (77.8-86.4)	28.9-30.0 (84-86)

^aThe minimum temperature for Riser 3 is not known because measurements were not made during the entire test period.

^bVendor analysis only performed on date of second test series.

^cThe minimum ambient temperature during test series No. 1 is not known because measurements were not made during the entire test period.

TABLE C-4. SUMMARY OF OPERATING PARAMETERS AND METEOROLOGICAL DATA
DURING TESTING OF TOWER 84 AT EXXON REFINERY, BAYTOWN, TEXAS

Parameter	Pretest	Test series No. 1	Test series No. 2
Date	09/03/86	09/04/86	09/05/86
Run Nos.		CT-84-A-1 CT-84-A-2 CT-84-C-1 CT-84-C-2	CT-84-B-1 CT-84-B-2 CT-84-D-1 CT-84-D-2
Recirculating water flow, gal/min (gal/min)			
Riser A	20,060 (5,300)		
Riser B	19,680 (5,200)		
Riser C	23,100 (6,100)		
Riser D	23,100 (6,100)		
Fan amperage, amps			
Cell A	60	60	60
Cell B	60	60	60
Cell C	60	60	60
Cell D	63	63	63
Pump outlet pressure, psig			
Pump 84A		80	80
Pump 84B		80	80
Cold water line pressure, psig			
Water temperature, °C (°F)			
Basin		≤29.4 (≤85) ^a	28.9-29.4 (84-85)
Line to pump 84A		27.8-28.3 (82-83)	27.8-28.3 (82-83)
Line to pump 84B		27.8-28.3 (82-83)	27.8-28.3 (82-83)
Riser A		37.5-37.8 (99.5-100)	36.9-37.8 (98.5-100)
Riser C		37.5-37.8 (99.5-100)	36.9-37.8 (98.5-100)
Riser D		37.5-37.8 (99.5-100)	36.9-37.8 (98.5-100)
Makeup flow rate, gal/min (gal/min)			
Blowdown, gal/min (gal/min)			
Water chemistry on-line monitoring			
pH		6.8-7.1	6.8-7.0
Conductivity, μmhos		Unknown	Unknown
Free chlorine, ppm		0.35-0.57	0.15-0.30
Operator analysis			
pH		7.25	7.0
Conductivity, μmhos		1,200	1,100
Makeup conductivity, μmhos		160	150
Chromate, ppm		12.5	12.5

(continued)

TABLE C-4. (continued)

Parameter	Pretest	Test series No. 1	Test series No. 2
Vendor analysis ^b			
pH			6.9
Free chlorine, ppm			0.2
Chromate, ppm			12.5
Conductivity, μ mhos			1,100
Cycles			7.3
Chromate feed rate, ℓ/d (gal/d)			11.4 (3.0)
Meteorological data at tower			
Wind speed, kmh (mph)		4.8-35.4 (3-22)	6.4-29.0 (4-18)
Wind direction, 00-360		270-360	270-360
Ambient temperature, °C (°F)		≤ 33.3 (≤ 92) ^c	28.9-32.8 (84-91)
Meteorological data at Exxon station			
Wind speed, kmh (mph)		8.0-16.1 (5-10)	1.6-8.0 (1-5)
Wind direction, 00-360		90-110	120-180
Ambient temperature, °C (°F)		30.0-30.6 (86-87)	~ 30.0 (~ 86) ^d

^aThe minimum basin temperature is not known because measurements were not made during the entire test period.

^bVendor analysis only performed on date of second test series.

^cThe minimum ambient temperature is not known because measurements were not made during the entire test period.

^dAmbient temperature was only determined midway through the test.

