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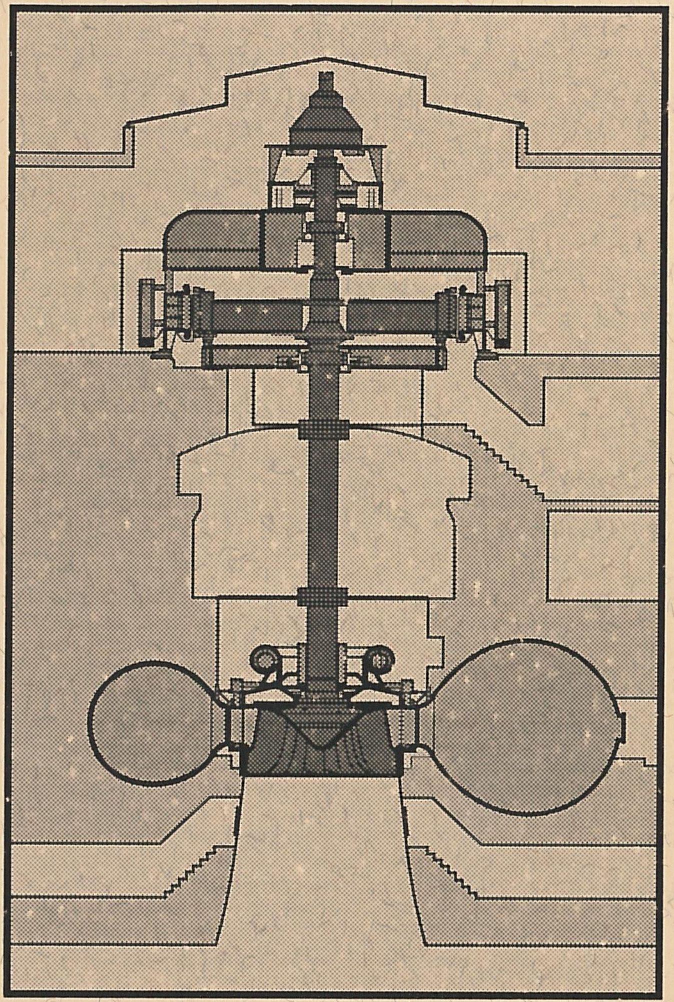

Ozone Abatement in Air-Cooled Hydroelectric Generators

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF RECLAMATION

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The Bureau of Reclamation prepared this monograph to provide comprehensive and practical procedures for measuring hydrogenerator stator housing ozone concentrations and generation rates, analyzing test results, evaluating abatement options, and selecting and designing an ozone abatement system. This document is intended for experienced engineers without ozone-specific expertise.

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by
Rod Rodriguez and Lori Rux

Technical Service Center
Denver, Colorado 80225

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

U.S. Department of the Interior
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CONTENTS

Page

Introduction . . . 1
  Purpose . . . 1
  Background . . . 1
Inspection and Testing . . . 2
  Inspection, testing, and personnel requirements . . . 2
  Instruments and materials needed to conduct tests . . . 3
  Preliminary test procedures . . . 4
  Guidelines for preparing inspection and test procedures . . . 7
  Instructions for conducting inspections and tests . . . 7
  Analysis of test results . . . 8
Abatement . . . 10
  Design alternatives . . . 10
  Design considerations . . . 12
  Maintenance . . . 18
Bibliography . . . 19

APPENDIXES

Appendix

A Inspection report . . . 21
B Ozone measurement report . . . 25
C Example 1 - Analysis of ozone measurements . . . 29
D Example 2 - Carbon filter sizing . . . 37

FIGURES

Figure

1 Photograph of stator housing ozone measurements taken and recorded with an ozone analyzer and strip chart recorder . . . 5
2 Photograph of stator housing ozone measurement taken with sampling pump and glass detector tube . . . 5
3 Photograph of an 8,000-ft^3/min ozone filtration system using standard activated carbon filter trays . . . 13
4 Ozone decay inside generator stator housing following unit shutdown . . . 32
5 Natural logarithm of ozone decay inside generator stator housing following unit shutdown . . . 32
6 Ozone accumulation inside generator stator housing following unit startup . . . 33
7 Ozone generation rate inside generator stator housing following unit startup . . . 33

INTRODUCTION

Purpose

This monograph provides comprehensive and practical procedures for measuring hydrogenerator stator housing ozone concentrations and generation rates, analyzing test results, evaluating abatement options, and selecting and designing an ozone abatement system. This document is intended for experienced engineers without ozone-specific expertise.

Background

The presence of ozone in an air-cooled hydrogenerator stator housing is usually an indication that high intensity electrical discharges (or partial discharges) are occurring in the machine. Discharges between the surfaces of the slot portion of the generator stator winding and the grounded stator core are referred to as slot discharges. Discharges that occur at either boundary of the voltage stress grading coating in the end turn area of the stator winding are often called grading coating discharges. Electrical activity can also occur in the end winding region where high potential differences exist, such as between adjacent line- and neutral-end coils or line-end coils of different phases. These discharges are known as end winding discharges.

Slot discharges result from defective or deteriorated semiconductive slot treatment or because the stator coils are loose in their slots. Grading coating discharges normally result from deficiencies in the voltage stress grading system. If the resistivity of the voltage grading treatment is too high, discharges occur at the interface between the grading coating and the semiconductive slot paint. If the resistivity is too low, discharges occur at the upper boundary of the stress grading treatment, i.e., away from the stator core. End winding discharges are a function of winding design, geometry and spacing between coils, the type of surface treatment, and end winding cleanliness. All three types of electrical discharges can cause air to ionize, producing ozone and other damaging byproducts. (Stator windings can also experience internal discharges due to voids in the groundwall insulation. These discharges are not likely to cause elevated ozone levels.)

In addition to the risk of a stator winding insulation failure resulting from intense electrical discharges, damage to the ferrous and rubber materials which are exposed to ozone can also be extremely serious. The following components are particularly susceptible to ozone: the iron stator core; brake ring; rotor shaft, hub, and rim laminations; air cooler fins and gaskets; unpainted water piping; and other exposed surfaces. Furthermore, normal leakage of stator housing air into the powerplant can result in increased background ozone levels in the plant work areas, prompting concern for worker health and safety.

Occupational Safety and Health Administration (OSHA) regulations limit a worker's exposure to ozone to 0.1 part per million (ppm) averaged over an 8-hour period. Fifteen-minute exposures of 0.3 ppm are allowed up to four times per day, with at least 60 minutes between successive exposures, subject to the 8-hour time-weighted exposure limit. At levels above 0.3 ppm, respirators or self-contained breathing apparatus are required.

Generators experiencing intense electrical discharges are capable of producing ozone well above the OSHA limits. An ozone accumulation above 1 ppm is considered high for an air-cooled hydrogenerator (Culbert, 1991). A properly sized ozone abatement system will lower the steady-state ozone levels inside and outside the stator housing and may extend the life of vulnerable machine components. It should be noted, however, that the localized effects of the electrical discharges, and subsequent ozone and acids, will continue to degrade the stator winding insulation and the iron core, particularly in the slots and air ducts. Severe damage to the core iron and laminar insulation could lead to hot spots in the iron and subsequently a failure of either the stator winding or core. Therefore, machines with elevated ozone levels should be thoroughly evaluated to pinpoint the cause of the electrical discharges and to determine appropriate remedial actions.

INSPECTION AND TESTING

Inspection, Testing, and Personnel Requirements

Increased ozone in a hydrogenerator is usually a symptom of electrical discharge activity resulting from deterioration of the stator winding insulation. If the ozone level increases persistently, then the electrical discharge activity is probably intensifying because of further insulation deterioration. Physical inspection of the stator winding, core, and other machine components is a valuable means for identifying the location and root cause of the electrical discharges as well as for assessing damage and possible corrective actions. Best results will be achieved when the inspection is performed by a person knowledgeable in machine design and construction; stator winding insulation systems, materials, and failure modes; and machine diagnostic tests, inspection techniques, and repair procedures. A valuable tool for the inspector is a record of previous visual inspections and electrical tests. This information will guide the inspector to areas already known to be problematic. A comprehensive report on the inspection should always be made and archived. Color photographs, video recordings, sketches, and material samples, in addition to written descriptions, will become a very helpful reference during the next inspection, which will probably occur several years down the line (Kerszenbaum, 1996). A sample inspection form is given in appendix A.

The ozone in a hydrogenerator can be described by the following mass balance relationship (Bureau of Reclamation, 1977):

Rate of generation	=	Rate of accumulation	+	Removal by decay	+	Removal by leakage	+	Removal by ventilation/treatment

The amount of ozone produced is primarily a function of the stator winding condition, temperature, and operating voltage, and of the humidity in the stator housing (Franklin et al., 1995). By adding an ozone abatement system or by increasing the size of an existing system, the amount of ozone that accumulates, decays, and leaks out of the stator housing can be reduced.

