♻ EPA
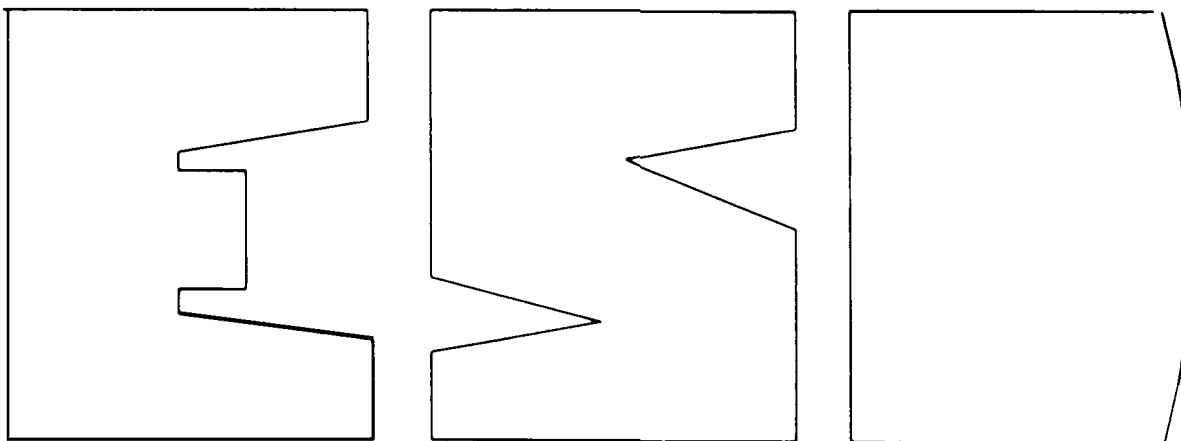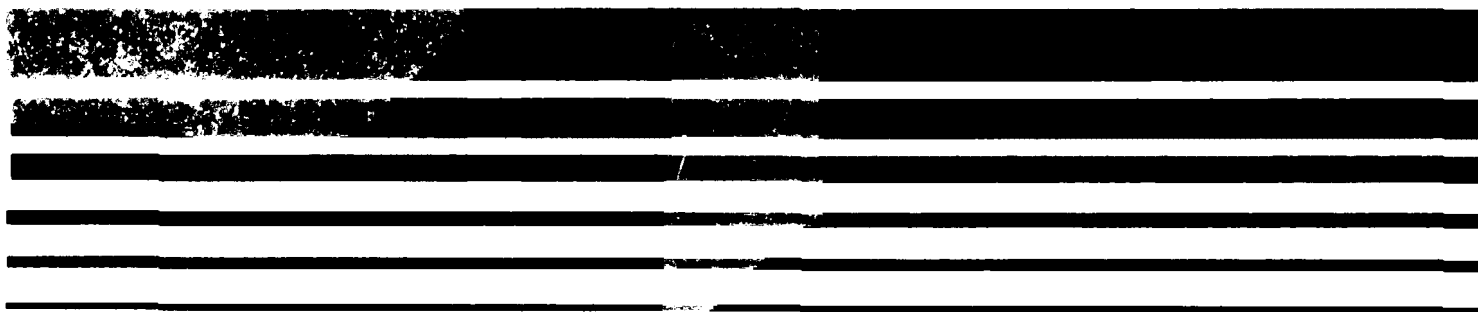
Municipal Waste Combustor Operator Training Program

Course Manual

MUNICIPAL WASTE COMBUSTOR OPERATOR TRAINING PROGRAM

COURSE MANUAL

Prepared for:

U. S. Environmental Protection Agency
Industrial Studies Branch/ESD
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

April 13, 1993

NOTICE

This manual is part of a model state training program which addresses the training needs of municipal waste combustor (MWC) operators. This manual generally describes the generic equipment design features, combustion control relationships, and operating and maintenance procedures which are designed to be consistent with the purposes of the Clean Air Act Amendments of 1990.

This training program is not designed to replace the site-specific, on-the-job training programs which are crucial to proper operation and maintenance of municipal waste combustors.

Proper operation of combustion equipment is the responsibility of the owner and operating organization. Therefore, owners of municipal waste combustors and organizations operating such facilities will continue to be responsible for employee training in the operation and maintenance of their specific equipment.

DISCLAIMER

This Course Manual was prepared for the Industrial Studies Branch, Emission Standards Division, U. S. Environmental Protection Agency. It was prepared in accordance with USEPA Contract Number 68-CO-0094, Work Assignment Number 7. Partial support was also provided by the University of Virginia through its Sesquicentennial Associates Program.

The contents of this report are reproduced as received from the contractor. The opinions, findings and conclusions expressed are those of the authors and not necessarily those of the U.S. Environmental Protection Agency. Any mention of product names does not constitute an endorsement by the U. S. Environmental Protection Agency.

AVAILABILITY

This document is issued by the Office of Air Quality Planning and Standards of the U. S. Environmental Protection Agency. It was developed as part of a set of training materials to assist operators of municipal waste combustors in becoming certified as required by the federal and state regulatory agencies.

Individual copies of this publication are available to state regulatory agencies and other organizations providing training of operators of municipal waste combustors. Copies may be obtained from the Air Pollution Training Institute (APTI), USEPA, MD-17, Research Triangle Park, NC 27711. Others may obtain copies, for a fee, from the National Technical Information Service, 5825 Port Royal Road, Springfield, VA 22161.

Although this government publication is not copyrighted, it does contain some copyrighted materials. Permission has been received by the authors to use the copyrighted material for the original intended purpose as described in the section titled Course Manual Introduction. Any duplication of this material, in whole or in part, may constitute a violation of the copyright laws, and unauthorized use could result in criminal prosecution and/or civil liabilities.

The recommended procedure for mass duplication of the course materials is as follows:

Permission to use this material in total may be obtained from the APTI, provided the cover sheet is retained in its present form. Permission to use part of this material may also be obtained from the APTI, provided that the APTI and the authors are properly acknowledged.

TABLE OF CONTENTS

COURSE MANUAL INTRODUCTION

This manual was developed for the U. S. Environmental Protection Agency (USEPA) in support of improving the air pollution control practices at municipal waste combustors (MWCs). The USEPA is required to develop a model state training and certification program for solid waste incinerator operators under Title III, Section 129 of the Clean Air Act Amendments of 1990. The manual is an integral part of the model state MWC operator training and certification program. As such, state and regional air pollution control agencies are encouraged to develop training programs which make use of this manual.

TRAINING PROGRAM GOAL

The primary goal of the training program is to provide an adequate level of understanding to MWC operators to successfully complete the requirements of the ASME QRO Standard for provisional certification as resource recovery facility operators.

The training program focuses on the knowledge required by operators for understanding the basis for proper operation and maintenance of municipal waste combustors. Particular emphasis is placed on the various aspects of combustion which are important for environmental control. Fundamental information is related to applications and to the operator's own work experiences. Trainees are encouraged to comment and ask questions during the training program. Such discussion will both increase the utility of the program and make it more interesting.

The program was designed to augment the normal site-specific, on-the-job, and supervised self-study training programs which are typically provided by the vendor, owner, or operating company. The program is not a substitute for such hands-on operator training programs.

TRAINING PROGRAM INTENDED AUDIENCE

The training program concentrates on the range of MWC units covered by the ASME Standard for Qualifications and Certification of Resource Recovery Facility Operators (ASME QRO-1-1989). This includes unit sizes from capacities as small as 24 tons/day up through the regional waste-to-energy plants which may have capacities greater than 4,000 tons/day. Therefore, the course focuses on the special training needs of operators of the larger sizes of MWC units, which typically have continuous ash removal systems and an intermittent or continuous waste feeding system. This course does not focus on the training needs of operators of small batch-fired incinerators.

Other persons who are expected to be trainees in this program include MWC operating and management staff members, technical managers, mechanics and maintenance personnel, instrument and control technicians, general engineers and design engineers.

In addition, regulatory officials, particularly those involved in permit review, are expected to find this program both informative and useful.

PROGRAM AGENDA

The training program is designed for a five-day sequence of learning units. This manual follows the sequence of the recommended agenda which is found in the _Municipal Waste Combustor Operator Training Program, Instructor's Guide_. However, the course can depart from the recommended agenda to accommodate the special scheduling needs of the speakers.

MANUAL ORGANIZATION

The manual presents information in the subject areas addressed in the ASME Examination for Provisional Certification as Chief Facility Operators and Shift Supervisors. Additional information about qualifications may be obtained from a review of the ASME Standard. The manual will also be useful in state and/or private entity training programs which are conducted under equivalent state standards for operator training and certification.

The sequence of topics was selected to reinforce the integration of the basic or fundamental aspects with the more familiar applied materials. Generally, a unit of fundamental information is followed by an applications unit. For instance, units on combustion chemistry are interspersed with units on equipment design and operation.

The manual begins with an introduction of the training program and its relationship to the operator certification process. The program considers the operator's role in the regulatory environment and in public relations.

This manual focuses on the technical and operational aspects of good combustion practices in MWC units. The characteristics of municipal solid waste (MSW), its fuel properties, and the influence of waste processing are presented. These are followed by learning units on combustion principles and MWC equipment features. Next comes a sequence on good combustion practices, air pollution control, instrumentation, and flue gas treatment. The training program concludes with consideration of automatic control theory, control systems, trouble shooting, special system considerations, and risk management.

COURSE LIMITATIONS

To the extent possible, this manual was written in a manner consistent with USEPA policy regarding municipal waste combustors and the demonstrated features of good combustion practice.

Detailed administrative and legal aspects of unit operations are not emphasized in the program because the regulations under which units operate will vary with location and time. Operators are urged to obtain specific regulatory information and permit requirements from the owner/operator organization.

1. INTRODUCTION

Slide 1-1

```
CLEAN AIR ACT AMENDMENTS
(CAAA) OF 1990

Develop Training & Certification
Require Operators to be Trained
Publish New Source Performance Stds.
    & Emission Guidelines
Regulate Through State Plans
```

The Clean Air Act Amendments (CAAA) of 1990[1] call for the U. S. Environmental Protection Agency (USEPA) to develop a model state training and certification program for operators of municipal solid waste combustors (MWCs). In addition, the amendments make the operation of such a unit unlawful unless each person having control over the processes affecting its emissions has satisfactorily completed an appropriate training program.

New Source Performance Standards[2] (NSPS) and Emission Guidelines[3] (EG) became effective on February 11, 1991. The NSPS and EG are applicable to MWC units with capacities of 225 Mg/day (250 tons/day) or greater. Operators of MWC units must satisfy federal training and certification requirements. These requirements are generally administered by the various states. Some states have adopted regulations requiring ASME certification of operators, whereas other states have developed their own operator certification programs.

Slide 1-2

```
MUNICIPAL WASTE COMBUSTOR
OPERATOR TRAINING PROGRAM

Goal:   Adequate Understanding to Pass
        ASME General Examination for
        Provisional Certification
```

The primary goal of this operator training program is to provide an adequate level of understanding to enable MWC operators to complete the requirements of the ASME Standard for provisional certification as resource recovery facility operators (ASME QRO-1-1989).[4] The actual testing required for the ASME Certification is administered separately by the ASME and is not included in this training program.

```
+------------------------------------------------------+
|              MUNICIPAL WASTE COMBUSTOR                |
|              OPERATOR TRAINING PROGRAM                |
|                                                      |
|    Focus:   Basis for Equipment Operation            |
|                    and Maintenance                   |
|             Basis for Good Combustion Practice        |
|                    and Environmental Control          |
+------------------------------------------------------+
```

The training focuses on the knowledge required by operators to understand the basis for proper operation and maintenance of municipal waste combustors. Particular emphasis is placed on the various technical and operational aspects of combustion which are important for environmental control.

Slide 1-4

```
+------------------------------------------------------+
|              COURSE MANUAL ORGANIZATION              |
|                                                      |
|         1     Introduction                           |
|      2,12     Environmental Concerns & Regulations   |
|       3-4     Characteristics of MSW                 |
|       5-9     Combustion Principles                  |
|      6-11     MWC Equipment Features                 |
|     13,14     Instrumentation                        |
|     15-21     Air Pollution Control                  |
|     22-23     Automatic Control                      |
|     24-25     Operating Practices & Upsets           |
|     26-28     Special System Considerations          |
|     29-30     Risk Management                        |
+------------------------------------------------------+
```

The course manual begins with an introduction to the training program and its relationship to the operator certification process. Next, the operator's role in the regulatory environment and in public relations is discussed. This is followed by consideration of municipal solid waste (MSW) characteristics, its fuel properties, and the influence of solid waste processing.

Learning units are presented on combustion principles and on MWC equipment design and operational features. Next is a sequence of learning units on good combustion practice, instrumentation, air pollution control, and flue gas treatment.

The training program concludes with consideration of automatic control theory, control systems, trouble shooting, special system considerations and risk management.

Slide 1-5

```
TRAINING PROGRAM TESTING

Pre-Test
Post-Test
    Same Form and Difficulty
    Measures Training Effectiveness
```

The Pre-Test is a measure of knowledge at the beginning of the training program, and the Post-Test measures it at completion. The Pre-Test and Post-Test are designed to be of approximately the same level of difficulty. Questions are based on the material presented in the course manual. The tests are to be taken under "closed book, time limited" testing conditions.

Pre-Test scores are expected to vary widely due to variations in individual educational background and experience. A Pre-Test score is also an indication of the need for training. The level of improvement in grades on the Post-Test over those of the Pre-Test is a measure of the learning which has occurred.

The Pre-Test and Post-Test are not necessarily equivalent in difficulty to the ASME General Examination for Provisional Certification, although they are designed to focus on the same subject areas. The ASME QRO Provisional Certification Examination, the Pre-Test, and the Post-Test are in the form of multiple-choice questions.[4]

Slide 1-6

```
ASME PROVISIONAL CERTIFICATION

PROVISIONAL CERTIFICATION REQUIREMENTS
    High School Diploma or Equivalent
    Five Years of Acceptable Experience
    Pass General Examination
```

The qualifications for ASME QRO Provisional Certification[4] are the same for both shift supervisors and chief facility operators. To obtain provisional certification, the applicant must pass the General Examination. The examination may be retaken whenever it is offered.