TABLE C-5. SUMMARY OF EMISSION TEST RESULTS--DEPARTMENT OF ENERGY GASEOUS DIFFUSION PLANT, PADUCAH, KENTUCKY

Data/Units	Run No. ^a					
	4-(8,7)-1	4-(7,8)-2	4-(7,8)-6	5-(10,9)-3	5-(10,9)-5	6-(12,11)-3
General						
Date	6/24/86	6/24/86	6/25/86	6/25/86	6/25/86	6/25/86
Start time	09:25	12:58	13:12	09:15	08:25	09:14
Sampling period, min	120	120	120	120	120	120
Isokinetic ratio, Percent	98.5	97.9	97.3	98.5	98.2	95.3
Cell recirculation rate, L/min	15,370	15,370	15,370	15,530	15,530	16,330
(gal/min)	(4,061)	(4,061)	(4,061)	(4,102)	(4,102)	(4,315)
Barometric pressure, in. Hg	29.66	29.66	29.72	29.75	29.72	29.75
Cr ¹⁶ concentration in cooling water, ppm	7.97	7.99	8.62	8.04	8.52	8.09
Gas stream						
Temperature, °C (°F)	38 (100)	40 (104)	41 (106)	41 (105)	39 (102)	34 (93)
Moisture, percent by volume	6.5	7.3	7.8	7.5	6.9	4.2
Flow rate, m ³ /min (acfm)	17,289 (610,553)	17,591 (621,217)	16,359 (577,715)	17,517 (618,599)	17,411 (614,870)	16,140 (569,966)
Flow rate, dsm ³ /min (dscfm)	15,104 (533,384)	15,129 (534,290)	13,976 (493,548)	15,054 (531,616)	15,124 (534,108)	14,863 (524,892)
Cr¹⁶ emissions measured by Method-13 x10⁶c						
Concentration, mg/dsm ³ (gr/dscf)	>385 (>0.168)	>612 (>0.267)	>1,040 (>0.456)	>439 (>0.192)	>268 (>0.117)	>748 (>0.327)
Emissions, kg/h (lb/h)	>344 (>759)	>544 (>1,200)	>853 (>1,880)	>391 (>862)	>239 (>528)	>637 (>1,400)
Total chromium emissions measured by Method-13 x10⁶b						
Concentration, g/dsm ³ (gr/dscf)	>386 (>0.169)	>618 (>0.270)	>1,050 (>0.460)	>478 (>0.209)	>272 (>0.119)	>757 (>0.331)
Emissions, kg/h (lb/h)	>345 (>760)	>549 (>1,210)	>859 (>1,890)	>426 (>939)	>242 (>534)	>644 (>1,420)
Total chromium emissions measured by absorber paper x10⁶b						
Emissions, kg/h (lb/h)	343 (756)	345 (761)	1,140 (2,510)	828 (1,830)	1,058 (2,330)	142 (313)

^aThe run No. identifies the riser cell, fan stack(s) and test series, respectively. Emissions results for these runs were not included in the averages because the recirculating water flow rates were less than 90 percent of the design flow rates. In addition, during run No. 7-(14,13)-1 water was leaking through the side of the distribution deck and running down the fan-side of the drift eliminator. Because of analysis error, a fraction of the Cr¹⁶ was not analyzed in these samples. Therefore, the emissions are presented with "greater than" symbols.

TABLE C-5. (continued)