Typical ozone readings taken from inside a generator stator housing measure only the accumulated ozone. Sizing an abatement system using the accumulated value would not minimize the adverse effects of ozone because ozone accumulation measurements neither account for the ozone that contacts and reacts with the surfaces inside the machine (decays) nor for the ozone that escapes (leaks) out of the stator housing into the workplace. Hence, a series of tests is needed to determine the total amount of ozone produced and the constituent components of the total. Using this information, an abatement system can be designed that will reduce the ozone concentration to the desired level.

The following parameters must be determined to properly size an ozone abatement system:

1. Ozone generation rate
2. Ozone decay coefficient
3. Ozone leakage air flow
4. Steady-state ozone level

Instruments and Materials Needed to Conduct Tests

The preferred method for making ozone measurements involves the use of an electronic instrument which can continuously monitor and record ozone concentrations. Such analyzers are available from Advanced Pollution Instruments, Dasibi, IN USA, Monitor Labs, and others. These instruments measure ozone by the ultraviolet (UV) light absorption technique. Ozone has a peak absorption of UV light at 253.7 nanometers. The amount of light absorbed is directly proportional to the concentration of ozone. This relationship is expressed by the Beer-Lambert Law:

$$I(1) = I(0)e^{(-XLC)}$$

where:	$I(1)$	=	intensity of UV light after absorption
	$I(0)$	=	intensity of UV light before absorption
	X	=	constant: ozone absorption coefficient
	L	=	length of absorption path
	C	=	ozone concentration

Given an appropriate absorption cell length, L, C can be calculated by measuring $I(0)$ and $I(1)$. Ultraviolet absorption is recognized by the Environmental Protection Agency, American Society for Testing and Materials, and National Institute of Standards and Technology as the reference ozone measurement method.

Generally, analyzer measurement ranges should include 0 to 10 and 0 to 100 ppm, with a minimum sensitivity of 0.01 ppm on the 0 to 10 scale. Depending on the features selected, such analyzers range in cost from about $6,000 to $10,000. Bureau of Reclamation (Reclamation) area offices can make arrangements with the Hydroelectric Research and Technical Services Group (D-8450) to borrow an ozone analyzer on a short-term basis.

Ozone measurements versus time can be manually tabulated or automatically logged using a strip chart recorder attached to the analog output of the ozone analyzer. Use of a strip chart recorder is preferable because it allows a large number of measurements to be taken under steady-state operating conditions over several hours without the need for an attendant. Furthermore, automatic data recording equipment is more likely to capture an unanticipated event and is less susceptible to human error. Refer to figure 1 for a photograph of typical ozone measurement instrumentation.

Abatement options can be evaluated once the required ozone parameters are determined. Stator housing ozone concentrations should be measured at 6-month intervals to evaluate stator winding condition and/or to verify ozone abatement system performance. For best results, subsequent ozone readings should be taken under the same conditions as previous measurements. The measurement location, generator terminal voltage, loading, temperature, and relative humidity should be documented. A sample ozone measurement data sheet is given in appendix B.

A simple method is available for making initial or followup ozone concentration measurements (although it is not suitable for measuring the ozone generation, leakage, or decay parameters). This method involves inexpensive glass detector tubes which are filled with an inert reagent carrier material and impregnated with an indicating reagent. In the presence of ozone, the reagent changes color, and approximate ozone concentrations can be read directly from the discoloration on the tube's printed scale. To perform a test, an operator breaks open the tube in the stream of air to be measured (or pumps the tube to draw an air sample into the tube). The tube changes color, and the approximate ozone concentration is read. One brand of gas analysis tube is made by Dräger and is available from chemical supply companies. Typical measurement ranges include 0.025 to 3.0 ppm and 0.01 to 100 ppm. A box of 10 tubes can be purchased for about $60. A sampling pump can be purchased for about $300. The gas detection method is not as accurate as the UV absorption technique. Refer to figure 2 for a photograph of a sampling pump used to make stator housing ozone measurements.

The following equipment is required to perform an inspection of the hydrogenerator and to make ozone measurements:

1. Video borescope
2. Camera
3. Inspection mirrors
4. Flashlight
5. Ozone analyzer
6. Strip chart recorder
7. Cart for analyzer and recorder
8. Thermohygrometer
9. Paper, pens, and pencils

Preliminary Test Procedures

Any existing carbon filter must be de-energized and completely isolated before conducting the ozone generation rate and decay rate measurements. Failure to completely isolate the carbon filter may result in erroneous ozone measurements because of carbon adsorption through passive filters. Isolation can be accomplished by blocking and sealing the supply and return air openings in the stator housing.

During the operating tests, significant quantities of ozone may leak into the generator room, creating a potential health hazard for test personnel. Additional personnel throughout the powerplant may be exposed to excessive ozone levels if air from the generator room is transferred to other rooms or is recirculated. If necessary, and weather conditions permit, the heating, ventilating, and air-conditioning (HVAC) system supplying air to the generator room should be manually switched to the 100-percent outdoor air mode.

To ensure that ozone measurements accurately reflect the steady-state ozone concentration within the stator housing, multiple taps may be installed along the circumference and at various elevations. The multiple readings can be averaged to determine the steady-state ozone concentration.

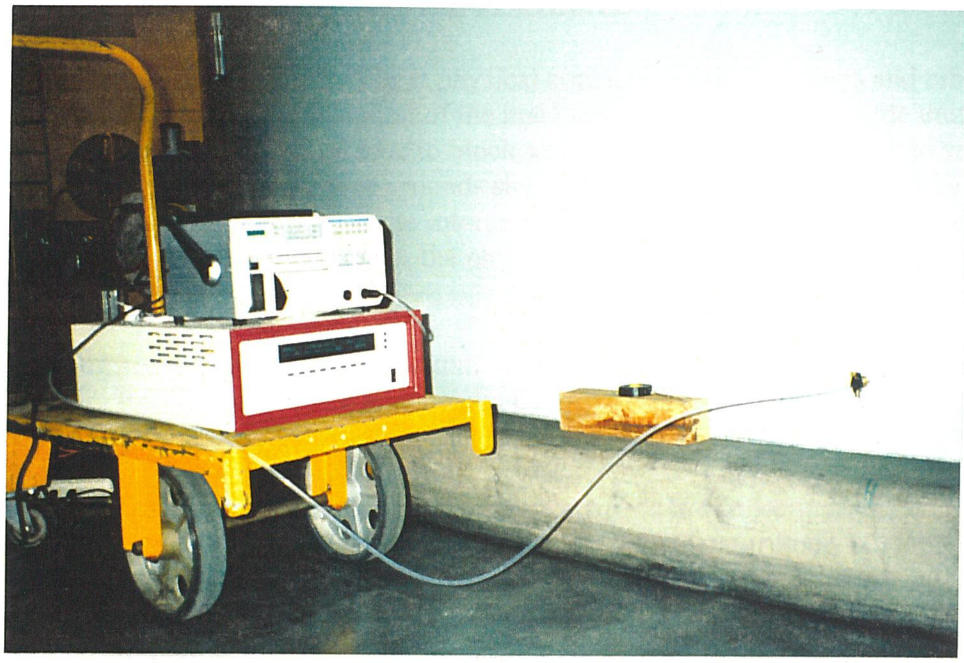

Figure 1. - Photograph of stator housing ozone measurements taken and recorded with an ozone analyzer and strip chart recorder.