Up to two of the five years of acceptable experience can be met by applicants who have completed a baccalaureate degree with a major in a physical science or engineering or who have completed 60 credits of course work in advanced math, chemistry, fluid dynamics, thermodynamics, material science, combustion, and/or environmental, mechanical, civil, chemical or electrical engineering.

Slide 1-7

```
┌─────────────────────────────────────────────────────┐
│      ASME PROVISIONAL CERTIFICATION EXAMINATION       │
│                                                       │
│          General Examination (Written)                │
│              Solid Waste Management (25%)             │
│              Theory (25%)                             │
│              Operations (50%)                         │
└─────────────────────────────────────────────────────┘
```

The ASME General Examination for Provisional Certification is a written, multiple-choice, closed-book test, which is administered as a national examination. The examination will cover solid waste management and regulations, theory, and operations, with the questions distributed as indicated by the percentages listed.

Slide 1-8

ASME GENERAL EXAMINATION SUBJECT AREAS[5]

Part 1	Part 2	Part 3
25% of examination	25% of examination	50% of examination
Solid waste collection, transfer, and management, covering the following:	Theory, covering the following:	Operation of a resource recovery facility, covering the following:
• Municipal solid waste composition • Collection techniques • Seasonal and industrial impact on the character of refuse • Ash disposal • Landfills • Composting • Environmental public relations • Environmental regulation and requirements	• Combustion • Chemistry • Thermodynamics • Material science • Mechanical and electrical operation and technology • Air pollution control technology • Air emission stack monitoring	• Material handling equipment • Boiler operations • Generator and turbine operations • Ash handling and disposal operations • General operations and maintenance procedures and techniques • Worker safety • Control room operations • Continuous emissions monitors and their calibration

Courtesy of ASME Codes & Standards, Printed with Permission

The subject areas of the General Examination are listed in the ASME Standard for Qualifications and Certification of Resource Recovery Facility Operators (ASME QRO-1-1989).[4,5] Specific information about the examination application procedures can be obtained by writing the ASME, Codes & Standards, United Engineering Center, 345 East 47th Street, New York, NY 10017-2392.

Slide 1-9

```
LEARNING UNITS IN ASME EXAM AREAS

Part 1, Solid Waste Management (25%)
     Learning Units:  2, 3, 4, 12

Part 2, Theory & Technology (25%)
     Learning Units:  5, 7, 9, 13, 15, 16
                      17, 20, 21, 22, 27

Part 3, Operations (50%)
     Learning Units:  6, 8, 10, 11, 12
                      14, 15, 18, 23, 24
                      25, 26, 28, 29, 30
```

The current training program focuses on the subjects to be covered in the ASME General Examination. Although many of the learning units include overlapping subject areas, their primary focus can be distributed as indicated above. In general, the operational aspects of equipment are based on either component or system designs, which are dependent upon MSW properties, regulations, and theoretical considerations.

Slide 1-10

```
ASME CERTIFICATION EXAMINATIONS

OPERATOR CERTIFICATION
     Operator Examination (Oral)
          Site-Specific Equipment
          Operations and Maintenance
          Procedures & Regulations
```

The Operator Examination is a site-specific, oral examination administered by three outside examiners. The Shift Supervisors and Chief Facility operators will be tested on many of the same topics in equipment design, operation, maintenance and procedures.

Some questions in the Operator Examination will depend upon whether the applicant is applying for certification as a Shift Supervisor or a Chief Facility Operator. The Shift Supervisor's examination will include special emphasis on operational aspects, while the Chief Facility Operator's examination will include sections on overall unit operation, maintenance, and performance; job duties and responsibilities; and formulation of operational policies and procedures.

```
┌─────────────────────────────────────────────────────┐
│        ASME OPERATOR CERTIFICATION QUALIFICATIONS     │
│                                                       │
│    SHIFT SUPERVISOR                                   │
│    CHIEF FACILITY OPERATOR                            │
│                                                       │
│         Hold a Valid Provisional Certification        │
│         Have 6 Months Acceptable Experience as        │
│              Shift Supervisor or                      │
│              Chief Facility Operator                  │
│         Pass a Site-Specific Operator Exam            │
└─────────────────────────────────────────────────────┘
```

The procedures for obtaining ASME Operator Certification are approximately the same for both Shift Supervisors and Chief Facility Operators. A person's experience as either a Shift Supervisor or Chief Facility Operator may be an indicator of which certification is appropriate.

REFERENCES

1. Clean Air Act Amendments of 1990 and Conference Report to Accompany S. 1630, Report 101-952, U. S. Government Printing Office, October 26, 1990.

2. U. S. Environmental Protection Agency, "Standards of Performance for New Stationary Sources; Municipal Waste Combustors," Federal Register, Vol. 56, No. 28. February 11, 1991, pp. 5488-5514.

3. U. S. Environmental Protection Agency, "Emission Guidelines; Municipal Waste Combustors," Federal Register, Vol. 56, No. 28. February 11, 1991, pp. 5514-5527.

4. "Standard for the Qualification and Certification of Resource Recovery Facility Operators," ASME QRO-1-1989, American Society of Mechanical Engineers, New York, March 31, 1990.

5. "Memorandum on Provisional Certification Examination," Addressed to Individuals Interested in QRO Provisional Certification, by Alan Bagner, Director of Accreditation and Certification, ASME, 345 East 47th Street, New York, NY 10017, December 26, 1991.

2. ENVIRONMENTAL CONCERNS AND REGULATIONS

Slide 2-1

```
PUBLIC RELATIONS IN WASTE MANAGEMENT

    Out of Sight, Out of Mind
    Concern About Health & Environment
         Toxic and Carcinogenic Air Pollution
         Ground Water Contamination
```

The public attitude about solid waste management has been illustrated by the phrase "out of sight, out of mind". Our national life-style has been portrayed as one of consumerism in a throw-away economy. Planned obsolescence often appears to be a basic assumption in the manufacturing of consumer goods. For example, people in the urban areas of the United States generate about twice as much waste as those in comparable European societies.

The public relations aspects of solid waste management have become crucial, as the public has expressed genuine health and environmental concerns related to toxic and carcinogenic gaseous emissions and ground water contamination from solid waste disposal products.

Slide 2-2

```
ACRONYMS

NIMBY    Not in My Back Yard
YIMBY    Yes, in My Back Yard
BANANA   Build Absolutely Nothing Anywhere
         Near Anybody
NIMTO    Not in My Term of Office
```

Public concerns are often caricatured through the use of acronyms, as illustrated above. There are many examples where one or more of these have been related to the siting of new public service facilities, such as waste management facilities, highways, airports, and power lines.

The NIMBY concern focuses on the expected adverse impact of a particular proposal on individual property and environmental values. By contrast, the YIMBY advocacy is based upon the assumptions that the operation will have proper quality assurance controls and that financial rewards will be available to the host community. The BANANA acronym reflects the reality that almost every location is in someone's back yard. The NIMTO acronym characterizes the disowning of a problem by a public official who assures the public that the proposed solution can be avoided, at least for the time being.

```
PUBLIC RELATIONS PHENOMENA

Basis for Public's Mistrust
    Impact of Past "Acceptable Practices"
Concern About Waste Disposal Costs
```

Public opposition to new facilities may relate to its mistrust of the proposers and the scientific establishment. The basis for public mistrust may relate to the examples of certain facilities which previously were presumed to have been operated acceptably but were later found to produce toxic emissions, endangering the environment and public health. Outrage may be expressed by those who feel their legitimate concern has been discounted.

The public may also be concerned about the increase in waste disposal costs, which are brought about by expensive technological solutions, environmental requirements, and political realities. Environmentally responsible solid waste management has become increasingly costly. For example, federally mandated standards of performance for new and existing municipal waste incinerators are estimated to cost an additional $10.00 per ton of refuse processed.[1] The public is generally willing to pay for proper disposal of its own waste, but may well resist paying for disposal of the wastes of others.

Slide 2-4

```
HISTORIC LANDFILL ISSUES

Closed Dumps
Regulated Sanitary Landfills
Ground Water Contamination
Superfund Clean-Up
```

Public issues have shifted over the years as new information has become available. Regulations have evolved which forced the closing of dumps and established standards for sanitary landfills. In 1989, it was estimated that over 30,000 landfills in the nation had been closed and that many of the existing landfills would be closed in the next 15 years.[2] Landfill closures occur because of capacity limitations, inadequate provisions for ground water protection, and environmental problems associated with earlier disposal practices.

Landfills containing significant amounts of hazardous waste materials may be designated for Superfund clean-up activities. Superfund remediation projects have very considerable costs.

```
┌─────────────────────────────────────────────────────────┐
│   FEDERAL SOLID WASTE LAWS & REGULATIONS                 │
│                                                          │
│   Resource Conservation and Recovery Act, RCRA           │
│       Subtitle C:  Hazardous Waste Regulation            │
│               Manifest System                            │
│               Hazardous Waste Incineration Standards     │
│       Subtitle D:  Solid Waste Regulation                │
│               Sanitary Landfill Standards                │
└─────────────────────────────────────────────────────────┘
```

Federal solid waste legislation began in 1965 and has evolved as the Resource Conservation and Recovery Act of 1984[3] (RCRA). RCRA is administered by the USEPA, Office of Solid Waste.

RCRA is probably best known for its "manifest" system, which requires a "cradle-to-grave" documentation of the movement of hazardous materials from their manufacture until ultimate disposal. Mandatory reductions in the production of selected hazardous wastes and design standards for hazardous waste disposal sites have been established through RCRA. Under RCRA Subtitle D, standards have been established for the design and operation of sanitary landfills.

Legislation related to RCRA includes the Comprehensive Environmental Response Compensation and Liability Act of 1980 (CERCLA) and the Superfund Amendment and Reauthorization Act of 1986 (SARA). These acts established the procedures for selecting hazardous waste sites, remediating such sites, and recovering the costs from responsible parties.

```
┌───────────────────────────────────────────────────┐
│   HISTORIC INCINERATION ISSUES                     │
│                                                    │
│   Smoke & Odor From Incinerators                   │
│   Toxic Emissions                                  │
│   Ground Water Contamination From Ash              │
└───────────────────────────────────────────────────┘
```

Early concerns about incinerators focused on smoke, odor, and carbon monoxide emissions. These were addressed by state and local regulations. The first federal standard for incinerators was the 1971 New Source Performance Standard (NSPS) which applied to units burning greater than 50 tons/day, limiting their particulate emissions to a maximum of 0.08 grains per dry standard cubic foot (gr/dscf).[4]

In recent years the public has become increasingly concerned about acid rain, toxic air pollutant emissions, and proper ash disposal procedures.

Slide 2-7

```
INCINERATOR AIR POLLUTANTS

Particulate Matter (PM)
Carbon Monoxide
Nitrogen Oxides
MWC Acid Gases
    Hydrogen Chloride & Sulfur Dioxide
MWC Organics
    Dioxins, Furans & Other Organics
MWC Metals
    Lead, Cadmium, Mercury & Other Metals
```

Currently regulated air pollutants from incinerators are listed above. Additional federal regulations for lead, cadmium, and mercury emissions from MWCs are currently under development.

Slide 2-8

```
FEDERAL AIR POLLUTION LAWS & REGULATIONS

Clean Air Act, CAA

State Implementation Plans
    State Rules and Regulations Must be at
    Least as Strict as the Federal Guidelines
    and Approved by the USEPA
```

Federal air pollution legislation began with the passage of the Air Pollution Control Act of 1955.[4] Since then, revisions and amendments to the law have occurred seven times, with the most recent being the passage of the Clean Air Act (CAA) Amendments of 1990.

The U. S. Environmental Protection Agency (USEPA), Office of Air Quality Planning and Standards, administers federal air quality regulations. A provision of the CAA requires the USEPA to take into consideration the full range of economic consequences of its regulations. In general, a regulation is first publicly proposed. After a review period, it may be modified and then promulgated.

The USEPA generally specifies the federal requirements, with enforcement provided by state agencies. Each state develops its own plan for implementing air quality control, which must be approved by the USEPA. State implementation plans must include regulations which are at least as strict as the applicable federal standards.

Slide 2-9

```
NATIONAL AMBIENT AIR QUALITY STANDARDS (NAAQS)

Criteria Air Pollutants (emitted by sources)
Secondary Air Pollutants (formed indirectly)
Non-Attainment Areas
Prevention of Significant Deterioration, PSD
```

National Ambient Air Quality Standards (NAAQS) have been established by the administrator of the USEPA to define levels of air quality which protect public health and welfare. NAAQS have been established for both criteria and secondary air pollutants.

Non-Attainment areas are those which exceed the NAAQS for a particular pollutant, such as ozone or sulfur dioxide.

Prevention of Significant Deterioration (PSD) measures have been established to help maintain the quality of air in selected regions, with less contamination than that specified in the NAAQS. PSD rules have required facilities to apply the "Best Available Control Technology" (BACT).[5]

PSD rules have been specifically applied to MWC units built after June 1, 1975 if their capacity was greater than 250 tons/day.[5] Therefore, as the technology has advanced, the degree of emissions control required for new units has considerably exceeded that of the previously mentioned NSPS of 1971.

Slide 2-10

```
CRITERIA POLLUTANTS

Particulate Matter (PM)
Sulfur Dioxide
Carbon Monoxide
Nitrogen Dioxide
Lead
Ozone
```

Criteria pollutants are those emitted air pollutants which have appropriately documented health effects for which a NAAQS has been established. Secondary criteria air pollutants are those formed indirectly in the atmosphere (e.g., ozone) rather than being directly emitted.