Data/Units	Run No. ^a					
	6-(2.11)-5	7-(14.13)-1 ^b	7-(14.14)-2 ^b	7-(14.13)-6	7-(14.13)-7	7-(14.13)-8
General						
Date	6/26/86	6/24/86	6/24/86	6/26/86	6/27/86	6/27/86
Start time	08:25	09:24	13:02	13:12	08:23	11:14
Sampling period, min	120	120	120	120	120	60
Isokinetic ratio, percent	101.3	95.7	96.6	102.5	95.4	96.1
Cell recirculation rate, l/min (gal/min)	16,330 (4,315)	13,710 (3,622)	13,710 (3,622)	15,760 (4,164)	15,760 (4,164)	15,760 (4,164)
Barometric pressure, in. Hg	29.72	29.66	29.66	29.72	29.72	29.72
Cr ⁶ concentration in cooling water, ppm	8.52	7.99	7.99	8.50	8.32	8.32
Gas stream						
Temperature, °C (°F)	34 (93)	32 (89)	35 (95)	34 (94)	38 (101)	36 (96)
Moisture, percent by volume	5.3	4.6	5.6	5.4	6.7	5.8
Flow rate, m ³ /min (acfm)	15,477 (546,571)	17,463 (616,712)	15,191 (536,468)	14,779 (521,901)	14,580 (590,275)	14,402 (589,771)
Flow rate, dsm ³ /min (dscfm)	13,903 (490,960)	15,885 (560,981)	13,520 (477,453)	13,234 (467,373)	12,954 (498,942)	13,320 (508,593)
Cr ⁶ emissions measured by Method-13 x10 ^{6c}						
Concentration, mg/dsm ³ (gr/dscf)	>332 (>0.145)	>2,656 (>1.161)	>229 (>0.100)	>452 (>0.198)	>406 (>0.178)	>469 (>0.205)
Emissions, kg/h (lb/h)	>281 (>620)	>2,427 (>5,351)	>180 (>397)	>369 (>813)	>340 (>750)	>329 (>726)
Total chromium emissions measured by Method-13 x10 ⁶						
Concentration, g/dsm ³ (gr/dscf)	>335 (>0.146)	>2,668 (>1.166)	>230 (>0.101)	>455 (>0.199)	>409 (>0.179)	>471 (>0.206)
Emissions, kg/h (lb/h)	>283 (>624)	>2,438 (>5,375)	>181 (>399)	>371 (>818)	>342 (>755)	>331 (>730)
Total chromium emissions measured by absorbent paper x10 ⁶						
Emissions, kg/h (lb/h)	510 (1,124)	132 (291)	51 (112)	111 (245)	93 (205)	157 (346)
						75 (165)

TABLE C-7. SUMMARY OF EMISSION TEST RESULTS FOR TOWER 68 AT EXXON REFINERY, BAYTOWN, TEXAS

Data/Units	Run No. ^a						
	CT-68-1-1	CT-68-2-1	CT-68-3-1	CT-68-4-1	CT-68-5-1	CT-68-5-2	CT-68-5-3
General							
Date	9/1/86	9/1/86	9/2/86	9/2/86	9/1/86	9/1/86	9/2/86
Start time	14:17	14:17	09:33	12:29	10:50	14:00	10:33
Sampling period, min	120	120	120	120	120	120	120
Isokinetic ratio, percent	104.0	99.7	104.9	103.6	102.9	102	102.8
Cell recirculation rate, l/min (gal/min)	15,870 (4,193)	13,290 (3,511)	13,290 (3,511)	15,870 (4,193)	27,090 (7,157)	27,090 (7,157)	27,090 (7,157)
Barometric pressure, in. Hg	30.25	30.25	30.2	30.20	30.25	30.25	30.20
Cr ⁺⁶ concentration in cooling water, ppm	7.64	7.58	7.45	7.33	7.44	7.82	7.65
Gas stream							
Temperature, °C (°F)	28.9 (84.1)	30.8 (87.5)	33.2 (91.8)	31.7 (89.0)	30 (86)	31.7 (89.1)	30.7 (87.3)
Moisture, percent by volume	3.90	4.34	4.98	4.57	4.14	4.57	4.32
Flow rate, m ³ /min (acfm)	9,604 (339,149)	8,463 (298,864)	9,307 (328,656)	9,038 (319,185)	26,143 (923,231)	27,880 (984,581)	27,557 (962,591)
Flow rate, dsm ³ /min (dscfm)	9,055 (319,790)	7,894 (278,777)	8,541 (301,626)	8,372 (295,673)	24,505 (865,368)	25,868 (913,507)	25,396 (896,828)
Cr ⁺⁶ emissions measured by Method-13 x10 ⁶							
Concentration, mg/dsm ³ (gr/dscf)	44,356 (19,380)	8,713 (3,807)	983 (0.4293)	528 (0.2305)	38,691 (16,9051)	3,542 (1,5476)	1,628 (0.7111)
Emissions, kg/h (lb/h)	25,057 (55,192)	4,115 (9,063)	528 (1,163)	275 (605)	58,562 (128,991)	5,606 (12,348)	2,548 (5,613)
Total chromium emissions measured by Method-13 x10 ⁶							
Concentration, g/dsm ³ (gr/dscf)	44,486 (19,437)	8,713 (3,807)	991 (0.433)	528 (0.231)	38,691 (16,905)	3,308 (1,445)	1,628 (0.711)
Emissions, kg/h (lb/h)	25,131 (55,355)	4,115 (9,063)	533 (1,174)	275 (605)	58,562 (128,991)	5,235 (11,531)	2,548 (5,613)
Total chromium emissions measured by absorbent paper x10 ⁶							
Emissions, kg/h (lb/h)	149.4 (329)	79.8 (176)	136.8 (302)	144.9 (319)	175.1 (386)	145.6 (321)	-- (--)