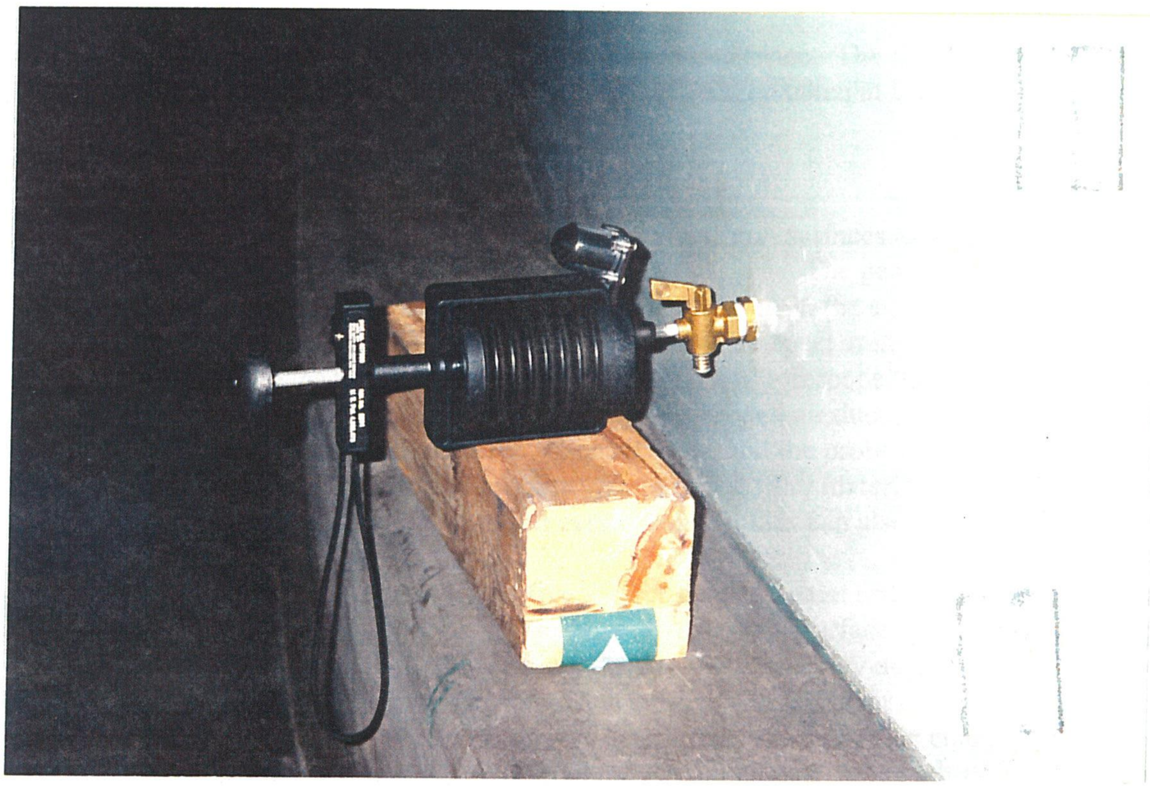

Figure 2. - Photograph of stator housing ozone measurement taken with sampling pump and glass detector tube.

Guidelines For Preparing Inspection and Test Procedures

Inspection of a hydrogenerator requires direct physical contact with the windings and other elements that are normally energized during operation of the machine. Prior to inspection, the unit should be put under an established electrical clearance to block all sources of electrical energy to any part of the machine. In addition, personal protective grounds should be placed on each winding phase. If the inspection involves standing or sitting on the rotor, a mechanical clearance is also required. Once the machine is under the appropriate clearances, the physical inspection can be performed by one or two experienced people in roughly 4 hours.

Using the following procedure, the required ozone measurements can usually be made during one 10-hour work shift. Refer to example 1 in appendix C—Analysis of Ozone Measurements—for additional details.

1. Unit is operating online at full load. Measure steady-state ozone concentration level in stator housing (1 to 2 hours). Also make ozone measurements on generator floor, outdoors, and in various powerplant work areas, such as the control room, break room, shops, and offices (1 hour).

2. Unit is operating online at no load. Measure steady-state ozone concentration level in stator housing (1 hour).

3. De-energize and stop unit. Measure ozone decay rate in stator housing (2 to 4 hours).

4. Energize unit and operate at full load. Measure ozone generation rate (1 to 2 hours).

If time allows, the ozone generation rate should be measured twice. The first 15 minutes are the most critical. If data are recorded manually, measurements should be taken at least every 30 seconds.

Instructions for Conducting Inspections and Tests

Ozone is a very corrosive element and can attack unpainted iron surfaces as well as organic materials in the machine, such as lamination insulation and rubber gaskets. The generator should be examined for red iron oxide deposits or loose powder on machine surfaces, in the stator core air ducts, or in other areas in the stator housing. A borescope can be used to inspect areas of the assembled machine that would otherwise be inaccessible. Insertion of a side-view borescope through the air gap can provide an excellent view of the stator bore surface, wedges, and air ducts. Likewise, inspection panels can be removed from the back of the stator wrapper, and the probe can be guided through the cooling air ducts to examine the air duct surfaces, stator slots, filler materials, and winding surface treatment. Mirrors with articulated joints and expandable handles can also facilitate the inspection.

During winding manufacture, a semiconductive surface coating (paint or tape) is applied to the slot portion of the stator winding to provide good contact between the surface of the stator winding and the grounded stator core. However, this semiconductive treatment may degrade in operation because of heat or chemical effects or as a result of abrasion caused by movement of the winding within the slots. Once the semiconductive coating begins to deteriorate, the capacitive charging currents for the groundwall insulation may be channeled through too few contact points, resulting in very high current densities at these high resistance connections. Excessive heating, burning, and sparking (slot discharge) may result, eventually rendering the semiconductive slot treatment ineffective. Modern thermosetting insulation systems are most susceptible to this deterioration process. Damaged semiconductive coatings and winding looseness may be difficult to assess without removing slot wedges (which, in turn, requires removal of one or more rotor pole pieces). A video borescope can greatly facilitate inspection of the assembled machine via the stator core cooling air ducts. Look for erosion of the coil surfaces and missing semiconductive coating, especially in line-end coils.

The inspection should include close examination of the stator end windings at the slot exits. The voltage stress grading paint or tape can become nonconductive as a result of electrical and thermal stresses. In severe cases, the interface between the grading coating and the semiconductive slot coating breaks down and a gap forms at the coil surface between the two coatings. Once the voltage stress grading treatment is no longer electrically connected to ground, intermittent electrical discharges occur across this gap, increasing in frequency and intensity as the coating edges erode. This mechanism can lead to excessive quantities of ozone. When inspecting the end windings, look for a band of discoloration or eroded material around the circumference of the coil at the interface of the grading coating and the semiconductive slot coating. End winding discharges will only be observed on line-end coils, not on neutral-end coils. In some cases, the connection between the stress coating and the semiconductive slot treatment can be re-established by overcoating the interface with silicon carbide-loaded paint. The stator winding manufacturer, the Hydroelectric Research and Technical Services Group (D-8450), or the Electrical Plants Group (D-8430) should be consulted regarding repair possibilities.

Sampling lines for modern ozone analyzers usually consist of 1/4-inch outer diameter Teflon tubes with stainless steel compression fittings. Teflon and stainless steel are the preferred materials for ozone measurements because they are relatively resistant to ozone. Nonetheless, some time should be allowed for the Teflon surface to passivate when ozone first comes into contact with it. Tube lengths should not exceed 50 feet and should be kept shorter if possible.

The stator housing can be accessed in many ways to make ozone measurements. For example, a bolt can be temporarily removed from either an upper deck plate cover or the side of the stator housing to feed a sampling tube into the stator. The tube should extend into the hole about 3 to 4 inches and should be secured with duct tape. At standard conditions (pressure = 1013.25 millibars, temperature = 273.3 degrees Kelvin), the density of ozone is 2.14 kilograms per cubic meter (kg/m^3), compared to the density of air, which is 1.43 kg/m^3. Therefore, higher ozone concentrations may be obtained in the lower areas of the stator housing. To accommodate this possibility, a hole can be drilled through the stator housing about 1 or 2 feet above the floor and fitted with a 1/4-inch petcock. To take a measurement, the petcock is opened and the sampling tube inserted and sealed with duct tape. This arrangement is convenient when ozone measurements are to be made frequently.

For portability and ease of use, the ozone analyzer and strip chart recorder can be placed on a cart and wheeled to various powerplant locations. In addition to stator housing ozone measurements, spot checks can be made in the turbine pit, plant shops, control room, break room, offices, and other work areas where ozone may accumulate.

Analysis of Test Results

The following mass balance relationship for ozone in a hydrogenerator was given earlier (to model a generator without an ozone abatement system, the *Removal by treatment/ventilation* term has been eliminated):

Rate of generation	=	*Rate of accumulation*	+	*Removal by decay*	+	*Removal by leakage*

Solving for the *Rate of accumulation* and rewriting in mathematical terms, the mass balance equation can be expressed as:

$$\frac{dc}{dt} = S - kc - \left(\frac{Q_l}{V}\right)c \tag{1}$$

where:
c = ozone concentration (ppm)
t = time (min)
S = rate of ozone generation (ppm/min)
k = ozone decay coefficient in stator housing (min^{-1})
Q_l = leakage of ozone from the stator housing (m^3/min)
V = air volume in housing (m^3)

Ozone Decay Coefficient, k

Using equation (1), the ozone decay coefficient, *k*, can be determined from measurements obtained immediately after generator shutdown (i.e., the field breaker is opened and the rotor stopped). When the generator is de-energized, the source, *S*, is zero. With the rotor stationary, the leakage term, Q_l, is essentially zero because no forced circulation of air is occurring in the housing; thus, no pressure differential exists to cause an outflow of air. Equation (1) reduces to:

$$\frac{dc}{dt} = -kc \tag{2}$$

Integrating the above equation yields the ozone decay curve:

$$c = c_0 \exp(-kt) \tag{3}$$

A plot of ln(c) versus time yields a straight line with slope equal to the negative of the ozone decay coefficient, *k*. The initial condition is $c = c_0$ at $t = 0$.