Regulation of emissions of criteria pollutants are generally based on health and welfare effects. For instance, sulfur dioxide emissions from identified sources are regulated to assure that the ambient level concentrations do not exceed the NAAQS.

```
┌─────────────────────────────────────────────────────────┐
│              NATIONAL EMISSION STANDARDS FOR             │
│              HAZARDOUS AIR POLLUTANTS (NESHAP)           │
│                                                         │
│           Identify Toxic Air Pollutant Emissions        │
│           Set Maximum Emission Limits                   │
│                 Apply Equally to New & Existing Units   │
└─────────────────────────────────────────────────────────┘
```

One section of the CAA establishes the procedures for regulating hazardous air pollutants. If the Administrator of USEPA establishes that a particular of emission is toxic, National Emission Standards for Hazardous Air Pollutants (NESHAPs) regulations are required to be established to protect health. The maximum concentrations allowable under NESHAPs are the same for both new and existing units.

```
┌─────────────────────────────────────────────────────────┐
│          CLEAN AIR ACT AMENDMENTS OF 1990               │
│                                                         │
│      New Units:   New Source Performance Standards      │
│      Existing Units:   Emission Guidelines              │
└─────────────────────────────────────────────────────────┘
```

The CAAA requires the EPA to adopt standards for both new and existing MWCs after taking into consideration the Maximum Available Control Technology (MACT). Federal standards for new and modified stationary sources are known as New Source Performance Standards (NSPS). In February 1991, the USEPA updated their earlier NSPS for municipal waste combustor (MWC) units. These now apply to units having capacities greater than 250 tons/day.[6] One example of the regulatory changes from 1971 is that the PM limit went from 0.08 to 0.015 grains/dscf.

Likewise, federal standards for existing units, known as Emission Guidelines (EG), were published for existing MWC units with capacities greater than 250 tons/day.[7] The NSPS and EG include requirements which are technology-based, rather than health-based. Technology-based emission limits are based on control available through the application of the Best Demonstrated Technology (BDT).

The NSPS and EG require continuous emission monitoring systems (CEMS), the use of Good Combustion Practice (GCP), as well as annual stack tests to demonstrate compliance with particulate matter, dioxin/furan, and acid gas emission limits. In addition to the previously discussed operator certification requirements, a site-specific training manual must be maintained and updated annually and used by all staff associated with MWC unit operations.

Slide 2-13

```
PUBLIC RELATIONS IN WASTE MANAGEMENT

    Problems Which Are "Owned" Can Be Solved
    Public Must Be Informed
    Environmental Controls Are Available
    Method of Payment Required
```

Good public relations are crucial to achieving environmentally responsible waste management. The public generally must "own the problem" before it will develop the desire to solve it. The public and its trusted representatives must be fully informed about the magnitude of the problem and the trade-offs between risks and costs. The public needs to obtain clear information rather than misinformation.

Although advocates generally conclude that environmentally acceptable solutions are available, public and political support is required for implementing them. To reach the goal of environmentally responsible waste management, the public will have to accept and support methods for paying the associated costs.

Slide 2-14

```
PUBLIC RELATIONS POSITIVES

Good Signs
        Clean Air Act Amendments of 1990
        Recycling
        Waste Minimization
        Conservation and Renewable Energy
```

There are good indications that the public is ready to do its part. For example, after years of debate, the Clean Air Act Amendments of 1990 were passed. More stringent air pollution controls are now being required, in spite of their expense.

A second good sign is that recycling appears to be capturing the public's attention. In the 1980s, over half the aluminum cans produced were recycled.[8] In 1988, a national goal was established to recycle 25% of the MSW generated,[9] with some states proposing to recycle up to 50%.[10] Of course, a basic life-style change is required to move from our throw-away economy to one that emphasizes creating less waste and recycling. In addition, recycling programs tend to be labor intensive and expensive, with the secondary materials markets underdeveloped and unstable.

As a parallel, it is interesting to note that national energy consumption did not grow from 1973 to 1986,[11] although the population grew. Energy conservation

occurred primarily because of energy price increases. However, from 1986 to 1991 prices dropped and consumption increased.

Slide 2-15

```
+-------------------------------------------------------+
|        OPERATOR'S ROLE IN PUBLIC RELATIONS            |
|                                                       |
|   Operators Must                                      |
|        Be Trustworthy                                 |
|        Be Certified as Being Qualified                |
|        Know What Is Expected                          |
|        Demonstrate Willingness to                     |
|             *   Execute Responsibilities              |
|             *   File Reports                          |
|             *   Communicate                           |
|             *   Assure Safety                         |
+-------------------------------------------------------+
```

Certification of operators (chief facility operator, shift supervisors) is required as a method of protecting against operations which threaten the health and welfare of both the public and employees.

The operator's primary responsibility in public relations is to be trustworthy. Sanctions may be imposed on certified operators who fail to make accurate reports and/or to operate units properly. If management or the public concludes that an operator's integrity has been compromised, the operator's job may be in jeopardy. Management will generally fire an untrustworthy person rather than risk exposure to equipment failures, accidents, downtime, sanctions, fines, and lawsuits.

In addition to being qualified and certified, the operator must assure that the unit operates appropriately as required by the permit or regulations. Although the unit may have a control system which is designed to automatically correct unit operations and is "fail safe", operators are required to understand the control systems so they can anticipate and make appropriate changes in control settings. The operator must be able to supervise those who assist in operating the unit.

Where violations of standards occur, the operator is required to file timely reports about the type, severity, duration, and cause of the violation.

The operator must communicate effectively with both staff and upper management. Questions must be asked, answers listened to, changes advocated, and decisions made that assure the proper operation and maintenance of the equipment. Such actions can help conserve the capital investment of equipment and help assure the productivity of the unit. The operator, as a representative of management, has responsibility for assuring that safe operating procedures are developed and followed and that personal safety equipment is available and used.

REFERENCES

1. Lloyd Compton, "Assessing the Costs of EPA's New Regulations for Existing WTE Facilities," <u>Solid Waste and Power</u>, June 1991, pp. 18-26.

2. Donald A Wallgren, "Modern Landfill Technology: The Cornerstone of an Integrated Solid Waste Management Program," <u>Integrated Solid Waste Management</u>, Frank Kreith, editor, Genium Publishing Corporation, Schenectady, NY, 1990, pp. 121-133.

3. Terry Grogan, "The Environmental Protection Agency's Municipal Solid Waste Program: Current Action and Future Plans," <u>Integrated Solid Waste Management</u>, Frank Kreith, editor, Genium Publishing Corporation, Schenectady, NY, 1990, pp. 155-164.

4. Kenneth Wark and C. F. Warner, <u>Air Pollution, Its Origin and Control</u>, 2nd Edition, Harper & Row, Publishers, NY 1981, pp. 41-61.

5. C. David Gaige and Richard T. Halil, Jr., "Clearing the Air About Municipal Waste Combustors," <u>Solid Waste and Power</u>, January/February 1992, pp. 12-17.

6. U. S. Environmental Protection Agency, "Standards of Performance for New Stationary Sources; Municipal Waste Combustors," <u>Federal Register</u>, Vol. 56, No. 28. February 11, 1991, pp. 5488-5514.

7. U. S. Environmental Protection Agency, "Emission Guidelines; Municipal Waste Combustors," <u>Federal Register</u>, Vol. 56, No. 28. February 11, 1991, pp. 5514-5527.

8. Jerry Powell, "Recycling in the '80s: How are We Doing?" <u>Resource Recycling</u>, Vol. 8, No. 2, May/June 1989, pp. 30-31.

9. U. S. Environmental Protection Agency, "The Solid Waste Dilemma: An Agenda for Action," EPA/530-SW-89-019, 1989.

10. David Spencer and Jerry Powell, "Recycling," <u>Integrated Solid Waste Management</u>, Frank Kreith, editor, Genium Publishing Corporation, Schenectady, NY, 1990, pp. 59-98.

11. <u>Energy Conservation Trends, Understanding the Factors That Affect Conservation Gains in the U.S. Economy</u>, U. S. Department of Energy, DOE/PE-0092, September 1989, pp. 2-16.

3. MUNICIPAL SOLID WASTE TREATMENT

Slide 3-1

```
INTEGRATED SOLID WASTE MANAGEMENT

        Source Reduction
        Recycle and Reuse
        Incinerate
        Landfill
```

The available components of an integrated solid waste management program include source reduction, recycling, incineration, and landfill disposal. The set of disposal methods selected will vary depending on the size of population, availability of sites, and political acceptance.

Slide 3-2

```
SOURCE REDUCTION - WASTE MINIMIZATION

REDUCE QUANTITY
        Improve Efficiency
        Improve Product Life
        Reusable versus Throwaway
        Packaging Materials
REDUCE TOXICITY
        Material Substitution
```

Source reduction or waste minimization focuses on process changes which reduce both the amount and toxicity of materials entering the waste stream.[1] Examples of quantity reduction include the use of returnable bottles and the purchase of bulk items which require less packaging material. Waste minimization relates to socioeconomic value issues, such as life-style (consumption), product life, and efficiency. Although elements of source reduction are advocated by many members of the public, high rates of consumption and a throw-away economy are often considered basic to our way of life.

Source reduction also includes the substitution of less toxic and environmentally preferred materials in manufacturing products. Substitution may be achieved through governmental regulations on manufacturing, such as for asbestos, PCB oils, and pesticides. Other substitutions can be achieved through consumer market forces, such as reduced use of styrofoam cups. In general, the use of cadmium and other toxic materials in ink is being phased out, so that such hazardous waste will not result from the recycling of paper.

Although it is not common in solid waste management, source reduction could be stimulated by requiring the cost of disposal to be included in the purchase price. Many communities now require the payment of a disposal fee for each tire sold, as the tire is presumed to eventually be discarded as waste.

Slide 3-3

```
RECYCLING

    Positive Public Perception
    Separation of Reusable Products
    Raw Material Markets
    Conserve Natural Resources
    Reduce Environmental Impact
    Extend Landfill Life
```

Recycling is perhaps the most positively accepted component in waste management. Source separation at the curb-side or drop-off centers and on-site mixed waste mechanical techniques are used to segregate raw materials such as aluminum, ferrous metals, newsprint, and glass. These are sold either to primary manufacturers or in secondary materials markets. The costs of recycling programs are off-set by materials sales. However, the materials markets traditionally fluctuate and may become marginal, with the "soft" newsprint market being a recent example.

Sales to primary manufacturers can result in reduced mining activities and energy consumption, thereby conserving natural resources and reducing the environmental impact. However, care must be taken in the reclamation effort, as undesirable and/or hazardous waste streams may be created. An example is the de-inking operations for newsprint which may produce toxic contaminants if cadmium is used in the ink.

An important credit for recycling is the extension of landfill life due to the direct reduction in disposal requirements.

Slide 3-4

```
COMPOSTING

Aerobic Decomposition (with Oxygen)
        Biological Microorganisms Required
        Produces Carbon Dioxide & Moisture
Anaerobic (Without Oxygen) Decomposition
        Produces Methane
```

Composting is another important area of recycling MSW.[2] Composting of grass clippings, leaves, and other yard wastes can be accomplished adjacent to where they are produced or at a composting center. Yard wastes may be banned from a landfill because they use valuable capacity. In addition, yard wastes are undesirable in MSW fuel because of high moisture and low heating value.

Most of the early composting facilities in the United States were characterized by their limited capital investment, mechanical processing, and control of the biological process. Aerobic (with air) composting in windrows or long piles uses traditional biological decomposition of organic materials through the action of microorganisms in the presence of oxygen. Carbon dioxide and moisture is produced.

Systems using anaerobic decomposition (without air) can be designed to provide faster decomposition at higher temperatures. Anaerobic decomposition requires a closed vessel to control the methane gas and odors which are produced.

The trend is toward regional facilities which are "under roof," provide mechanical processing, and control the decomposition process. This increases the decomposition rates, minimizes odors and kills pathogens and weed seeds.[3] Normal composting requires aeration, mixing, adequate time and temperature and moisture control.

Composting of organic materials such as paper products and waste from restuarants and food processing industries is often accomplished in closed vessels.[4] If composting materials include sewage sludge, special concerns include the environmental impact of its potential heavy metals content.

Slide 3-5

```
COMPOST MARKET REQUIREMENTS

     Process Requirements
     Pre-Processing
     Post-Processing
     Market Development
```

The compost from MSW and sewage sludge will be effectively free of viral, bacterial, and parasitic pathogens if the process maintains temperatures above 130° F for several days, as required under RCRA Subtitle D.[5]

Mechanical pre-processing can be accomplished with shredders and screens (for size control and removal of glass and metals). Post-processing may be required to remove additional glass, rocks, and plastic to meet market product specifications.

The market value of compost is that of a humus-type soil conditioner, with minimal value as a fertilizer. Compost can improve the soil's ability to retain water and aid in aeration by decreasing soil's crusting tendency.

Slide 3-6

```
LANDFILL REQUIREMENTS UNDER RCRA

     Containment System
        Cap System
        Bottom Liner
     Leachate Collection & Treatment
     Ground Water Monitoring
     Gas Monitoring & Collection
```
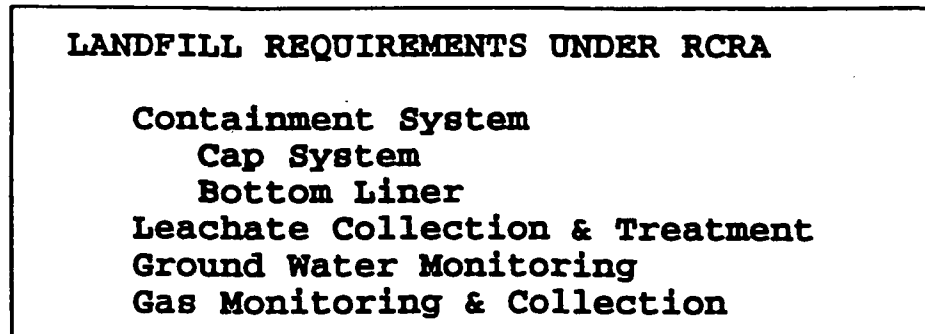
There are various requirements for a modern sanitary landfill under RCRA, Subtitle D.[5] The particular concern is to prevent the leaching of heavy metals from the wastes into the ground water and to control the emissions of methane and other landfill gases which are formed from waste decomposition.

Systems for containment and liquid and gas collection are required. Also, ground water wells and gas probes are installed for monitoring at selected locations.

An on-site leachate treatment plant will probably be located at larger landfills. Also, such sites may have a gas extraction system which recovers methane. The methane can be piped to a combustion device for power production.