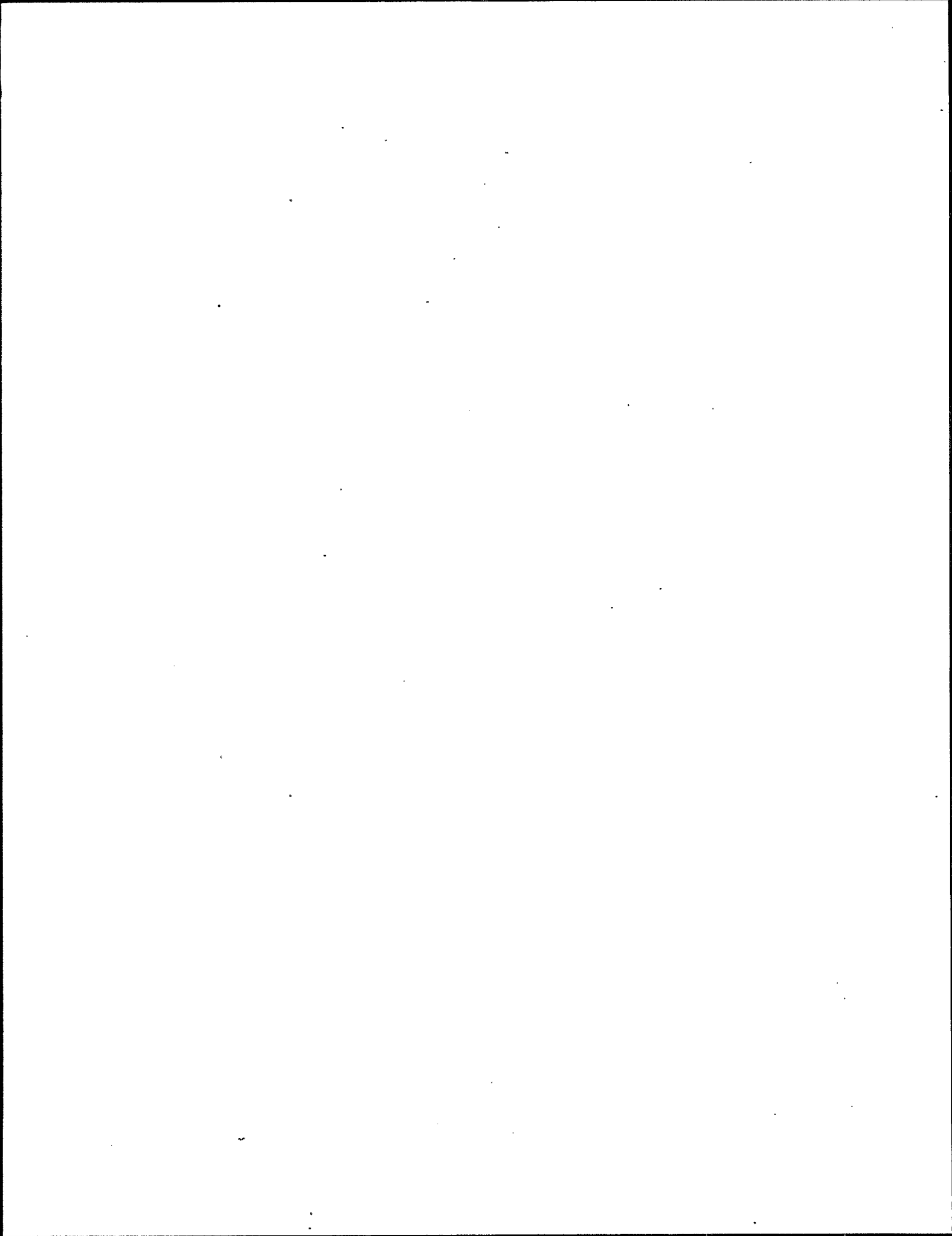
^aThe run No. identifies the cooling tower, cell number, and test series, respectively.