Ozone Generation Rate, S, and Ozone Leakage, Q_l

The ozone generation rate, *S*, can be determined from the initial slope of the ozone production versus time curve obtained during generator startup. When a generator is just being started, ozone concentration in the housing is nearly zero ($c = 0$), and equation (1) can be written:

$$S = \frac{dc}{dt} \tag{4}$$

At steady-state operation, $dc/dt = 0$, and equation (1) becomes:

$$0 = S - kc - \left(\frac{Q_l}{V}\right)c \tag{5}$$

To determine the leakage term, Q_l, substitute the calculated ozone generation rate, S, the measured steady-state ozone concentration, c, and the calculated ozone decay coefficient into equation (5). The approximate air volume, V, can be obtained from design specifications for the stator housing carbon dioxide (CO_2) fire protection system.

An example of ozone test results analysis is given in appendix C.

ABATEMENT

Design Alternatives

The interval between ozone testing and permanent repairs may be several months or perhaps years. The severity of the problem, the damaging effects to equipment, health hazard to personnel, and economic factors must be considered before deciding if repairs or abatement procedures should be undertaken. Some Reclamation powerplants use carbon filters to manage ozone. The abatement procedures described below are the most feasible to implement for Reclamation applications.

1. Improve the performance of an existing carbon filter system:

    a. Install prefilters.—Carbon filters are effective adsorbers of undesirable gaseous contaminants such as ozone; however, they are not normally used as particulate filters. The fine rust particles produced when ozone causes corrosion on ferrous surfaces can clog the surface of the carbon filters and reduce gas adsorption effectiveness and service life. Installation of prefilters will enable the carbon filters to retain higher effectiveness and prolong filter life.

    Install prefilters upstream from the carbon filters. The type and efficiency of the prefilters should be as recommended by the carbon filter manufacturer. The most common and minimum acceptable prefilters are the 2-inch-thick, extended surface area, medium efficiency (30-percent) type. However, some carbon filter manufacturers may recommend extended surface filters with efficiencies of 60 to 65 percent.

    Proper installation of prefilters is critical. Great care should be exercised to ensure that air leakage around the filters is eliminated as much as possible. If necessary, all potential leakage points should be sealed.

    Some filter manufacturers market packaged composite panel filters, which include the prefilter and carbon as one unit. These filters are not recommended for use in stator housing ozone abatement filter systems because the quantity of carbon is minimal. However, these filters can be effective if installed in the main HVAC system to eliminate ozone transferred throughout the powerplant.

Installing a prefilter increases the static pressure requirements of the fan. Filter manufacturer product literature indicates that prefilters are usually rated at 300 and 500 feet per minute (ft/min) face velocity. The initial resistance for new, commercial grade, 2-inch-thick, extended area prefilters is about 0.12 and 0.30 inch water gage (w.g.) at rated face velocities of 300 and 500 ft/min, respectively.

Fan operating conditions must be adjusted to compensate for increased pressure. To maintain the same air flow with the existing fan, the fan speed and possibly the motor horsepower may need to be increased. A differential pressure gage or adjustable switch with a warning light should be installed across the prefilters to indicate when servicing is necessary.

b. Increase the air flow.—One should evaluate fan and carbon filter manufacturer performance data for excess capacity. If the existing fan performance data indicate that the fan has excess capacity, the air flow may be increased provided the carbon filters are not already operating at maximum capacity. Carbon tray filters operate at a maximum housing face velocity of 500 ft/min. If the existing filters are operating at maximum velocity, any air flow increase must be made in conjunction with a new set of filters installed in parallel with the new filters.

   Potential problems associated with increased air flow include increases in fan and motor speed, brake horsepower, duct sizes, and floor space.

2. Install surplus carbon filter units.—Ozone problems experienced at several Reclamation powerplants have been successfully controlled with carbon filters. The carbon filters are no longer required once the cause of the ozone generation has been corrected. These filters may be available for use at other powerplants at minimal cost.

   Installation should be simple if the surplus filter capacity matches the required capacity for ozone abatement. However, if the capacity of the surplus filter is less than required, performance data should be obtained to determine if the capacity can be increased as discussed above. Multiple filters may be required if the capacity cannot be increased. Additional floor space must be dedicated for the filters. Using multiple filters may impose additional considerations related to the CO_2 fire extinguishing system. These considerations are discussed elsewhere in this monograph.

3. Install new carbon filter units.—New filters must be purchased if surplus filters are not available or cannot be modified to provide the required air flow. Typical commercially available carbon filters have efficiencies of 90 to 99 percent depending on the amount of leakage through the housing. The new filters must be sized for the ozone generation rate and desired steady-state concentration. If budget constraints preclude immediate corrective measures to eliminate the cause of ozone generation, a safety factor should be included when sizing the filter. The safety factor should be a function of the generation rate, the existing steady concentrations, and the anticipated time before repairs can be undertaken.

   Sizing the filter is relatively simple once the ozone generation rate has been determined. An example illustrating the required information and procedure for sizing a carbon filter system is provided in appendix D.

   The advantages inherent with this option include single unit installation in most cases, minimum floor space required, fewer penetrations in the stator housing, and minimal ductwork.

4. Install an outdoor air ventilating system.—This option relies on dilution ventilation by supplying 100-percent outdoor air to the stator housing. The option is feasible for powerplants with easily accessible generator room windows or where other means for obtaining outdoor air are available.

   Equipment requirements include an inline fan (axial or centrifugal as dictated by pressure and air flow requirements), ducts, louvers, standard air filters, dampers, and controls. Powerplants in climates where outdoor temperatures exceed 104 degrees Fahrenheit (°F) will also require a water cooling coil and associated piping, valves, and controls to cool the air.

   The system can be thermostatically controlled to use 100-percent unconditioned outdoor air when the temperature does not exceed generator ambient requirements. When the outdoor temperature exceeds 104 °F, a thermostatically controlled valve opens the cooling water circuit to cool the supply air.

   This abatement method has several advantages: carbon is not required; therefore, the maintenance costs for carbon removal, installation, shipping, and reactivation are eliminated; generator downtime is virtually eliminated; and air flow can be increased within the manufacturer's limits to account for increased ozone generation rate.

   The disadvantages include difficulty of obtaining access to outdoor air, increased complexity caused by outdoor air temperature controls, and excessive equipment and installation cost.

Design Considerations

The abatement method most likely to be used by Reclamation is a carbon filter system. Outdoor air ventilation systems are less likely to be used because of the greater complexity and cost. Figure 3 shows a photograph of a typical ozone abatement system using standard activated carbon filter trays.

Although this discussion specifically addresses carbon filter systems, the design considerations are applicable to any of the abatement methods previously discussed under design alternatives. These considerations are especially important if the abatement method adopted precludes installation of isolating dampers or automatic control of the abatement system. However, designers and field personnel are cautioned that abatement systems which violate National Fire Protection Association (NFPA) 12 code requirements for CO_2 systems are not acceptable. Every design must be evaluated to ensure compliance with the applicable provisions of NFPA 12.

1. Filter sizing.—Ozone abatement is undertaken to ensure personnel safety and to protect equipment from the corrosive effects of ozone. The OSHA threshold limit value (TLV) for ozone is 0.1 ppm. This level will accomplish both purposes and can be easily achieved in most instances. However, when the ozone generation rate is excessive, the quantity of filtered air required for abatement may also be excessive. To select the smallest equipment necessary, designers should consider the following factors before proceeding with a design:

   a. OSHA occupied space ozone requirements.—The OSHA TLV level of 0.1 ppm is intended to ensure personnel safety and must be maintained in occupied spaces only. The OSHA TLV level does not apply to an operating generator that cannot be occupied. However, generator rooms are frequently occupied for maintenance or inspection purposes while the generating units are operating; therefore, these spaces are subject to OSHA TLV requirements.