Slide 3-7

MODERN LANDFILL SYSTEM
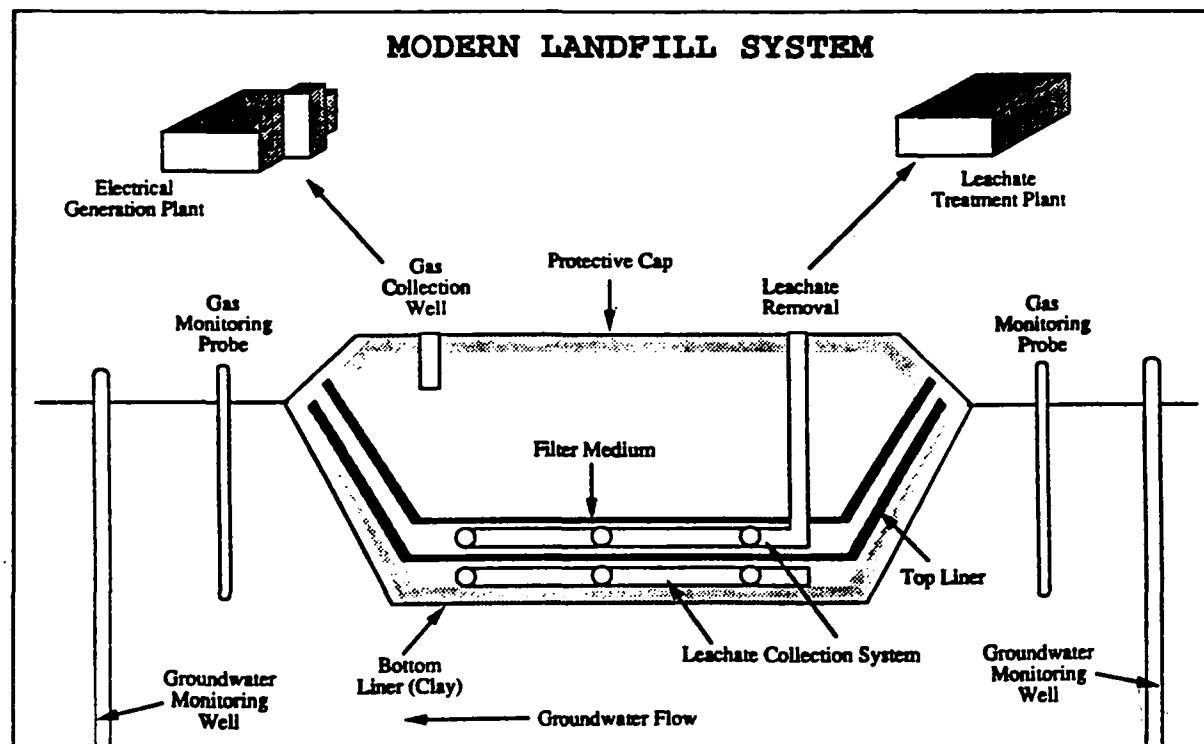
Upon initial construction of a landfill, the entire bottom is covered with a liner, which may be formed from both clay and synthetic materials such as high-density polyethylene. Next, a leachate collection system is installed to capture and remove liquids, including those from precipitation and those formed by decomposition of waste. The top of the landfill is covered with a cap to prevent the infiltration of water from precipitation into the landfill and to control landfill gas emissions.[6]

Slide 3-8

```
MONOFILL

Special Landfill
     Hazardous Waste: Concentrations
     Below Specified Limits
          MWC Ash
          HWI Ash
          Hazardous Waste
          Chemical Waste
```

A monofill is a special landfill which accepts only a single type of waste. Examples of such waste types would include ash from MWC units, ash from hazardous waste incinerators, and certain low-level hazardous and chemical wastes. Monofills would have special design, operating, and monitoring requirements in addition to those of modern sanitary landfills.

Issues related to the disposal of MWC ash in sanitary landfills and monofills are related to their heavy metals content and leaching characteristics. These issues will be presented in Learning Unit 18.

Slide 3-9

```
MUNICIPAL WASTE COMBUSTORS, MWC

   Incineration
        Volume Reduction
   Waste-to-Energy Resource Recovery
        Volume Reduction & Energy
```

In the past decade, MWC technology has shifted from incinerators to waste-to-energy resource recovery units.[7] Although MSW is still considered to be garbage, which should be disposed of safely and economically, it can also be considered as a renewable energy resource. Waste-to-energy MWC units produce important revenue

associated with the sale of either steam or electricity. However, MSW has a relatively low value as a fuel.

In the late 1960's there were some ill-fated ideas about selling garbage to the power plants. From an economic view-point, the value of MSW fuel is positive only if the costs of alternate disposal techniques are taken into account. Consequently, MSW may be considered to have increased value where landfill capacities are limited and transportation costs to landfills are high.

Combustion of MSW does not eliminate the need for landfills, although it does reduce the amount of such residues sent to the landfill. The ash residues have around 25% of the weight and 10% of the volume of the original MSW.[8,9]

Slide 3-10

```
┌─────────────────────────────────────────────────────┐
│        MUNICIPAL WASTE COMBUSTORS                     │
│                                                       │
│        Mass Burning Units                             │
│        Refuse-Derived Fuel (RDF) Units                │
└─────────────────────────────────────────────────────┘
```

Mass burning technology of mixed MSW is often adopted where the projected earnings from selling raw materials recoverable from MSW do not support the increased processing costs. Recovery of materials such as aluminum, ferrous metals, and glass have economic value which depends upon market conditions. Because metals, glass, and masonry materials have essentially no heating value, they are generally considered as undesirable components in MSW fuel. However, mass burn system designs are able to compensate for the presence of such non-combustibles.

Refuse-derived fuel (RDF) technology makes use of various combinations of front-end processing to remove a reasonable amount of the non-combustibles and materials with limited heating value, such as metals, glass and yard wastes. The RDF fuel is also more homogeneous in size and composition than raw MSW.[10]

RDF generally has less moisture than MSW, because of the drying associated with frictional heating during shredding and drying during conveying. "Fluff RDF" generally has heating values which are about 25% larger than that of its MSW. This is because of its lower ash (inorganic) and moisture contents.

RDF is generally considered to be a better fuel than MSW, because its heating value is increased over that of raw MSW. However, RDF generally burns with a lower combustion efficiency than raw MSW, based on carbon monoxide emissions. This issue will be further discussed in Learning Unit 12.

```
┌─────────────────────────────────────────────────────┐
│              FRONT-END PROCESSING                    │
│                                                      │
│     Elimination of Undesirable Materials             │
│     Size Reduction                                   │
│     Pre-Combustion Materials Recovery                │
│        for Refuse-Derived Fuel, RDF                  │
│                                                      │
└─────────────────────────────────────────────────────┘
```

Front-end processing includes on-site fuel modification and materials recovery from MSW before it is burned. At a minimum, its purpose is to eliminate certain undesirable materials from the waste stream for both mass burning or RDF units. Gas tanks must be removed as they could explode and damage the combustion equipment. Bulky white-goods and metal objects (e.g., water tanks and barrels) have no heating value and are basically un-treatable. Such bulky items would generally interrupt the air supply to the fuel.

Some materials which are undesirable at one unit may be acceptable in a unit of a different design. For instance, a car tire or mattress is often unacceptable at modular, mass burn units, but may be acceptable at larger mass burn units. Some facilities exclude tires because they are a source of SO_2 emissions.

Slide 3-12

```
┌─────────────────────────────────────────────────────┐
│        RDF PROCESSING EQUIPMENT                      │
│                                                      │
│        Flail Mill Shredder                           │
│        Trommel Screen                                │
│        Magnetic Separator                            │
│        Eddy Current Separator                        │
│        Hammer Mill Shredder                          │
│        Disk Screen or Air Classifier                 │
│                                                      │
└─────────────────────────────────────────────────────┘
```

RDF is generally produced in a materials recovery facility (MRF). Waste processing equipment at a particular site may include various conveyors, shredders, screens, and separators.

Various classifications of RDF are listed in the next learning unit. "Shred-and-burn" RDF systems often produce a "coarse RDF" which features size reduction without materials recovery. Coarse RDF is less disruptive of the air flow through the fuel bed than would be the mass burning of its original MSW.
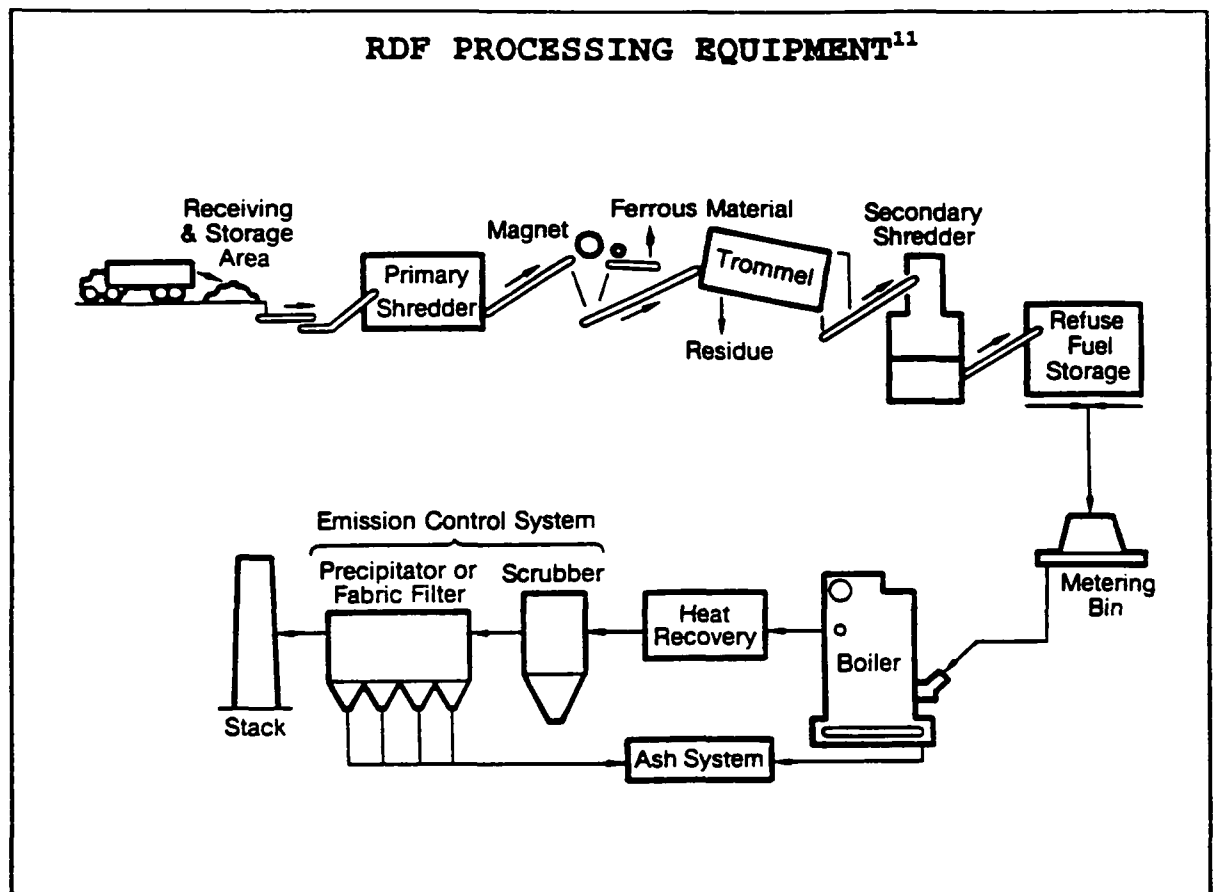
RDF PROCESSING EQUIPMENT[11]

From Joseph G. Singer, <u>Combustion Fossil Power</u>, 4th Edition, 1991, reprinted with permission of Combustion Engineering, Inc.

An example arrangement of waste processing equipment components for the production of RDF is illustrated above.

After the primary shredding process, materials may be removed by screening and separation devices.[10] The resulting higher quality RDF is called "fluff RDF." Its production includes metals separation, removal of fines (sand and glass grit, grass, etc.) and size reduction to about one-third that of coarse RDF.

Magnetic separator designs provide electromagnets which cause the removal of the ferrous metals from the waste stream. Eddy current units use special electrical equipment which causes aluminum to be removed as it passes over the unit.

Some facilities will have staff who hand-pick aluminum cans and other items from the shredded material on a conveyor.
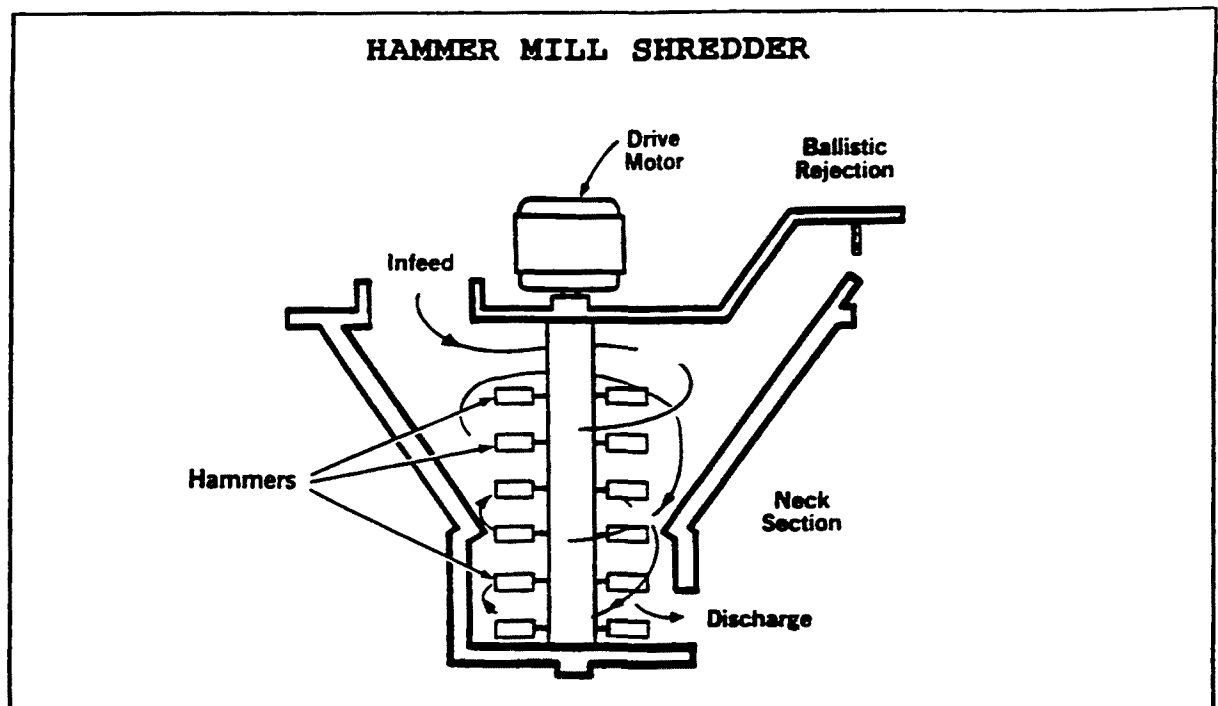
HAMMER MILL SHREDDER

From J. D. Blue et al., "Waste Fuels: Their Preparation, Handling, and Firing," Standard Handbook of Power Plant Engineering, Thomas C. Elliott, editor, McGraw Hill Book Co., NY, 1989, reprinted with permission.