TABLE C-8. SUMMARY OF EMISSION TEST RESULTS FOR TOWER 84 AT EXXON REFINERY, BAYTOWN, TEXAS

Data/Units	Run No. ^a									
	CT-84-A-1	CT-84-A-2	CT-84-B-1	CT-84-B-2	CT-84-C-1	CT-84-C-2	CT-84-D-1	CT-84-D-2		
Gener										
Date	9/4/86	9/4/86	9/5/86	9/5/86	9/4/86	9/4/86	9/5/86	9/5/86	9/5/86	9/5/86
Start time	9:50	12:30	08:50	11:30	09:53	12:24	08:35	11:04	11:04	11:04
Sampling period, min	120	120	120	120	120	120	120	120	120	120
Isokinetic ratio, percent	109.5	111.5	105.9	107.7	106.1	106.8	102.5	104.0	104.0	104.0
Cell recirculation rate, l/min (gal/min)	19,100 (5,046)	19,100 (5,046)	20,140 (5,320)	20,140 (5,320)	22,910 (6,054)	22,910 (6,054)	23,000 (6,079)	23,000 (6,079)	23,000 (6,079)	23,000 (6,079)
Barometric pressure, in. Hg	30.35	30.35	30.25	30.25	30.35	30.35	30.25	30.25	30.25	30.25
Cr ⁺⁶ concentration in cooling water, ppm	8.19	8.33	8.33	8.68	8.17	8.47	8.05	8.71	8.71	8.71
Gas stream										
Temperature, °C (°F)	33.1 (91.5)	31.0 (87.9)	32.6 (90.6)	32.6 (90.8)	34.1 (93.4)	33.5 (92.4)	32.4 (90.3)	33.7 (92.7)	33.7 (92.7)	33.7 (92.7)
Moisture, percent by volume	4.92	4.38	4.79	4.81	5.21	5.04	4.75	5.11	5.11	5.11
Flow rate, m ³ /min (acfm)	17,305 (611,105)	17,659 (620,455)	18,070 (638,138)	18,720 (661,075)	16,598 (585,805)	16,567 (585,069)	15,859 (560,063)	14,470 (511,002)	14,470 (511,002)	14,470 (511,002)
Flow rate, dsm ³ /min (dscfm)	15,978 (564,258)	16,423 (579,964)	16,679 (589,016)	17,271 (609,927)	15,254 (538,701)	15,290 (539,977)	14,689 (518,718)	13,295 (469,513)	13,295 (469,513)	13,295 (469,513)
Cr ⁺⁶ emissions measured by Method-13 x10 ⁶										
Concentration, mg/dsm ³ (gr/dscf)	4,042 (1,7660)	389 (0,1700)	650 (0,2841)	205 (0,0896)	8,665 (3,787)	373 (0,163)	232 (0,1014)	11,927 (5,2115)	11,927 (5,2115)	11,927 (5,2115)
Emissions, kg/h (lb/h)	4,244 (9,348)	427 (941)	689 (1,519)	229 (504)	8,418 (18,558)	365 (804)	210 (462)	9,898 (21,801)	9,898 (21,801)	9,898 (21,801)
Total chromium emissions measured by Method-13 x10 ⁶										
Concentration, g/dsm ³ (gr/dscf)	4,065 (1,776)	402 (0,175)	652 (0,285)	206 (0,090)	8,993 (3,930)	375 (0,164)	234 (0,102)	11,957 (5,224)	11,957 (5,224)	11,957 (5,224)
Emissions, kg/h (lb/h)	4,269 (9,402)	441 (972)	691 (1,522)	230 (506)	8,737 (19,262)	368 (811)	211 (466)	9,923 (21,856)	9,923 (21,856)	9,923 (21,856)
Total chromium emissions measured by absorbent paper x10 ⁶										
Emissions, kg/h (lb/h)	68.7 (151)	-- (--)	126.6 (279)	-- (--)	50.6 (112)	-- (--)	46.8 (103)	-- (--)	-- (--)	-- (--)
Total chromium emissions measured by ion exchange paper x10 ⁶										
Emissions, kg/h (lb/h)	-- (--)	-- (--)	-- (--)	132.9 (293)	-- (--)	48.8 (107)	-- (--)	53.1 (117)	53.1 (117)	53.1 (117)