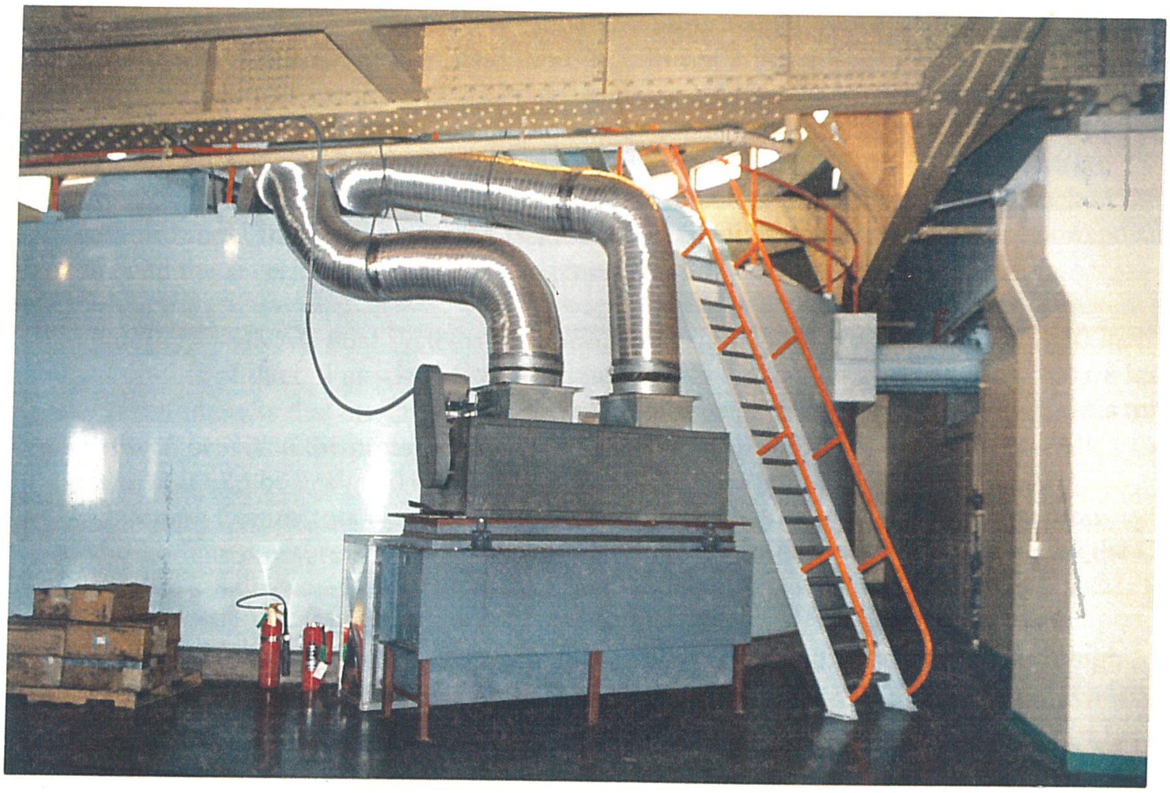

Figure 3. - Photograph of an 8,000-ft^3/min ozone filtration system using standard activated carbon filter trays.

The issue of worker exposure can be mitigated by restricting entry into the stator housing during machine operation unless self-contained breathing apparatus are used. Alternatively, ozone levels in the stator housing can be reduced to OSHA limits by operating the ozone removal system for a sufficient period of time after the machine is de-energized. The rotor should be allowed to spin during this time to facilitate air mixing and improve ozone removal.

b. Generator housing ozone requirements.—A steady-state ozone concentration of no greater than 1.0 ppm in the stator housing is recommended. Above this level, ozone can cause rapid deterioration of the generator components susceptible to ozone. Also, maintaining the stator housing ozone levels to less than 1.0 ppm should prevent excess ozone from entering the plant and work environment due to normal air housing leakage.

c. Temporary installation.—An ozone abatement system is intended to be a temporary installation. Extraordinary measures can rarely be justified and should not be undertaken to achieve the OSHA TLV ozone level within a stator housing if it cannot be accomplished at a reasonable cost. However, in potentially occupied areas, the required abatement measures must be implemented to maintain OSHA standards.

d. Safety factors.—A reasonable safety factor should be included in the abatement system design. Depending on the severity of the problem, the ozone generation rate may continue to increase before repairs are undertaken. A safety factor should be added to the required air flow to ensure the system can continue to operate with adequate filtration capacity. The safety factor should be increased to reflect the anticipated time before permanent repairs are undertaken. Safety factors of 50 to 100 percent may be warranted provided sufficient space is available for installing the oversized equipment.

Installation of an abatement system must be accomplished without sacrificing the need for adequate work space around the stator housing. In some instances, a reasonable safety factor may result in equipment too large to install in the available space. When circumstances do not permit installation of the required equipment, the largest equipment possible should be installed. Allowances should made for accepting higher ozone levels within the stator housing while maintaining the OSHA target level in potentially occupied areas such as the generator room. In these cases, repairs should be expedited to minimize generator exposure to ozone and the severity of damage to the generator components.

e. Duct design.—HVAC duct systems are normally designed for a pressure loss of 0.10 inch w.g./100 feet of duct. For special applications such as abatement systems, the pressure loss may result in ducts that are too big for the available space. When necessary, duct sizes may be reduced provided the pressure loss of 0.35 inch w.g./100 feet is not exceeded. All ductwork should be designed and installed in accordance with Sheet Metal and Air Conditioning Contractors National Association (SMACNA) HVAC duct construction standards. The pressure class and sealing requirements for ductwork are affected by the $C0_2$ system and are discussed later in this section.

   When space is available, round duct is preferable over rectangular because it has a high strength to weight ratio and is relatively easier to seal. Flexible duct is not recommended because it has much higher resistance than other ducts.

f. Maintenance.—Depending on the abatement method selected, the generating unit may have to be shut down to conduct maintenance. To reduce generator downtime, the abatement system should be designed to provide easy maintenance.

2. Effect of poor air distribution.—Retrofit HVAC installations are frequently hampered by poor air distribution caused by limited space for locating equipment. Two commonly neglected factors which may adversely affect the design of a carbon filter system are system effect losses and ventilating system effectiveness.

   a. System effect.—System effect is a pressure loss attributed to poor air distribution design near fan suction and discharge openings. The space in and around stator housings is limited for installing filter units, air ducts, and supply and return grilles. These constraints may lead to designs with poor air distribution. The most common system effect loss occurs when an elbow is installed too close to the fan discharge or suction. The system effect at the fan discharge causes a higher than expected pressure loss, which is often neglected and results in reduced air flow. To prevent or minimize system effect losses, elbows should be installed at least four duct diameters from a fan discharge. Whenever space constraints preclude the proper clearances, the system design pressure should be adjusted to account for system effect losses. On a factory-assembled air handling unit, system effect losses are less likely to occur on the suction side. The *SMACNA HVAC Duct Construction Standards* provide design recommendations and adjustments to cope with potential system effect losses.

   b. Ventilating system effectiveness.—Ventilating system effectiveness is an estimate of the amount of fresh air that actually mixes with contaminated air. When applied to the carbon filter system, effectiveness may be defined as the fraction of total filtered air supplied to the supply air that mixes with housing air. The remaining fraction of supply air is considered to pass through the housing without reducing contaminant levels. The most common cause of reduced effectiveness is poor relative positions between supply air terminals and return air terminals. Discharging supply air toward return air terminals will cause part of the supply air to short circuit or bypass the housing. This condition should always be avoided.

American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) Standard 62-89 provides equations (appendix D) that account for ventilating system effectiveness when determining steady-state concentration of gaseous contaminants. The equation can be solved for air flow if required values are known. ASHRAE Standard 62-89 suggests that a recirculating system has an effectiveness of 100 percent (ASHRAE, 1989). An effectiveness value suggested in the ASHRAE *HVAC Systems and Equipment Handbook* is 0.80 (ASHRAE, 1992). This value probably applies to office or similar spaces with ceiling supply grilles and return plenums instead of complicated spaces such as stator housings. As an example, an effectiveness of 0.80 (80 percent), implies that 0.20 (20 percent) of the filtered supply air bypasses the space unaffected by the pollutant. Therefore, an additional 20 percent filtered air is required just to provide the minimum air requirements.

Another factor related to effectiveness that may affect the air flow requirements is the reasonable assumption that the normally high cooling air flows in the stator housing ensure thorough ozone and air mixing. Some experiments have shown that mixing may not be as thorough as previously assumed.

Accounting for system effects and poor effectiveness is essential when sizing a critical system intended to reduce gaseous contaminants such as ozone. Both factors are commonly neglected by HVAC designers. Unfortunately, effectiveness values applicable to stator housings are not available. The complex air flow patterns within a stator housing hinder the calculation of a specific value reflecting all possible conditions. Without accurate data, designers should consider an effectiveness value of 0.80 as an upper limit.