A hammer mill shredder can reduce most material items to below 2.5 inch sizes.[12] By contrast, flail mills are designed to tear open plastic bags and to provide moderate size reduction. In some facilities, flail mills are the primary shredder and hammer mills are the secondary shredder.
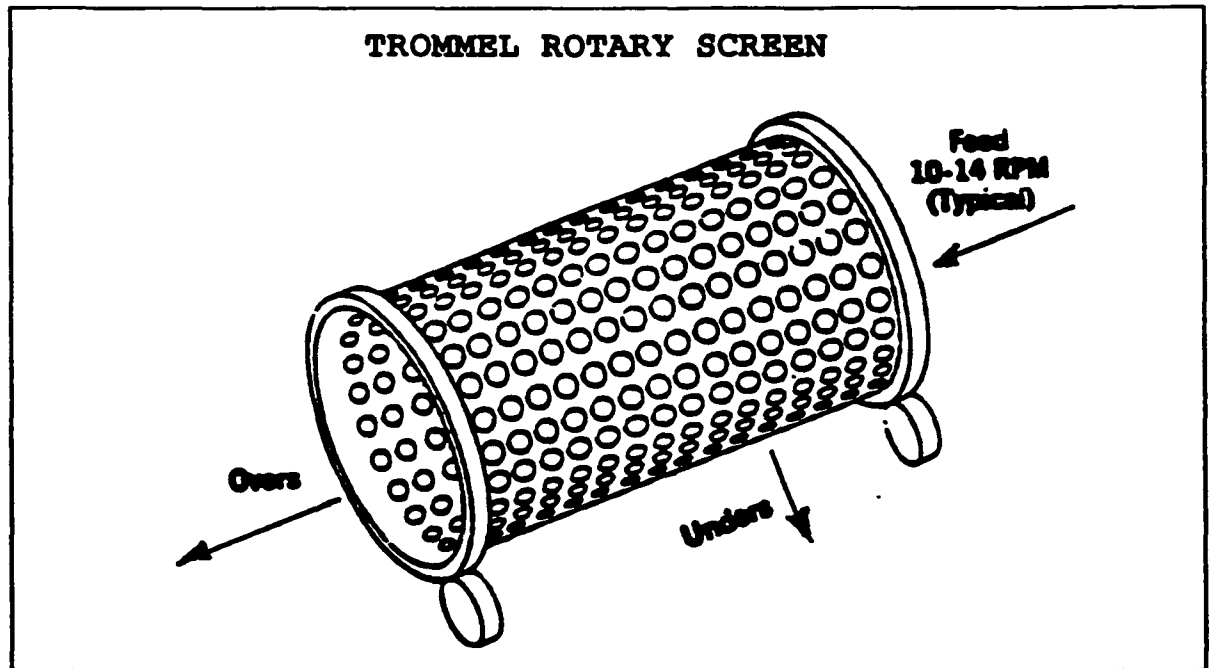
TROMMEL ROTARY SCREEN

From J. D. Blue et al., "Waste Fuels: Their Preparation, Handling, and Firing," Standard Handbook of Power Plant Engineering, Thomas C. Elliott, editor, McGraw Hill Book Co., NY, 1989, reprinted with permission.

Trommel and disk screens have special abilities to sort materials into two or more size categories, which can tend to segregate some materials according to compositions. For instance, very small sized materials such as grass and grit can be separated from streams which have larger sizes and higher combustibles content.
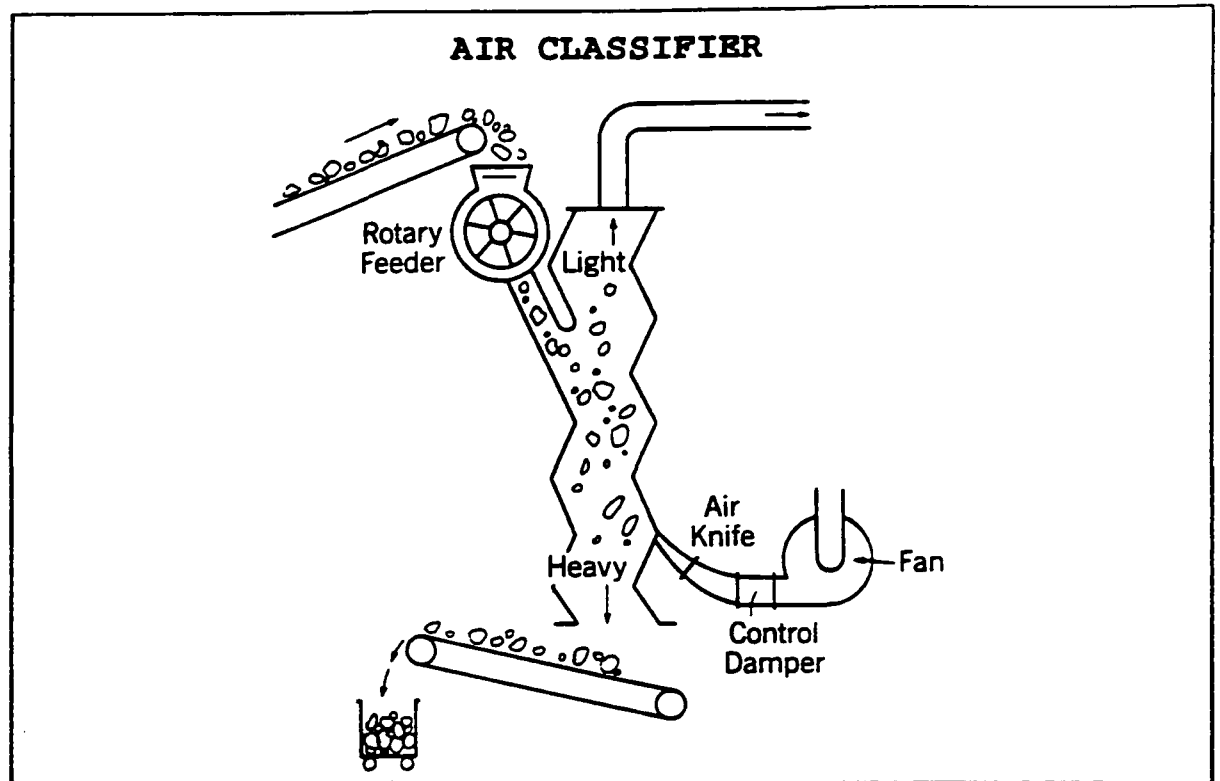
AIR CLASSIFIER

From J. D. Blue et al., "Waste Fuels: Their Preparation, Handling, and Firing," <u>Standard Handbook of Power Plant Engineering</u>, Thomas C. Elliott, editor, McGraw Hill Book Co., NY, 1989, reprinted with permission.

Air classifiers were developed to remove small dense particles such as glass and grit from the larger and less dense combustible material, called fluff. The fluff is more easily entrained in high velocity air, and the denser grit falls-out. Many facilities use disc screens to achieve such size reductions.

Slide 3-17

POST COMBUSTION PROCESSING

Ferrous Metal Extraction from Ash

Many mass burn units use magnets to recover ferrous metals from the bottom ash, after the combustion has been completed.

REFERENCES

1. Harry M. Freeman, "Source Reduction as an Option for Municipal Waste Management," Integrated Solid Waste Management, Frank Kreith, editor, Genium Publishing Corporation, Schenectady, NY, 1990, pp. 39-58.

2. Elliot Epstein and Todd Williams, "Solid Waste Composting Gains New Credence," Solid Waste and Power, June, 1988, pp. 275-278.

3. Jeffrey K. Turner, "MSW Composting, 1990s-Style," Solid Waste and Power, January/February, 1992, pp. 18-25.

4. R. A. Denison and J. Ruston, Editors, Recycling & Incineration, Evaluating the Choices, Environmental Defense Fund, Island Press, Washington, DC, 1990, pp. 84-89.

5. Resource Conservation and Recovery Act, Part 40, CFR Part 257, Subtitle D.

6. Donald A Wallgren, "Modern Landfill Technology: The Cornerstone of an Integrated Solid Waste Management Program," Integrated Solid Waste Management, Frank Kreith, editor, Genium Publishing Corporation, Schenectady, NY, 1990, p. 129.

7. Scott Siddens, "A Decade of Innovations in WTE Incineration," Solid Waste and Power, April, 1990, pp. 16-23.

8. Jeffrey L. Hahn, "Managing Ash--Closing in on Policy Decisions," Solid Waste & Power, August 1989, pp. 12-18.

9. Richard A. Denison and John Ruston, Recycling & Incineration, Evaluating the Choices, Environmental Defense Fund, Island Press, Washington, DC, 1990, p. 9.

10. Victor Brown and Henry Hefty, "Aiming for High-Spec RDF," Solid Waste and Power, April, 1990, pp. 38-44.

11. Joseph G. Singer, Combustion, Fossil Power, 4th Edition, Combustion Engineering, Inc., Windsor, CT, 1991, p. 8-22.

12. J. D. Blue et al., "Waste Fuels: Their Preparation, Handling, and Firing," Standard Handbook of Power Plant Engineering, Thomas C. Elliott, editor, McGraw Hill Book Co., NY, 1989, pp. 3-145 to 3-146.

4. CHARACTERIZATION OF MSW FUELS

Slide 4-1

```
SOLID WASTE ACRONYMS

HWI     Hazardous Waste Incinerator
MRF     Materials Recovery Facility
MSW     Municipal Solid Waste
MWC     Municipal Waste Combustor
MWI     Medical Waste Incinerator
RDF     Refuse-Derived Fuel
```

The acronyms listed above are often used in discussions of waste management. Their distinctive differences are important in regulatory and operational considerations.

Slide 4-2

```
CHARACTERIZATION OF WASTE COMPOSITION

Source
Type
Material Constituents
Ultimate Analysis (Element by Weight)
Proximate Analysis (Group by Weight)
```

MSW can be characterized by its source, type, constituents, elemental or ultimate analysis, and proximate analysis. These distinguish MSW and provide useful information about its properties.

Slide 4-3

```
MUNICIPAL SOLID WASTE SOURCES:

        Household waste
        Commercial (Retail)
        Institutional
        Specific Items
```

Municipal Solid Waste (MSW) is composed of the discards from household, commercial and institutional sources.[1] Since MSW includes both unprocessed and processed wastes from these sources, MSW includes wastes which have undergone source separation and on-site processing to recover useful materials and form RDF.

Household wastes are the materials discarded by single and multifamily dwellings, including motels and hotels as well as both permanent and temporary residential units.

Commercial (or retail) materials include those discarded from stores, offices, restaurants, warehouses, and the non-manufacturing activities in industry.

Institutional wastes include the materials discarded by schools, hospitals, and government facilities.

Although local definitions may vary, the NSPS definition of MSW includes: motor vehicle maintenance parts which are limited to batteries, tires and used motor oil.

Slide 4-4

```
MUNICIPAL SOLID WASTE EXCLUDES:

Industrial Process Waste
Segregated Medical Waste
Hazardous Waste
Specific Items
```

Municipal solid waste (MSW), as defined in the NSPS,[1] excludes segregated medical waste, industrial process waste, and hazardous waste. MSW is further defined to exclude mixtures of medical waste and medical waste discards (MSW from hospitals) which contain less than 30 percent by weight of medical waste discards. Some MWCs are permitted to burn segregated medical waste, if MSW represents at least 70% of the charge.

The federal definition of MSW excludes certain specific materials such as sewage, construction and demolition debris, industrial process and manufacturing waste, motor vehicles and engine blocks.

Slide 4-5

```
MEDICAL WASTE SOURCES

Human & Animal Diagnosis
Human & Animal Treatment
Human & Animal Immunization
Processing of Biologicals
```

Medical waste is the solid waste associated with the diagnosis, treatment and immunization of humans and animals, including the solid waste from research, production and testing of biologicals.[1] The term biologicals refers to vaccines made from living organisms.

Segregated medical wastes are wastes from the above sources which are required to be transported in special packages with labels and markings.[2] Such waste is often referred to as "red bag" waste, although it may be contained in a specially marked corrugated paste-board box. In general, operators should know whether their permit allows any labelled medical waste to be burned at their facility.

Slide 4-6

```
REGULATED MEDICAL WASTES[3]

Heterogeneous Mixture of Materials Capable
of Producing Infectious Diseases in Humans

1.   Cultures & Stocks of Infectious Agents
     & Associated Biologicals (incl. Vaccines)

2.   Human Pathological Wastes (Human Tissues,
     Organs, Body Parts, Body Fluids)

3.   Blood & Blood Products

4.   Sharps (Needles, Syringes, Scalpel Blades,
     Pipettes, Broken Glass)

5.   Contaminated Animal Carcasses & Body Parts

6.   Isolation Wastes

7.   Unused Sharps
```

The terms regulated medical wastes, controlled medical waste, and segregated medical wastes are often used interchangeably to identify the above types of infectious materials which are included in segregated medical waste.[3,4,5]

Slide 4-7

```
HAZARDOUS WASTE CONSTITUTES DANGER TO

          Public Health
          Welfare
```

Hazardous wastes are those which may constitute a danger to public health and welfare of the environment.[2] To be hazardous, the substance must contain a hazardous component which is above an established threshold concentration. Hazardous waste is not part of MSW, as it is regulated under the Resource Conservation and Recovery Act (RCRA).