TABLE C-9. SUMMARY OF SENSITIVE PAPER DRIFT MEASUREMENTS

Site/location	Cell	Sensitive paper drift rate percent of recirculation
Department of Energy, Paducah, Ky.	4	0.0083
	5	0.0093
	6	0.0009
	7	0.0003
National Bureau of Standards, Gaithersburg, Md.	A	0.0002
	B	0.0004
	C	0.0001
	D	0.0001
Exxon Refinery, Baytown, Tex. (Tower 68)	1	0.0047
	2	0.0103
	3	0.0072
	4	0.0040
	5	0.0045
Exxon Refinery, Baytown, Tex. (Tower 84)	A	0.0009
	B	0.0006
	C	0.0005
	D	0.0008



APPENDIX D.

D.1 CHROMIUM DISCHARGE REGULATIONS

Most States have wastewater discharge regulations that limit the amount of chromium that may be discharged into publicly owned treatment works or to surface waters from any type of source.¹ Although some of these State regulations are fairly stringent, none prohibit the discharge of chromium-laden wastewater. No State regulations directly affect air emissions of chromium from cooling towers although there are States that have ambient air quality standards for chromium (e.g., Maine) or hazardous air pollutant regulations for some chromium compounds (e.g., Connecticut).^{2,3}

At the present time, no information has been found on chromium environmental regulations in countries other than the U.S.

D.2 REFERENCES FOR APPENDIX D

1. Memorandum from M. Upchurch, MRI, to Comfort Cooling Tower Project Files. August 4, 1986. State water effluent regulations for chromium discharge.
2. State Air Laws. Environment Reporter. Bureau of National Affairs, Inc., Washington, D.C. Volume 2. p. 396:0105. January 9, 1987.
3. State Air Laws. Environment Reporter. Bureau of National Affairs, Inc., Washington, D.C. Volume 1. pp. 331:0534-0538. October 24, 1986.

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APPENDIX E.

The following data were used to estimate the total annual market value of corrosion inhibitor chemicals sold for use in CCT's. Annual weighted average chromate costs for one tower are estimated as follows:

Chromates

Building size, m	No. of CCT's, thousands ^a	Percent of total CCT's	Annual chromate costs ^b	Weighted average cost
673	18.55	7.4	17	1
1,460	83.50	33.3	36	12
3,405	51.20	20.4	85	17
6,224	42.00	16.8	155	26
12,338	31.50	12.6	306	38
37,626	23.75	9.5	935	89
	<u>250.5</u>			<u>183</u>

TOTAL = \$183

Annual weighted average nonchromate costs for one tower are estimated as follows:

Nonchromates

Building size, m	No. of CCT's, thousands ^a	Percent of total CCT's	Annual phosphate costs ^b	Weighted average cost
673	18.55	7.4	33	2
1,460	83.50	33.3	72	24
3,405	51.20	20.4	169	35
6,224	42.00	16.8	309	52
12,338	31.50	12.6	613	77
37,626	23.75	9.5	1,869	177
	<u>250.5</u>			<u>367</u>

TOTAL = \$367

^aTable 4-4.

^bTable 7-1.