3. Effect of CO_2 discharge pressure on filter system components.—Designers should ensure that the carbon filter system components, especially ducts (which are probably the weakest components) and joints (which are most likely to leak), can sustain the pressure from a CO_2 discharge without leakage or damage. Any leaks occurring after a CO_2 discharge may prevent the minimum CO_2 concentration (30 percent by volume) and retention time (30 minutes) from being attained. Furthermore, CO_2 leaked into the generator room may pose additional health hazards or hinder the ability of personnel to respond to an emergency situation.

   To ensure that the filter system components can sustain a CO_2 discharge, stator housing design and relief pressures should be obtained from manufacturer's drawings or design data. If this information is not readily available, Reclamation's *Hydrogenerator Design Manual* provides some guidance. This manual states that air housing pressure relief doors are designed to open when the pressure inside the air housing exceeds the pressure outside the air housing by 0.2 pounds per square inch (lb/in^2) or about 5.5 inches w.g. The pressure relief doors close when the pressure differential has decreased to about 0.1 lb/in^2 or about 2.7 inches w.g. The typical design pressure for normal air flow may range from 1 to 2 inches w.g. depending on system configuration. To ensure that the integrity of the fire extinguishing system is not compromised, the filter system should be designed to sustain the pressure rise caused by a CO_2 discharge. Based on the air housing pressure relief setting plus a reasonable safety factor, the filter system components should be designed for a SMACNA 6-inch w.g. pressure class with class A sealing.

4. National Fire Protection Association code requirements for isolation of CO_2.—Paragraph 2-2.2.2 of the 1993 edition of NFPA 12—Carbon Dioxide Extinguishing Systems—states, "Where forced air ventilating systems are involved, they preferably shall be shut down or closed, or both before or simultaneously with the start of the carbon dioxide discharge, or additional compensating gas shall be provided." Compliance with this code requirement is mandatory to prevent dilution caused by loss of CO_2 through the forced air distribution system and to ensure personnel safety.

   During the design and installation of carbon filters, the following arguments may be proposed for not complying with NFPA 12: generator CO_2 systems are provided with a delayed discharge to ensure the required concentration is maintained; most carbon filters for hydrogenerator applications are closed systems relying on recirculating air instead of ventilating air; CO_2 is not easily adsorbed by activated carbon; carbon filter installation is temporary; and isolation is an unnecessary expense. These arguments appear reasonable. However, reasonable arguments for providing isolation are discussed below. Plant personnel must be aware of the arguments on both sides of this issue and weigh the risks and consequences of not providing isolation.

5. Effect of filter system on stator housing volume.—Single or multiple openings will be required in the stator housing to connect ductwork from the filters. These openings, if not adequately sealed, increase the potential for CO_2 leakage into the generator room. Unless ductwork is isolated from the stator housing, during a CO_2 discharge, the net volume of the stator housing will increase. This increase is especially true in applications where the filter must be installed in a remote location and significant ductwork is required between the generator housing and the filter. The term "significant," as used here, implies volume as well as length. In applications where the filter system is close-coupled to the generator housing, the volume increase will be relatively small, and the reduced CO_2 concentration should not be significant. CO_2 systems usually include safety factors which should be capable of accommodating modest volume increases anticipated when a close-coupled filter system is installed. However, a close-coupled carbon filter requires ductwork, which is prone to leakage even when appropriate sealing class and methods are employed. All modifications affecting the stator housing volume should include calculations to verify that the design CO_2 concentration will not be reduced beyond the system's ability to extinguish a fire.

6. Filter system isolation and control.—The intent of NFPA 12 suggests possible control schemes which should be considered.

   a. Manual controls.—When ozone abatement is a short-term solution, manual control of the carbon filter fan may be acceptable on close-coupled carbon filter systems where the increased volume will not significantly affect the CO_2 concentration. However, additional controls should be provided to ensure the power supply to the fan is automatically interrupted when a CO_2 discharge is imminent.

   b. Automatic controls.—Automatic fan and damper controls should be installed if carbon filters will be installed for an extended time and/or filters are installed at a remote location requiring significant ductwork. Motor operated, two-position, spring return, normally closed dampers, suitable for the intended purpose, should be installed at supply and return air duct connections to the housing. The dampers should be the low-leakage type comparable to those used for halon systems. Fan controls should be interlocked to energize and de-energize simultaneously with the generator. Furthermore, controls should be interlocked with the generator fire detection system to de-energize the fan and close dampers if a CO_2 discharge is imminent.

Designers should note that installing control dampers to isolate the filter system may provide a maintenance advantage. The dampers can be manually closed to isolate the filter unit for carbon or prefilter replacement without requiring generator unit shutdown. However, this procedure should only be attempted if the filters can be replaced before the generator room ozone level exceeds the acceptable OSHA TLV level, currently 0.1 ppm, for 8-hour exposure.

Maintenance

A carbon filter system requires very little maintenance except for replacing the prefilters and carbon filters.

1. Prefilters.—Prefilters are readily available and require very little time to replace. For normal HVAC applications, some manufacturers of medium, 30-percent-efficiency filters recommend replacement when the final resistance is about 1 inch. However, this replacement interval may not be the most satisfactory for prefilters on ozone abatement systems.

   Fans, like pumps, are selected to operate at a specific air flow and pressure point along a fan characteristics curve. As the filters accumulate dirt, the filter resistance increases, and the fan operating point rises to compensate. This pressure rise is usually accompanied by reduced air flow. The severity of air flow reduction depends on the fan characteristics curve. A fan with a steep characteristics curve will incur less air flow reduction than a fan with a flat curve.

   The normal practice of allowing the filter resistance to double or triple before replacement can cause significant air flow reduction, resulting in reduced ozone filtration and increased ozone levels. Furthermore, dirty filters may release particulates that can settle on carbon and reduce its effectiveness. A reasonable alternative for ozone abatement systems is to replace the prefilters when either of the following conditions is achieved: the differential pressure across the prefilter rises to the manufacturer's recommended replacement value or the differential pressure causes the actual air flow drop to but not below the minimum required air flow. For example, assume an ozone abatement system requiring 6,000 cubic feet per minute (ft^3/min) is selected for normal operation at 8,000 ft^3/min. This system has a 33-percent air flow safety factor. Provided the maximum allowable differential pressure is not exceeded, the prefilter should be replaced when the air flow decreases to 6,000 ft^3/min. Replacement at this air flow will ensure that the air flow required to maintain the desired ozone concentration will not be compromised while the fan is operating under reduced air flow caused by a dirty prefilter.

2. Carbon filters.—Carbon filters usually require special ordering and require more time to replace. Two options are generally available to plant personnel:

   a. Maintain a supply of bulk carbon for in-house replacement.—This option requires unnecessary storage of bulk carbon, which may not be used for many months depending on the severity of the ozone problem. Therefore, this option is not recommended except for rare cases where carbon must be replaced so frequently that the cost of shipping for regeneration is excessive. In this case, plant personnel must remove and replace the saturated carbon. A spare set of sealed trays should be maintained to expedite replacement time.

   b. Remove trays and return to regenerating plant.—This option requires maintaining one complete set of sealed spare carbon filter trays. Seals should not be broken until the carbon trays are ready for installation in the filter unit. When necessary, remove and replace the trays. Reactivation of used carbon is accomplished with heat, steam, or other chemical processes not normally available to plant personnel. In all probability, the complete set of trays with used carbon will have to be returned to a carbon reactivation facility for processing.

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APPENDIX A

Inspection Report Form

INSPECTION REPORT

Project: ______________________________ Unit: ____________________________________

Date: ________________________________ Inspected By: ____________________________

Reason For Inspection: ____

NAMEPLATE INFORMATION

Manufacturer: _________________________ Date Installed: ___________________________

Rated MVA: ___________________________ Power Factor: _____________________________

Speed (rpm): ____________ No. of poles: _____________ Frequency (Hz): ___________

Stator Winding
Manufacturer: ________________________ Date: ___________ Rewind Date: __________

Line Voltage (kV): ______________ Insulation Type: ________________________________

ADDITIONAL COMMENTS

____

____

____

____

INSPECTION RESULTS

Description	Y/N	S/U	Comments
Rotor out of bore?			
Rotor pole pieces removed?			
Borescope used?			
Core inspection plate removed?			
Cleanliness of bore (oil, dust, etc.).			
Air ducts clogged/unclogged?			
Iron oxide deposits?			
Stator winding condition.			
Upper winding cleanliness.			
Lower winding cleanliness.			
Circuit ring bus condition.			
Corona activity.			
End winding discharges?			
Grading coating discharges?			
Slot discharges?			
Blocking condition.			
Wedge condition.			
Wedges slipping out at ends?			
Slot filler condition.			
Filler slipping out at ends?			
Core laminations condition.			
Laminations bent in bore? broken?			
Y=Yes N=No S=Satisfactory U=Unsatisfactory			