Slide 4-8

```
HAZARDOUS WASTE

Oils
Flammable organics
Toxic metals & solvents
Explosives
Salts, Acids, Bases
```

Hazardous wastes are grouped as: waste oils and chlorinated oils; flammable wastes and synthetic organics; toxic metals, etchants, pickling and plating wastes; explosives, reactive metals and compounds; and salts, acids, and bases.[6]

Slide 4-9

```
INCINERATOR INSTITUTE OF AMERICA CLASSIFICATIONS[7]

Type 0     Trash with 8,500 Btu/lb
           10% moisture, 5% incombustible
Type 1     Rubbish with 6,500 Btu/lb
           25% moisture, 10% incombustible
Type 2     Refuse with 4,300 Btu/lb
           50% moisture,  7% incombustible
Type 3     Garbage with 2,500 Btu/lb
           70% moisture,  5% incombustible
Type 4     Human & Animal Parts, with 1,000 Btu/lb
           85% moisture,  5% incombustible
Type 5     Industrial By-Product Wastes which are
           gaseous, liquid, & semi-liquid
Type 6     Industrial Solid Byproduct Waste
           rubber, plastic, wood wastes
Type 7     Municipal Sewage Sludge Wastes
           residue from processing of raw sludge
```

Classification standards for solid waste were established by the Incinerator Institute of America (IIA) in 1968.[7] Average MSW could be approximated as a combination of IIA type 1 and type 2 waste. The IIA classification standard is generally considered to be out-of-date, although it is included in some local regulations. As discussed later, the American Society of Testing Materials has identified seven types of MSW fuels which are based on the composition, waste particle sizes, and the type of waste processing.

The IIA standard illustrates the fact that heating value is inversely related to fuel moisture. Moisture acts as a heat sink, requiring energy for evaporation, rather than contributing to heat release. Incombustibles, likewise, do not add any heating value to the fuel.

Therefore the major determining factors in the heating value of MSW are the moisture and ash contents. The other materials--such as plastic, textile, and paper--provide a relatively high amount of heat release, which is comparable to wood. The improvement in heating value associated with solid waste processing will be illustrated in discussions about RDF at the end of this learning unit.

Slide 4-10

MSW COMPOSITION/GENERATION[8,9]	Weight Percent	Million tons/yr
Paper and cardboard	40.0	71.8
Yard wastes	17.6	31.6
Metals	8.5	15.3
Glass	7.0	12.5
Plastics	8.0	14.4
Food wastes	7.3	13.2
Wood	3.6	6.5
Rubber and leather	2.6	4.6
Textiles	2.2	3.9
Miscellaneous	3.2	5.8
Total	100.0	179.6

The national average composition percentages and generation totals for MSW for 1988 in the United States are presented above.[8,9] The average person generates about 3.2 lb/day of MSW plus 0.4 lb/day of recovered materials.[10]

The compositions of MSW vary considerably depending on the time and the local conditions. The average metals and glass contents presented above may be over-estimated, due to national recycling efforts which have grown since the projections were made. In general, more waste is produced in urban regions and in affluent regions, however these same areas tend to emphasize recycling. Less wastes are generally produced in the winter than in other seasons, partly because of reduced purchasing activities and less yard wastes being generated.

Slide 4-11

```
┌─────────────────────────────────────────────────────────┐
│        ESTIMATE OF DAILY MSW FOR A REGION               │
│                                                          │
│   Example Population:        200,000 persons            │
│   Per Capita Production:     3.2 lb/day-person          │
│                                                          │
│   Daily Amount Produced:     640,000 lb/day or          │
│                              320 tons/day               │
└─────────────────────────────────────────────────────────┘
```

By multiplying 3.2 lb/day-person by the appropriate population, one can estimate the MSW produced in a region per day. Since there are 2,000 lb/ton, the daily tonnage produced can be established by dividing the daily pounds by 2,000.

Slide 4-12

AVE. ULTIMATE ANALYSIS[11,12] Element	As Received Percent by Weight	Dry Basis Percent by Weight
Carbon	25.6	34.2
Hydrogen	3.4	4.5
Oxygen	20.3	27.1
Nitrogen	0.5	0.7
Chlorine	0.5	0.7
Sulfur	0.2	0.2
Inorganics (ash)	24.3	32.6
Moisture	25.2	
Total	100.0	100.0

The ultimate analysis presents the distribution of total weight among the various chemical elements plus the moisture and ash (mineral incombustibles). Knowledge of the weight distribution among the elements can be used to estimate the amount of various products of combustion. For instance, uncontrolled sulfur dioxide and hydrogen chloride emissions can be estimated by using the ultimate analysis.

The inorganic constituents (incombustible ash) and moisture are also reported in the ultimate analysis. Note that ash and moisture make up about half the total weight of average MSW. The ash can be analyzed further to determine its constituents, such as silicon, iron, calcium oxide or other metal compounds.

Because of the variability of MSW composition, special techniques are required to obtain a representative sample. As indicated in the MSW example, the analysis can be based on the total weight of the sample "as received" in the laboratory. Alternately, a "dry basis" analysis of the sample can be presented, whereby the sample is dried in an oven before the elemental composition is determined.

```
┌─────────────────────────────────────────────────────────────┐
│         EXAMPLE OF PROXIMATE ANALYSIS OF RDF¹³              │
│                                                             │
│                    Yr. Average    Range During Year        │
│                    Percentage   Minimum    Maximum         │
│                    by Weight     Value      Value          │
│    Moisture          26.6         2.3        42.2          │
│    Ash               21.7        10.8        34.5          │
│    Volatile Matter   43.6        34.9        60.4          │
│    Fixed Carbon       8.1         0.0        21.6          │
│           Total     100.0                                  │
└─────────────────────────────────────────────────────────────┘
```

	Yr. Average Percentage by Weight	Range During Year Minimum Value	Maximum Value
Moisture	26.6	2.3	42.2
Ash	21.7	10.8	34.5
Volatile Matter	43.6	34.9	60.4
Fixed Carbon	8.1	0.0	21.6
Total	100.0		

The proximate analysis provides relative information about the burning mechanisms of the fuel. It presents the volatile matter, which is the fractional weight of the fuel which will burn as a gas, and the fixed carbon, which will burn as a solid. As in the ultimate analysis, the proximate analysis also indicates the amount of moisture which must be evaporated before the fuel will burn and the ash content.

One should note that both MSW and RDF are high volatility fuels, which burn primarily as a gas. However, a sufficient residence time will be required to obtain a high fraction of carbon burn-out from the ash.

The need for special design features to accommodate the fuel properties is indicated by the proximate analysis. As an example, because MSW and RDF are wet fuels, provisions for drying are required. Also, as both fuels have high volatility, relatively large furnace volumes will be required for the combustion of gases.

```
┌─────────────────────────────────────────────────────────────┐
│         COMPARISON OF MSW AND COAL VALUES¹⁴,¹⁵             │
│                                                             │
│    Higher Heating Value (Btu/lb)                           │
│       MSW                    2,000 -  7,700                │
│       Bituminous Coal        9,000 - 13,500                │
│       Fuel Oil              18,000 - 20,000                │
│                                                             │
│    Normal Fuel Size                                        │
│       MSW                    Powder - 6 ft                 │
│       Pulverized Coal        Fine Powder                   │
│       Stoker Coal            1/32 in. - 1.2 in.            │
│                                                             │
│    Ash Fusion Temperature (°F)                             │
│       MSW                    1,300 - 1,600                 │
│       Bituminous Coal        2,100 - 2,500                 │
└─────────────────────────────────────────────────────────────┘
```

COMPARISON OF MSW AND COAL VALUES[14,15]

Higher Heating Value (Btu/lb)
- MSW — 2,000 - 7,700
- Bituminous Coal — 9,000 - 13,500
- Fuel Oil — 18,000 - 20,000

Normal Fuel Size
- MSW — Powder - 6 ft
- Pulverized Coal — Fine Powder
- Stoker Coal — 1/32 in. - 1.2 in.

Ash Fusion Temperature (°F)
- MSW — 1,300 - 1,600
- Bituminous Coal — 2,100 - 2,500

Because so many operators have experiences with conventional fossil fuels, it may be helpful to illustrate some of the comparable fuel characteristics. These property variabilities affect the design and operational features of combustion equipment. Also, some MWC installations co-fire some other type of fuel than MSW.

For instance, combustion control is reasonably easy to obtain with fuel oils and natural gas, because they burn with near uniform fuel properties. Of course, there are source and/or grade dependent variations.

Coal properties may vary depending on its rank and the coal seam from which it is mined. Major variation in coal properties relates to its handling and exposure to the weather. Various applications attempt to moderate these variations, for instance, by grinding the coal to a fine powder before its firing in pulverized coal units.

Ash fusion temperatures represent temperatures at which liquid ash particles will begin to solidify. Ash fusion is a problem with MWCs because temperatures below the ash fusion temperature are often found on the fuel bed and heat exchange surfaces, causing the formation of clinkers.

Ash fusion temperatures are often reported as the "ash softening temperature" (the temperature at which a cone shaped ash sample will fuse into a hemispherical shape).[15] The fusion temperature depends upon whether reducing or oxidizing combustion conditions are present.

Slide 4-15

```
MSW FUEL VARIABILITY

Wet, Dry
Large Pieces, Small Particles
Combustibles, Incombustibles
Uniformity of Composition
```

A distinguishing feature of MSW fuel relative to conventional fuels is that of fuel variability. Material composition of refuse received at a local facility will also vary depending on the socioeconomic character of its neighborhood or source.

The moisture content and composition of MSW will vary considerably throughout the year and with the day of week, season, and climate. For instance, yard wastes may be delivered primarily just after the weekends in the summer and fall. Local precipitation generally adds moisture to the waste, unless covered containers are uniformly used.

The particle sizes may vary from that of a mattress or sheet of plywood to a dust particle. Therefore, combustion can only approach uniformity if there is appropriate materials segregation, pre-processing, and mixing.

Some components of waste have unique burning characteristics. Wet waste, such as yard wastes and food wastes, must be dried as the first stage in the burning process. Other materials, such as plastic bags, will volatilize quickly upon exposure to hot combustion gases. Newsprint will burn readily if hot air is delivered to its surface. However, newsprint burns poorly if air is restricted, as in the example of a telephone book.

Incombustible materials, such as metal objects, can restrict air flow to combustible materials.

Slide 4-16

EXAMPLE OF MSW COMPOSITION[13]	MSW Percent	RDF Percent
Paper and cardboard	46.6	78.8
Miscellaneous	18.9	6.6
Glass	9.5	1.4
Natural organics	6.6	1.5
Wood	6.4	4.3
Metals	6.4	0.7
Plastics	3.2	5.1
Textiles	1.7	1.6
Tar	0.7	0.0
Total	100.0	100.0

Solid waste processing involves various combinations and configurations of equipment.[16,17,18] Therefore, RDF compositions will depend on the particular situation.

The example above illustrates the material constituents of the MSW before and after processing into RDF at the Ames, Iowa facility.[13] As shown in the next slide, the example RDF has a lower moisture and ash content than the parent MSW. The processing facility included shredding of the MSW for improved size uniformity and materials separation through screening and magnetic recovery techniques.

Representative properties of RDF and MSW have been reported with RDF having a much lower moisture content but a slightly higher ash content than MSW.[15] This difference illustrates the variability of MSW. Properties at any site will be influenced by the source, factors of recycling and the design and operational features of the materials recovery facility.

Slide 4-17

EXAMPLE OF ULTIMATE ANALYSES	MSW As Received Percent by Weight	RDF As Received Percent by Weight
Component:		
Carbon	22.2	30.0
Hydrogen	5.4	6.0
Oxygen	33.3	37.2
Nitrogen	0.3	0.2
Chlorine	0.2	0.2
Sulfur	0.2	0.2
Inorganics (ash)	16.4	7.8
Moisture	22.0	18.4
Total	100.0	100.0

Slide 4-18

EXAMPLE OF ULTIMATE ANALYSIS	MSW Dry Basis Percent by Weight	RDF Dry Basis Percent by Weight
Component:		
Carbon	28.5	36.7
Hydrogen	6.9	7.4
Oxygen	42.7	45.6
Nitrogen	0.4	0.3
Chlorine	0.2	0.2
Sulfur	0.3	0.2
Inorganics (ash)	21.0	9.6
Total	100.0	100.0

The corresponding "as received" and dry-basis ultimate analyses for the previous MSW and RDF samples from Ames, Iowa are presented above. The "as received" MSW sample was obtained after the primary shredder, so it is probably dryer than the average of that delivered because of frictional heating in the shredder. The "dry basis" analysis was calculated from the "as received" analysis by dividing each component's percentage by (1.0 - moisture fraction).

The heating value was increased about 25% (from 4,830 Btu/lb for the MSW to 6,110 Btu/lb for the RDF).[13] This is because the front-end processing effectively cut the inorganic composition (glass & metals) to half that of the MSW feed. The carbon, hydrogen, and oxygen contents in RDF were all increased, relative to raw MSW. Also, RDF has better size uniformity.

CLASS	RDF BOILER FUEL DESCRIPTION[19]
1	Raw MSW fuel. Used as a fuel in the as-discarded form; Oversized bulky waste items have been removed.
2	Coarse RDF. Processed to a course size with or without ferrous metal separation, 95% passing thru a 6-inch mesh screen.
3	Prepared RDF. Processed to remove 90% of ferrous metal, glass, and other inorganics, sized with 99% passing thru a 6-inch square mesh screen.
4	Recovery Prepared RDF. Equivalent to Class 3, but with aluminum, other non-ferrous & glass removed for market sales.
5	Fluff RDF. Shredded; metals, glass and other inorganics removed, sized for 95% passing thru a 2-inch square mesh screen.
6.	Densified RDF. Combustibles compressed or densified into pellets, slugs, cubettes, briquettes, etc.