The total market value of chromate and nonchromate corrosion inhibitors used annually in CCT's is estimated by solving the following equation:

$$TV = 37,580 (\$183) + 213,020 (\$367) = \$85.1 \text{ million}$$

where:

TV = Total annual value of chromate and nonchromate corrosion inhibitors used in comfort cooling systems

37,580 = Estimated number of chromate-based comfort cooling towers

213,020 = Estimated number of nonchromate-based comfort cooling towers

\$183 = Average annual cost of using chromates per comfort cooling tower

\$367 = Average annual cost of using nonchromates per comfort cooling tower.

Note that the above costs represent only the cost to purchase the corrosion inhibitor chemicals themselves and do not include the cost of technical services that may be required of specialty chemical companies. However, the costs of such technical services are not expected to increase significantly as substitutes for chromates are used.

APPENDIX F.
SAMPLE CALCULATIONS OF FLOW RATES, TOWER PARAMETERS, AND
HEXAVALENT CHROMIUM (Cr^{+6}) EMISSION RATES

The calculations presented in this Appendix correspond with the discussion in Chapter 4. Equations presented in Chapter 4 are not repeated in this Appendix. Calculations of flow rates and tower parameters are presented for model tower No. 1 and calculations of Cr^{+6} emission rates are presented for Alabama. English units were used in the calculations in Chapter 4 and the results were converted to metric units. The results shown in Chapter 4 also are shown in this Appendix for consistency. However, the calculations in this Appendix may yield slightly different results than those shown because rounded results from previous equations and the results converted to metric units in Chapter 4 are used in the calculations.

F.1 COOLING TOWER CAPACITY

The size of model building No. 1 is 673 m^2 and the cooling requirement is 142 W/m^2 . Thus, the cooling tower capacity must be at least,

$$(673 \text{ m}^2)(142 \text{ W/m}^2) = 95,400 \text{ W} = 95,400 \text{ J/s}$$

F.2 RECIRCULATION RATE

$$\begin{aligned}\text{Recirculation rate} &= \frac{(95,400 \text{ J/s})(60 \text{ s/min})}{(4.18 \text{ J/g/}^\circ\text{C})(5.6^\circ\text{C})(1,000 \text{ g/l})} \\ &= 246 \text{ l/min}\end{aligned}$$

F.3 EVAPORATION RATE

$$\begin{aligned}\text{Evaporation rate} &= (0.00085/^\circ\text{F})(246 \text{ l/min})(5.5^\circ\text{C})(1.8^\circ\text{F/}^\circ\text{C}) \\ &= 2.08 \text{ l/min}\end{aligned}$$

F.4 BLOWDOWN RATE

$$\text{Blowdown rate} = \frac{2.08 \text{ g/min}}{(5-1)}$$

$$= 0.53 \text{ g/min}$$

F.5 AIRFLOW RATE

The airflow mass rate, G, is 1.5 times the water recirculating rate. The density of saturated air at 26.7°C (80°F) is 1,162 g/m³.

$$\text{Airflow rate} = \left(\frac{246 \text{ g}}{\text{min}}\right)\left(\frac{1,000 \text{ g}}{\text{g}}\right)\left(\frac{1 \text{ m}^3}{1,163 \text{ g}}\right)\left(\frac{1}{1.5}\right)$$

$$= 141 \text{ m}^3/\text{min}$$

F.6 STACK DIAMETER

Typical stack airflow velocity, V, is 520 m/min and area of the stack is given by $A = \pi d^2/4 = G/V$.

$$\text{Stack diameter} = \left[\frac{(4)(141 \text{ m}^3/\text{min})(\text{min}/520 \text{ m})}{\pi}\right]^{1/2}$$

$$= 0.59 \text{ m} = 1.9 \text{ ft}$$

Because equipment specifications are typically in English units, the size of the stack was rounded up to 2.0 ft (0.6 m).