APPENDIX B

Ozone Measurement Form

OZONE MEASUREMENTS

Project: ______________________ Unit: ______________________

Date: ______________________ Tested By: ______________________

Reason For Test: ____

Time	Ozone (ppm)	MW	Mvars	kV	Stator Temp	Comments

Stator Housing Temp: ______________________ Humidity: ______________________

Location of Test: ____

Test Equipment Used: ____

APPENDIX C

Example 1—Analysis of Ozone Measurements

EXAMPLE 1—ANALYSIS OF TEST RESULTS

This example provides an illustration of typical ozone generation and decay curves and the analyses performed on the ozone measurements. The following parameters will be determined:

1. Ozone decay coefficient, k (min^{-1})
2. Steady-state ozone concentration, c (ppm)
3. Ozone generation rate, S (ppm/min)
4. Ozone leakage air flow, Q_l (m^3/min)

From equation (1), the mass balance for ozone in a hydrogenerator is:

$$\frac{dc}{dt} = S - kc - \left(\frac{Q_l}{V}\right)c \tag{6}$$

where: t = time (min)
V = air volume in housing (m^3)

Ozone Decay Coefficient, k

The ozone decay curve shown on figure 4 was obtained after the generator was de-energized. The rotor was coasting down.

During the shutdown sequence, the ozone source, S, is zero, and the leakage air flow, Q_l, is negligible. Therefore, equation (6) reduces to:

$$\frac{dc}{dt} = -kc \tag{7}$$

Integrating equation (7) yields the equation for the ozone decay curve:

$$c = c_0 \exp(-kt) \tag{8}$$

From figure 4, the initial ozone concentration, c_0, equals 2.3 ppm at $t = 0$. The natural logarithm of the ozone decay curve is a straight line with slope equal to $-k$. A plot of ln(c) versus time is given on figure 5. The decay coefficient, k, is equal to 0.00862 ppm/min.

Steady-State Ozone Concentration, c

A plot of ozone production versus time during generator startup is given on figure 6. As shown, the ozone concentration, c, approaches a steady-state value of 2.3 ppm.

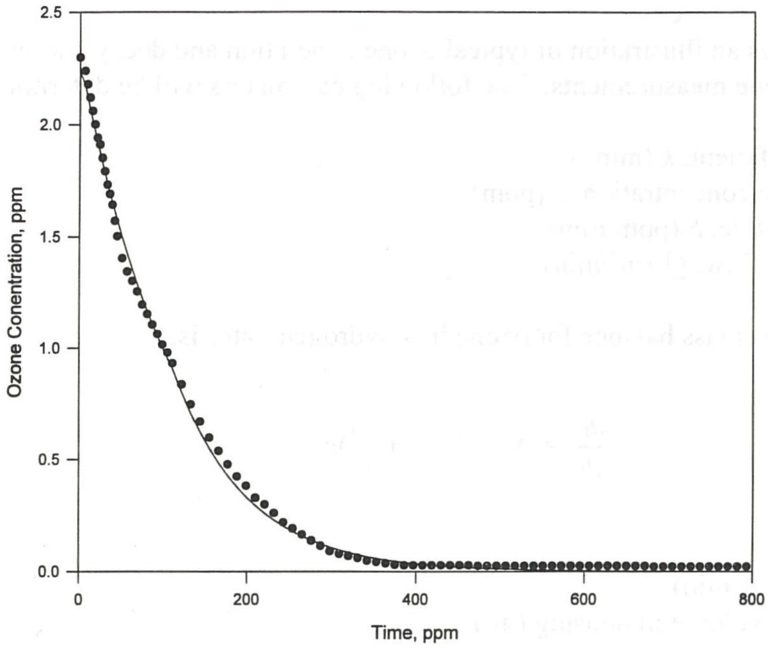

Figure 4. - Ozone decay inside generator stator housing following unit shutdown.

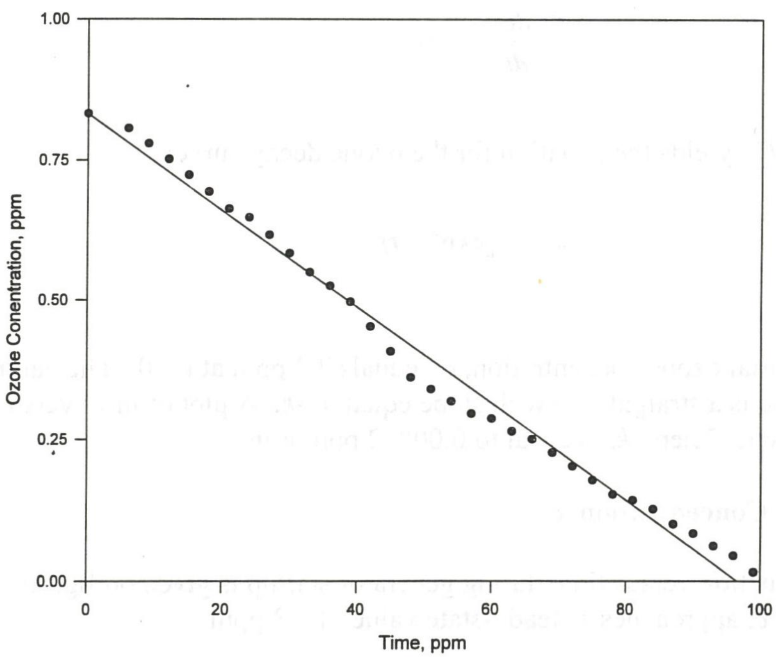

Figure 5. - Natural logarithm of ozone decay inside generator stator housing following unit shutdown.

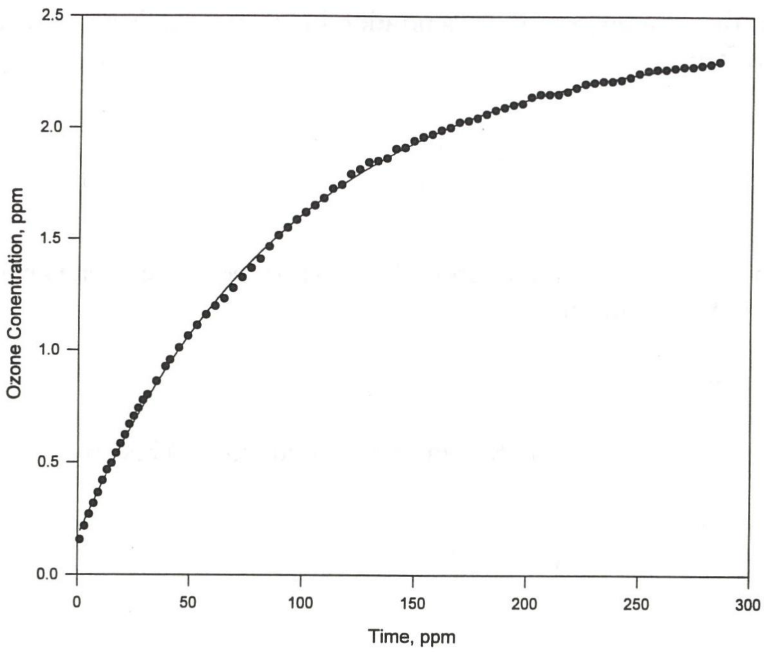

Figure 6. - Ozone accumulation inside generator stator housing following unit startup.

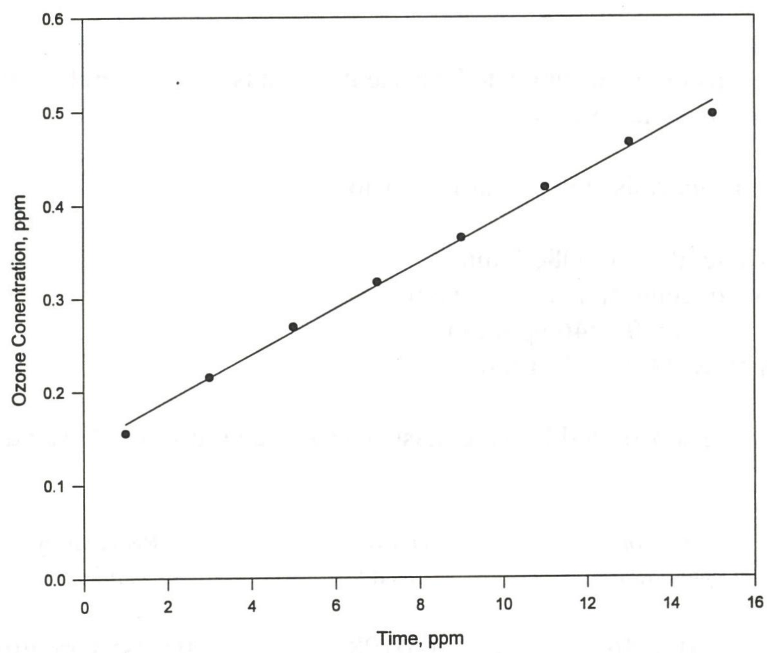

Figure 7. - Ozone generation rate inside generator stator housing following unit startup.