Various MSW fuel classification systems have been used to distinguish the processing operations used and the physical size features of RDF. In the above classification, the power industry has identified the forms of RDF which can be used as boiler fuels.[19]

```
ASTM FUEL CLASSIFICATIONS[20]

RDF-1      Municipal solid waste used as a fuel
(MSW)      in as-discarded form, without oversized
           bulky wastes

RDF-2      MSW processed to coarse particle size,
(c-RDF)    with or without ferrous metal separation,
           95% passing a 6-inch mesh screen

RDF-3      Shredded fuel derived from MSW, with
(f-RDF)    processing to remove metal, glass and
           other inorganics, 95% passing a 2-inch
           square mesh screen (Fluff RDF)

RDF-4      Combustible-waste fraction processed
(p-RDF)    into a powdered form, 95% passing a
           10-mesh (.035-inch) screen

RDF-5      Combustible-waste fraction densified
(d-RDF)    or compressed into the form of pellets,
           slugs, cubettes, briquettes, etc.

RDF-6      Combustible-waste fraction processed
           into a liquid fuel

RDF-7      Combustible-waste fraction processed
           into a gaseous fuel
```

Likewise the American Society of Testing Materials has established a general RDF classification scheme which also includes liquid and gaseous fuel types.[20]

REFERENCES

1. U. S. Environmental Protection Agency, "Standards of Performance for New Stationary Sources; Municipal Waste Combustors," Federal Register, Vol. 56, No. 28. February 11, 1991, pp. 5488-5514.

2. Louis Theodore, Air Pollution Control and Waste Incineration for Hospitals and Other Medical Facilities, Van Nostrand Reinhold, New York, 1990, pp. 228-229.

3. U. S. Environmental Protection Agency, "Standards for the Tracking and Management of Medical Waste: Interim Final Rule and Request for Comments," Federal Register 54:12373, 12374, Washington, D.C.March 24, 1989.

4. "EPA Guide for Infectious Waste Management," EPA/530-SW-86-014, May 1986, p. ix.

5. "Infectious Waste Management Regulations," Commonwealth of Virginia, Department of Waste Management, VR 672-40-01, May 2, 1990, p 3-4, 3-5.

6. L. Theodore, APTI Course 502, Hazardous Waste Incineration, Instructor's Guide, U. S. Environmental Protection Agency, Air Pollution Training Institute, Research Triangle Park, NC, March 7, 1986, p. 16-2.

7. "Incinerator Standards," Incinerator Institute of America, NY, Nov. 1968.

8. Paul Kaldjian, Characterization of Municipal Solid Waste in the United States: 1990 Update, U. S. Environmental Protection Agency, EPA-530-SW-90-042, June 1990.

9. William F. Davidson, "MSW Composition," MWC Operator Training Overview Course Manual, Edited by John Eppich, ASME Professional Development Program, West Palm Beach, FL, February 24-26, 1992, Lesson II.C, pp. 1-28.

10. William Franklin and Marjorie Franklin, "Solid Waste Characteristics," Integrated Solid Waste Management, Frank Kreith, editor, Genium Publishing Corporation, Schenectady, NY, 1990, pp. 33.

11. W. R. Seeker, W. S. Lanier, and M. P. Heap, Municipal Waste Combustion Study, Combustion Control of Organic Emissions, U.S. Environmental Protection Agency, EPA-530-SW-87-021-c, May 1987, pp. 3-3, 3-4.

12. Ronald E. Myers, "Municipal Waste Combustors - Background Information for Proposed Guidelines for Existing Facilities," U.S. Environmental Protection Agency, EPA-450/3-89-27e, August 1989, p. 2-5.

13. D. E. Fiscus et al., "Study of Existing RDF-Cofiring Experiences, Vol. 2: Appendixes to Phase I Final Report," Report ANL/CNSV-TM-134, Vol. 2, Argonne National Laboratory, October 1983, pp. C-1-14, C-1-15, & C-9-14.

14. Municipal Waste Incinerator Field Inspection Notebook, U.S. Environmental Protection Agency, EPA-340/1-88-007, July 1988, pp. 12-15.

15. Joseph G. Singer, Combustion Fossil Power, 4th Edition, Combustion Engineering, Inc., Windsor, CT, 1991, pp. 2-13, 2-31, 3-5 and 8-16.

16. Stuart H. Russell, "Solid Waste Preprocessing: The Return of an Alternative to Mass Burning," Proceedings of the 1988 Waste Processing Conference, ASME, Philadelphia, May 1988, pp. 73-76.

17. Mark C. Turner et al., "First Year of Operation at the SEMASS WTE Facility," Proceedings of the 1990 Waste Processing Conference, ASME, Long Beach, CA, June 1990, pp. 1-7.

18. Gary L. Boley, "Startup and Operations of the Mid-Connecticut Resource Recovery Project," Proceedings of the 1990 Waste Processing Conference, ASME, Long Beach, CA, June 1990, pp. 21-29.

19. J. D. Blue et al., "Waste Fuels: Their Preparation, Handling, and Firing," Standard Handbook of Power Plant Engineering, Thomas C. Elliott, editor, McGraw Hill Book Co., NY, 1989, pp. 3-139, 3-140.

20. "Classification of Refuse Derived Fuels," American Society of Testing and Materials.

5. COMBUSTION PRINCIPLES I: BASIC COMBUSTION

Slide 5-1

```
BASIC COMBUSTION CONCEPTS

Fuel and Air Characteristics
Products of Complete Combustion
Complete Combustion Reactions
Excess Air Considerations
```

Unlike combustion system design engineers, operators are seldom called upon to make combustion calculations. However, knowledge of the basic concepts of complete combustion will aid operators in understanding the complex combustion features of their unit operations.

Example calculations are presented in this learning unit to help operators understand some of the basic combustion concepts. Many of these concepts will be referred to in later learning units. For instance, the combustion calculations of this learning unit will be applied in Learning Unit 15, where the concepts of dilution and the techniques for correcting air pollutant concentrations to a standard basis will be presented.

Slide 5-2

```
COMBUSTION: CHEMICAL REACTION

Rapid Oxidation (Fuel & Oxygen)
    Heat and Light Given Off
Products of Combustion:
    Oxides
    Other Compounds
```

Combustion is the rapid oxidation of combustible material which converts its constituent elements into various oxides or compounds. The oxidation is rapid in combustion, as opposed to the slow oxidation of the rusting of metal. Combustion is accompanied by the release of substantial energy in the form of heat and light.

A fuel is a substance which experiences a rapid chemical reaction when adequately heated in the presence of oxygen. Both fuel and oxygen are required for the combustion process. The relative amounts of oxygen and fuel can vary widely, resulting in differing combustion characteristics of temperature and combustion products (emissions).

Slide 5-3

```
┌─────────────────────────────────────────┐
│                                         │
│    COMBUSTIBLE SUBSTANCES               │
│                                         │
│    Organic - Hydrocarbons               │
│          Paper, Wood, Plastic           │
│          Fossil Fuels                   │
│          Renewable Fuels                │
│                                         │
└─────────────────────────────────────────┘
```

MSW is composed of combustible materials, incombustible (ash) materials, and water (moisture).

The combustible fraction of MSW is primarily composed of organic materials, which are defined as the compounds of carbon. The phrase "organic material" is used because many of these compounds were formed from living plants or animals (organs).

Hydrocarbons are compounds which have both carbon and hydrogen as elemental constituents. Paper and wood are composed mainly of cellulose, a chemical material containing carbon, hydrogen and oxygen. Cellulose and plastic materials are considered as both organic and hydrocarbon materials because of their carbon and hydrogen compositions. Note that all hydrocarbons are organic compounds, but not all organic compounds are hydrocarbons (e.g., carbon monoxide is an organic material, not a hydrocarbon).

Fossil fuels, like coal and oil, were formed over many thousands of years from organic materials.

Renewable fuels are distinguished by their short production time. MSW is often considered to be a renewable fuel, because of its high paper, cardboard, yard waste and wood composition.

Slide 5-4

```
┌─────────────────────────────────────────┐
│                                         │
│    INCOMBUSTIBLE SUBSTANCES             │
│                                         │
│    Inorganic                            │
│          Metals                         │
│          Glass, Sand, Ceramics, Concrete│
│                                         │
└─────────────────────────────────────────┘
```

Inorganic materials are those which have no hydrocarbons in their composition. Examples of such inorganic materials include metal cans, glass bottles and ceramic materials.

The inorganic materials in MSW are generally considered to be non-combustible. However, some inorganic materials may oxidize, forming oxides such as iron oxide and aluminum oxide. Of course, some metals, such as sodium and phosphorus, are capable of rapid oxidation (as is evident in fireworks). However, these are not typical constituents in MSW.

Other elements in MSW which cause considerable concern are the halogens: chlorine, fluorine, and bromine. Although the halogen concentrations are fairly small, their impact in forming acid gases is very important.

Slide 5-5

EXAMPLE ULTIMATE ANALYSES	MSW As Received Percent by Weight	RDF As Received Percent by Weight
Component:		
Carbon	22.2	30.0
Hydrogen	5.4	6.0
Oxygen	33.3	37.2
Nitrogen	0.3	0.2
Chlorine	0.2	0.2
Sulfur	0.2	0.2
Inorganics (ash)	16.4	7.8
Moisture	22.0	18.4
Total	100.0	100.0

The example ultimate analyses of MSW and RDF was provided in the previous learning unit in Slide 4-17. This was actual data from the Ames Resource Recovery Facility.

The ultimate analysis provides the percentage of the total weight that is associated with the elements of carbon, hydrogen, oxygen, nitrogen, chlorine and sulfur, as well as the ash and moisture. Such ultimate analyses can be used in general calculations related to the combustion air requirements, as will be demonstrated later.

Note that the inorganic matter (ash) is the non-combustible fuel fraction which is primarily collected as the bottom ash and fly ash. That which is not collected is emitted up the stack into the atmosphere.

The moisture in the fuel will generally evaporate in a drying stage as the fuel is heated in the MWC. Fuel moisture acts primarily as a heat sink, requiring energy for its evaporation. Therefore, fuel moisture reduces the maximum combustion temperature but passes through the combustion process otherwise unchanged.

Slide 5-6

```
ATOMIC STRUCTURE OF MATTER

Atoms
Molecules of One Element
Molecular Compounds
Mixtures
"String Compounds"
```

A general discussion of the atomic structure of material is presented to aid in the understanding of combustion calculations. All matter is composed of elements in the form of atoms, and each element has its own unique atomic structure and atomic mass or weight.

Materials are found in a number of different forms. Some materials are in the form of single atoms of an element, such as gaseous helium. Other materials are in the form of molecules with multiple atoms of a single element, such as oxygen which has two oxygen atoms.

Other materials are in the form of molecular compounds of various elements, such as carbon dioxide, which is composed of a carbon atom and two oxygen atoms.

Many materials are actually mixtures of atoms and molecules (e.g., air).

Other materials are formed from complex "string compounds" which do not have a single molecular composition (e.g., paper or cellulose).

Slide 5-7

```
AIR

Mixture of Oxygen and Nitrogen
Oxygen -   21% by volume
Nitrogen - 79% by volume
3.76 moles of nitrogen per mole
       of oxygen in air
```

Air can be assumed to be a mixture of oxygen and nitrogen, with the other constituents being small enough to be neglected. If two gases are mixed together at constant temperature and pressure, their volume after mixing will be the sum of their individual initial volumes. Therefore, if 0.21 cubic feet of pure oxygen is mixed with 0.79 cubic feet of nitrogen, one cubic foot of air will be obtained.

```
     DEFINITION OF A POUND-MOLE

 Mass or Weight of Gas Equal to Its
     Molecular Weight in Pounds
 A Unique Number of Molecules,
     Regardless of the Gas
 379 Cubic Feet of Gas at Standard
     Conditions, Regardless of Gas
```

A mole of a particular gas has mass or weight equal to the molecular weight expressed in the system of units being used. For instance, a lb-mole of oxygen weighs approximately 32 pounds (lb) because the molecular weight of oxygen is approximately 32. Other systems of units deal with kilogram-moles and gram-moles. For our considerations, a mole will be considered to be a lb-mole.

The number of molecules in a lb-mole is a unique and very large number. It does not change from gas to gas. Thus, of the total molecules in a cubic foot of air, 79% of the molecules will be nitrogen and 21% will be oxygen.

The ratio of volume of nitrogen to the volume of oxygen is .79/.21 or 3.76. This ratio is equivalent to the ratio of the molecules of nitrogen to the molecules of oxygen, as well as the number of moles of nitrogen per mole of oxygen in air. Therefore, the air required to get one mole of oxygen will contain 3.76 (.79/.21) moles of nitrogen. This air will contain a total of 4.76 moles (1.0 moles oxygen + 3.76 moles of nitrogen).

At the standard conditions of 60°F and atmospheric pressure, a lb-mole of any gas occupies 379 cubic feet. Therefore, if one knows the number of moles, the corresponding volume which the moles occupy at standard conditions is easily calculated. This information is used by combustion system designers in sizing the fans, combustion chambers and ducts.

```
     STOICHIOMETRIC (THEORETICAL)
          AIR-FUEL MIXTURE

 Fuel Completely Burned
 Oxygen Completely Consumed
 Products of Complete Combustion
     Are Formed
```

The minimum amount of oxygen required for the complete combustion of a particular fuel is called theoretical or "stoichiometric oxygen." It varies from fuel to

fuel. A "stoichiometric mixture" of a particular fuel and air (oxygen) is one in which all the fuel and oxygen will be consumed under complete combustion conditions.

If combustion goes to completion under "stoichiometric conditions," there will not be any molecules of oxygen (uncombined) in the flue gas (products of combustion). However, if excess air is provided, oxygen will be found in the flue gas.

Slide 5-10

```
┌─────────────────────────────────────────────────┐
│                                                   │
│     PRODUCTS OF COMPLETE COMBUSTION               │
│                                                   │
│     *    Carbon Dioxide                           │
│     *    Water (vapor)                            │
│     *    Sulfur Dioxide                           │
│     *    Hydrogen Chloride (acid)                 │
│     *    Nitrogen (molecular)                     │
│     *    Oxygen (molecular)                       │
│                                                   │
└─────────────────────────────────────────────────┘
```

Under complete combustion conditions, each combustible element in the fuel will generally form its own unique combustion product. Carbon forms carbon dioxide; sulfur forms sulfur dioxide; chlorine forms hydrogen chloride; and hydrogen forms water, except for that small amount required if chlorine is present.

For simplicity, we will assume that the nitrogen in the fuel is converted to molecular nitrogen, and the nitrogen in the air remains as molecular nitrogen.

If complete combustion occurs under stoichiometric conditions, all the oxygen in the fuel and the theoretical oxygen from the supply air will presumably be consumed. Therefore, there will be no oxygen in the product gases.

For complete combustion under excess air conditions, any excess oxygen will be assumed to flow directly into the products of combustion as molecular oxygen.