F.7 RECALCULATED EXIT AIR VELOCITY

$$V = \frac{G}{A} = \frac{(141 \text{ m}^3/\text{min})(\text{min}/60 \text{ s})}{(\pi)(0.6 \text{ m})^2/4}$$

$$= 8.2 \text{ m/s}$$

F.8 DISTRIBUTION OF CHROMIUM-USING CCT'S

The ratio of the population of Alabama to that of the United States is used to represent the percentage of all towers nationwide that are located in Alabama.

$$\begin{aligned} \text{Percentage of all towers that are located in Alabama} &= \frac{3,893,046}{226,147,597} \times 100 \\ &= 1.72 \text{ percent} \end{aligned}$$

The total number of model tower No. 1's nationwide is 2,780. Thus, the number of model tower No. 1's in Alabama is,

$$\left(\frac{0.0172 \text{ tower in Alabama}}{\text{tower nationwide}} \right) (2,780 \text{ towers nationwide})$$

$$= 48 \text{ towers in Alabama}$$

F.9 HEXAVALENT CHROMIUM EMISSIONS RATE

The hourly Cr^{+6} emission rates are based on the lowest and highest emission factors obtained from EPA-sponsored emissions tests of industrial towers using low-efficiency drift eliminators. The lowest value was obtained at DOE-Paducah and the highest value was obtained at Exxon-Baytown.

$$\begin{aligned} \text{Lower-bound } \text{Cr}^{+6} \text{ emission rate} &= \left[\frac{0.000066 \text{ mg } \text{Cr}^{+6}}{(\text{ppm } \text{Cr}^{+6} \text{ recirculating})(\text{g } \text{H}_2\text{O recirculating})} \right] \times \\ &\quad \left[\frac{246 \text{ g } \text{H}_2\text{O}}{\text{min}} \right] \left[\frac{4.48 \text{ ppm } \text{Cr}^{+6}}{\text{recirculating}} \right] [60 \text{ min/h}] \\ &= 4.4 \text{ mg } \text{Cr}^{+6}/\text{h} \end{aligned}$$

$$\begin{aligned} \text{Upper-bound } \text{Cr}^{+6} \text{ emission rate} &= \left[\frac{0.001874 \text{ mg } \text{Cr}^{+6}}{(\text{ppm } \text{Cr}^{+6} \text{ recirculating})(\text{g } \text{H}_2\text{O recirculating})} \right] \times \\ &\quad \left[\frac{246 \text{ g } \text{H}_2\text{O}}{\text{min}} \right] \left[\frac{4.48 \text{ ppm } \text{Cr}^{+6}}{\text{recirculating}} \right] [60 \text{ min/h}] \\ &= 124 \text{ mg } \text{Cr}^{+6}/\text{h} \end{aligned}$$

Estimates of Cr^{+6} emissions from model tower No. 1 in Alabama are based on the tower utilization factor for the State. In Alabama, it is estimated that CCT's are operated 59 percent of the time.

$$\begin{aligned}\text{Lower-bound Cr}^{+6} \text{ emission rate} &= [4.4 \text{ mg Cr}^{+6}/\text{h}][8,760 \text{ h/yr}][0.59][\text{kg}/1,000,000 \text{ mg}] \\ &= 0.0226 \text{ kg Cr}^{+6}/\text{yr}\end{aligned}$$

$$\begin{aligned}\text{Upper-bound Cr}^{+6} \text{ emission rate} &= [124 \text{ mg Cr}^{+6}/\text{h}][8,760 \text{ h/yr}][0.59][\text{kg}/1,000,000 \text{ mg}] \\ &= 0.6420 \text{ kg Cr}^{+6}/\text{yr}\end{aligned}$$

Estimates of the total Cr^{+6} emissions from all model tower No. 1's in Alabama is based on the emission per tower and the number of towers in the State.

$$\begin{aligned}\text{Lower-bound Cr}^{+6} \text{ emission rate} &= [0.0226 \text{ kg Cr}^{+6}/\text{yr}/\text{tower No. 1}][48 \text{ tower No. 1's}] \\ &= 1.08 \text{ kg Cr}^{+6}/\text{yr}\end{aligned}$$

$$\begin{aligned}\text{Upper-bound Cr}^{+6} \text{ emission rate} &= [0.6420 \text{ kg Cr}^{+6}/\text{yr}/\text{tower No. 1}][48 \text{ tower No. 1's}] \\ &= 30.8 \text{ kg Cr}^{+6}/\text{yr}\end{aligned}$$

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(Please read Instructions on the reverse before completing)

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