Ozone Generation Rate, S

When the generator is first started, ozone concentration in the housing is nearly zero ($c = 0$), and equation (6) can be written:

$$S = \frac{dc}{dt} \tag{9}$$

The ozone generation rate, S, is determined from the initial slope of the ozone generation curve. From figure 7, S is equal to 0.0246 ppm/min.

Ozone air flow Leakage, Q_l

During steady-state operation, $dc/dt = 0$. Solving for Q_l, equation (6) becomes:

$$Q_l = V\left(\frac{S}{c} - k\right) \tag{10}$$

To calculate the leakage term, Q_l, substitute the ozone generation rate, S, the steady-state ozone concentration, c, and the ozone decay coefficient into equation (10). The approximate air volume, V, can be obtained from design specifications for the stator housing CO_2 fire protection system. In this example, the stator housing volume is 500 m^3.

$$Q_l = (500\ \mathrm{m}^3)\left(\frac{0.0246\ \mathrm{ppm/min}}{2.3\ \mathrm{ppm}} - 0.00862\ \mathrm{min}^{-1}\right) = 1.04\ m^3/\mathrm{min} \tag{11}$$

This value should be considered an estimate because it depends upon several measurements, each of which may contain experimental errors.

The results of the ozone analysis are summarized below:

1. Ozone decay coefficient, $k = 0.00862\ \mathrm{min}^{-1}$
2. Steady-state ozone concentration, $c = 2.3$ ppm
3. Ozone generation rate, $S = 0.0246$ ppm/min
4. Ozone leakage air flow, $Q_l = 1.04\ \mathrm{m}^3/\mathrm{min}$

The above values may be substituted into the mass balance equation (6). At steady-state ($dc/dt = 0$):

Rate of generation	=	*Removal by decay*	+	*Removal by leakage*
0.0246	=	0.0198	+	0.0048 (ppm/min)

Note that about 80 percent of ozone generated is removed by decay versus 20 percent which leaks out of the stator housing. These results confirm that an air purification system which removes ozone from the stator housing is an effective means of reducing the deterioration of the vulnerable stator components.

APPENDIX D

Example 2—Carbon Filter Sizing

EXAMPLE 2—CARBON FILTER SIZING

The following example illustrates the procedure for sizing a carbon filter once the test results have been analyzed and the generation rate ascertained. The required air flow, amount of carbon, and estimated breakthrough time will be determined.

Assume the following conditions:

1. Measured steady-state ozone concentration, $c_m = 2.3$ ppm
2. Ozone generation rate, $S = 0.0246$ ppm/min
3. Desired steady-state ozone concentration, $c_s = 0.1$ ppm
4. Generator housing volume, $V = 500\ \text{m}^3$

Generation Rate Unit Conversion

Before proceeding with the air flow calculation, the generation rate should be converted from parts per million per minute (ppm/min) to milligrams per minute (mg/min) as follows:

$$S_1 = S c_s V \tag{12}$$

where: S_1 = generation rate (mg/min)
S = generation rate (ppm/min)

The values for c_s and V are as previously given.

$$S_1 = (0.0246\ \frac{\text{ppm}}{\text{min}})(1.96\ \frac{\text{mg}}{\text{m}^3\text{·ppm}})(500\ \text{m}^3) = 24\ \frac{\text{mg}}{\text{min}} \tag{13}$$

Air Flow Determination

The required air flow can be determined from equation (1) derived from recirculation air flow equations in ASHRAE Standard 62-89:

$$Q = 35.32 \frac{S_1}{EFc_s} \tag{14}$$

where: Q = required air flow (ft^3/min)
S_1 = ozone generation rate (mg/min)
F = ozone filter efficiency (fraction)
E = effectiveness of ventilating system (fraction)
c_s = desired ozone steady-state level (mg/m^3)

Because carbon is an excellent adsorber of ozone, i.e., 99-percent efficient, an initial penetration rate of 1 percent is reasonable. The effectiveness of any ventilating system depends highly on the design of the air distribution system. Because location of air distribution grilles is usually limited by existing equipment, assume an effectiveness of 0.70. Select a concentration level to comply with

Occupational Safety and Health Administration (OSHA) requirements, i.e., 0.196 mg/m^3 (0.1 ppm). With these values, the required air flow can be calculated as follows:

$$Q = 35.32 \frac{24}{(0.70)(0.196)(0.99)} = 6{,}240 \ \text{ft}^3/\text{min} \tag{15}$$

Because of the uncertainty of the effectiveness value and to account for possible increases in the generation rate, a suitable safety factor should be included. Assume a 25-percent safety factor is reasonable for this example. The safety factor increases the air flow to 7,800 ft^3/min.

Weight of Carbon

Once the air flow is determined, the filter size, number of carbon trays, and weight of carbon are essentially established. Filter manufacturers build carbon filters in modular sizes of 1,000 or 2,000 ft^3/min with each module containing about 45 and 90 pounds (lb) of carbon, respectively. Note that these values are based on housing face velocities of 500 ft/min. For this example, an 8,000-ft^3/min carbon filter would require about 360 lb of carbon.

A more accurate method to estimate the amount of carbon required is to use the following equation:

$$W = 0.08 \frac{\rho d Q}{v} \tag{16}$$

where:
- W = weight of carbon (lb)
- ρ = density of carbon (lb/ft^3)
- d = depth of the carbon filter panel (inches)
- Q = air flow (ft^3/min)
- v = air velocity through a typical filter panel (ft/min)

The density of packed carbon varies from 31 to 34 lb/ft^3. Carbon filter trays are available in depths from 0.5 to 2 inches in 0.5-inch increments. The most common carbon filter has a nominal depth of 1.0 inch and an actual depth of 0.875 inch. The air flow velocity through a typical filter varies from 30 to 50 ft/min. Note that this velocity is considerably lower than the housing velocity, which may be as high as 500 ft/min. Generally, the most useful limiting value is the minimum weight of carbon required. To estimate the minimum amount of carbon, assume the highest air flow velocity through the filter occurs at the lowest carbon packing density. Therefore, the weight of carbon can be estimated as:

$$W = 0.08 \ \frac{(31)(0.875)(8{,}000)}{50} = 347 \ \text{lb} \tag{17}$$

Breakthrough Time

The breakthrough time is an estimate of the operating time before ozone begins to pass through the filter. This value is not indicative of the time interval between carbon replacement; however, it can be used as a warning that the frequency of ozone level monitoring should be increased. Carbon filters are usually replaced when the ozone level measured downstream from the fan and filter rises to 10 percent of the desired ozone level. Increased ozone levels before the estimated breakthrough period may indicate that ozone is bypassing the filters because of poor sealing or that the ozone generation rate has increased. Plant personnel should confirm which of these conditions actually exist. The breakthrough time can be estimated from the following equation derived from the ASHRAE *HVAC Applications Handbook*:

$$t = 267{,}700 \frac{fW}{Qc} \tag{18}$$

where:

t	=	breakthrough time (h)
f	=	retentivity ratio (pounds of ozone adsorbed to pounds of carbon at saturation)
W	=	weight of carbon (lb)
Q	=	air flow (ft^3/min)
c_s	=	desired ozone concentration (mg/m^3)

The retentivity can vary from 2 to 40 percent depending on the affinity of the carbon for the pollutant to be adsorbed. Carbon product literature generally promotes retentivities of 33 percent for ozone absorption. A value of 16 percent is reported for gases where good absorption by carbon is expected. Literature from one major carbon manufacturer suggests that the 33-percent value is based on ideal laboratory conditions, which are not attainable in the field. Therefore, the actual amount of adsorption may be less than the ideal conditions predict. A conservative approach may be to use a value midway between excellent absorption (33 percent) and good absorption (16 percent). Assuming a value of 25 percent, the estimated breakthrough time is:

$$t = 267{,}700 \frac{(0.25)(347)}{(8{,}000)(0.196)} = 14{,}811 \text{ hours} \tag{19}$$

Once the air flow has been determined, the required carbon filter can be selected, and the air distribution system can be designed in accordance with the design considerations previously discussed and routine ASHRAE and SMACNA procedures.

Mission

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American Public.