Slide 5-11

```
┌─────────────────────────────────────────────────┐
│                                                   │
│     PRODUCTS OF INCOMPLETE COMBUSTION             │
│                                                   │
│          *    Carbon Monoxide                     │
│          *    Dioxins                             │
│          *    Furans                              │
│                                                   │
└─────────────────────────────────────────────────┘
```

Combustion is generally not perfect, leading to the formation of products of incomplete combustion (PICs), such as carbon monoxide, dioxins, and furans. Their control will be discussed in Learning Unit 16.

Slide 5-12

```
┌─────────────────────────────────────────┐
│   OTHER COMBUSTION PRODUCTS              │
│                                         .│
│   *    Nitrogen Oxides                   │
│   *    Metal Vapors                      │
│   *    Metal Oxides                      │
│   *    Metal Chlorides                   │
└─────────────────────────────────────────┘
```

The nitrogen in the fuel can also form nitric oxide and other nitrogen compounds during combustion. These will be discussed in Learning Units 17 and 21.

The inorganic fraction of medical waste may contain heavy metals. These metals can remain unchanged or can oxidize or vaporize during the combustion process. The formation of metal oxides and vapors and their collection by air pollution control devices will be discussed in Learning Unit 18.

Slide 5-13

```
┌─────────────────────────────────────────┐
│   CHEMICAL REACTION EQUATION             │
│                                          │
│   Carbon:   C + O₂ --> CO₂               │
└─────────────────────────────────────────┘
```

A chemical reaction equation uses special procedures to represent the combustion of reactants into products of combustion. Symbols are used to represent the substances participating in the reaction. Those symbols on the left of the arrow represent the reactants, and those on the right represent products of combustion. The arrow indicates that the reaction goes from the reactants to products.

In simplest form, a capital letter represents a single atom of a particular element. A letter symbol followed by a subscripted number indicates a molecule composed of the given number of atoms of the element. Two adjacent capital letter symbols indicate a molecule of a compound formed from atoms of two elements. Numbers placed in front of letter symbols indicate the number of molecules or atoms. The number 1 is assumed when there is no number in front of the symbol.

From the above illustration, carbon (C) and oxygen (O_2) react to produce carbon dioxide (CO_2). One atom of carbon reacts with one molecule of oxygen (two oxygen atoms) to form one molecule of carbon dioxide (an atom of carbon and two atoms of oxygen).

Slide 5-14

```
┌─────────────────────────────────────────────────────────┐
│       BALANCED CHEMICAL REACTION EQUATIONS                │
│              COMBUSTION IN OXYGEN                         │
│                                                           │
│   Carbon:    C + O₂  -->   CO₂                            │
│                                                           │
│   Hydrogen: 2 H₂  +  O₂  -->   2 H₂O                      │
│                                                           │
│   Sulfur:    S + O₂ -->   SO₂                             │
│                                                           │
│   Chlorine:   H₂ + 2 Cl -->  2 HCl                        │
└─────────────────────────────────────────────────────────┘
```

The reaction equations listed above represent the complete combustion reactions of the major constituents in MSW. Note that the letter symbol for chlorine is Cl. The symbol for hydrogen chloride or hydrochloric acid is HCl.

In actual practice, a small fraction of the S, C and Cl will not react, but will remain in the ash. Generally, greater than 95% will react as indicated above.

Slide 5-15

```
┌─────────────────────────────────────────────────────────┐
│       BALANCED CHEMICAL REACTION EQUATIONS                │
│                                                           │
│   Each Type of Atom Is Conserved                          │
│   Each Element's Mass Is Conserved                        │
│   Total Mass Conserved                                    │
│   The Number of Molecules is Not Conserved                │
└─────────────────────────────────────────────────────────┘
```

A chemical reaction equation is called a balanced equation, since the number of atoms of each element is the same on both sides of the equation. Mass is also conserved, with the total mass of the reactants equal to the mass of the products of combustion. This is because the number of atoms of each element is the same on both sides of the reaction equation and the mass of each atom is unchanged.

One should note that although the atoms and the mass are conserved, the number of molecules of reactants is not necessarily the same as the number of molecules of products.

```
+-------------------------------------------------------+
|                                                       |
|     EXAMPLE OF BALANCING A COMBUSTION EQUATION        |
|                                                       |
|     Methane, CH4, with Stoichiometric Oxygen          |
|                                                       |
|        CH4 + 2 O2  -->    CO2 + 2 H2O                  |
|                                                       |
+-------------------------------------------------------+
```
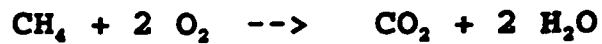
The balancing of a chemical equation for complete combustion in pure oxygen will be demonstrated. Assume that one molecule of methane, which is the main constituent in natural gas, is to be completely burned with stoichiometric oxygen.

The methane molecule is composed of one atom of carbon and four atoms of hydrogen. Because carbon and hydrogen elements are in methane, one knows that carbon dioxide and water will be the products of complete combustion.

The above slide illustrates the fact that the atoms of carbon, hydrogen, and oxygen are each conserved in the reaction process. For example, the same number of carbon atoms (1) are found on the left-hand side (reactants) and the right-hand side (products). Likewise, the atoms of hydrogen and oxygen are conserved.

Slide 5-17

```
+-------------------------------------------------+
|                                                 |
|        COMBUSTION REACTIONS IN AIR              |
|                                                 |
|        3.76 moles of nitrogen in air            |
|              per mole of oxygen                 |
|                                                 |
+-------------------------------------------------+
```

The previous example was simplified by assuming that combustion occurred in pure oxygen. However, the oxygen is obtained from air which is essentially a mixture of oxygen and nitrogen. Approximately 79% of the air molecules are nitrogen and 21% are oxygen.

Therefore, each molecule of oxygen obtained from air also has 3.76 (.79/.21) moles of nitrogen which go along for the ride.

In our example, 2 molecules of oxygen were required, so 2 x 3.76 or 7.52 moles of nitrogen will need to be in the combustion air.

```
+---------------------------------------------------------------+
|                                                               |
|     EXAMPLE OF BALANCING A COMBUSTION EQUATION                |
|                                                               |
|     Methane, CH4, with Stoichiometric Air                     |
|                                                               |
|     CH4  +  2 O2  + 7.52 N2  -->                              |
|                                                               |
|                      CO2 + 2 H2O + 7.52 N2                    |
|                                                               |
+---------------------------------------------------------------+
```

Because oxygen is obtained from air, the complete combustion reaction equation must be modified as indicated above. The nitrogen in the air must be added as both a reactant and product of reaction. The nitrogen is assumed to pass through the reaction unchanged, although it is heated.

```
+---------------------------------------------------------------+
|                                                               |
|              EQUIVALENT MOLECULAR FORM OF MSW                 |
|                                                               |
|     C1.85H5.4O2.08N.02Cl.006S.006   + 1.22 H2O               |
|                                                               |
+---------------------------------------------------------------+
```

It can be shown that 100 pounds of the example of MSW presented in Slide 5-5 has the equivalent molecular form illustrated above.

The atoms of each element in the "equivalent molecule" correspond to the percentage of the element in the ultimate analysis divided by its atomic weight. Note that the moisture is considered separately, since its form is unchanged as it passes through the combustion process.

Each "equivalent molecule" of this sample waste will have 1.22 molecules of water, which corresponds to 22 pounds of water (from the ultimate analysis) divided by 18, the molecular weight of water.

```
+---------------------------------------------------------------------+
|                                                                     |
|          THEORETICAL COMBUSTION OF MSW IN AIR                       |
|                                                                     |
|  C1.85H5.4O2.08N.02Cl.006S.006 + 1.22 H2O + 2.165 O2 + 8.14 N2 -->  |
|                                                                     |
|  1.85 CO2 + 3.92 H2O + 8.15 N2 + 0.006 HCl + 0.006 SO2             |
|                                                                     |
+---------------------------------------------------------------------+
```
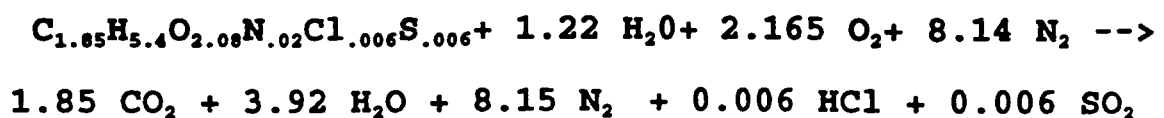
Because carbon, hydrogen, chlorine and sulfur elements are in the waste, one knows that carbon dioxide, water, hydrogen chloride and sulfur dioxide will be in the products of complete combustion. Also, the product gases will include nitrogen in molecular form. Note that nitrogen oxides are ignored in this example.

As in the previous example, it can be shown that atoms of each element are conserved (same number on the left-hand side and the right-hand side).

Slide 5-21

MASS ANALYSIS OF STOICHIOMETRIC FUEL & AIR MIXTURE			
REACTANTS	Moles	Molecular Wt lb/mole	Mass lb
$C_{1.85}H_{5.4}O_{2.08}N_{.02}Cl_{.006}S_{.006}$	1.0	61.6	61.6
1.22 H_2O	1.22	18	22.0
2.165 O_2	2.165	32	69.3
8.14 N_2	8.14	28	227.9
Total			380.8

The combustion equations can be used to find the air-to-fuel ratio, as follows. The molar weight of the "equivalent molecule" of dry MSW can be found by summing the product of the number of atoms of each element by its atomic weight. This gives: (1.85x12) + (5.4x1) + (2.08x16) + (.02x14) + (.006x35) + (.006x32) = 61.6 lb/mole. The corresponding weight of ash and water in the MSW was 16.4 and 22 lbs, respectively, for a total weight of 100 lbs.

Likewise, the weight of the air is found to be (2.165x32)+(8.14x28) = 69.3 + 227.9 = 297.2 lb-air. This corresponds to a stoichiometric air-to-fuel ratio of about 3.0 lb-air/lb-MSW. At 100% excess air, about 6.0 lb-air/lb-MSW would be required.

Slide 5-22

```
EXCESS AIR

Air in Excess of Theoretical
Fraction: Extra/Theoretical
Symbol: EA
Total Supply Air is
     (1+EA) x (Theoretical Air)
Oxygen in Flue Gas is
     EA x (Theoretical Oxygen)
```

Excess air is required in combustion to compensate for the inability to obtain perfect mixing of the fuel with the theoretical oxygen. Excess air can be expressed as the fraction of the extra air divided by the theoretical air or its equivalent percentage.

The expressions of "percent excess air" and "percent flue gas oxygen" (sometimes called excess oxygen) are often used in describing combustion conditions. Because these provide an indication of the average fuel and oxygen relationship, control systems often use these variables to achieve an optimum operating condition.

In chemical reaction equations, the symbol for the excess air fraction is EA. The total air supplied is (1+EA) times the theoretical air requirements. Because the theoretical oxygen is presumed to be fully consumed in forming combustion products, the corresponding un-reacted oxygen in the flue gas is EA times the theoretical oxygen. This will be demonstrated in the following example of methane combustion.

Slide 5-23

```
METHANE COMBUSTION IN THEORETICAL AIR:

CH₄ + 2 O₂ + 7.52 N₂ -->

              CO₂ + 2 H₂O + 7.52 N₂

METHANE COMBUSTION IN EXCESS AIR:

CH₄ + (1+EA)(2) O₂ + (1+EA)(7.52) N₂ -->

         CO₂ + 2 H₂O + (1+EA)(7.52) N₂ + (EA)(2) O₂
```
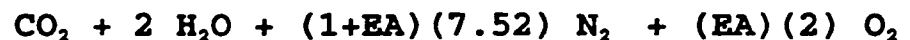
The complete combustion equations for methane under theoretical and excess air conditions are contrasted in the above slide. Note that the moles of carbon dioxide and water vapor produced do not change. However, since oxygen is present and nitrogen increases, the mole fractions of the product gas constituents will change.

Slide 5-24

```
METHANE COMBUSTION, 20 PERCENT EXCESS AIR

CH₄ + 2.4 O₂ + 9.024 N₂ -->

         CO₂ + 2 H₂O + 9.024 N₂ + 0.4 O₂
```
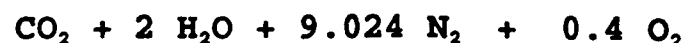
Consider the example of methane combustion under conditions of 20 percent excess air, as illustrated in Slide 5-24. If 0.2 is substituted for EA in the previous slide, the result will be as indicated.

If the techniques illustrated in Slide 5-21 were used, it could be shown that when methane burns under stoichiometric conditions, the air-to-fuel ratio is 17.2. Also, the corresponding air-to-fuel ratio for 20% excess air will be 20.6.

Slide 5-25

PRODUCT GAS ANALYSIS, METHANE @ 20% EA			
PRODUCTS	Moles	Molar Wt. lbm/mole	MASS lbm
CO_2	1.0	44.0	44.0
H_2O	2.0	18.0	36.0
O_2	0.4	32.0	12.8
N_2	9.024	28.0	252.7
Total	12.424		345.5
Dry Gas Total	10.424		309.5

The basic concepts of gas concentrations in flue gas mixtures will be presented in Learning Unit 15. The flue gas mixtures illustrated in Slides 5-20 and 5-25 will be used to illustrate these concepts.

As will be discussed in Learning Unit 14, many instruments report gaseous concentrations on a dry gas basis. A dry gas is obtained by physically absorbing the water vapor out of the mixture with a desiccant material.

For the example, note that the oxygen in the flue gas would be about 4% on a dry gas basis and the carbon dioxide would be about 10%. These are fairly typical operating numbers for commercial and industrial gas-fired equipment.

6. MUNICIPAL WASTE COMBUSTORS

Slide 6-1

ORGANIZATIONAL STRUCTURES		
BUILDER	**OWNER**	**OPERATOR**
Vendor	Public	Public
Vendor	Public	Private/Vendor
Vendor	3rd Party	Private/Vendor
Vendor	Vendor	Vendor

Various organizational structures have been developed for MWC units. A manufacturer or technology vendor will hold the exclusive rights to produce systems based on certain equipment patents. Therefore, the vendor generally establishes the design and builds the MWC unit. Of course, an architect and engineering firm and a general contractor may set specifications for construction of the building and unit.

The early MWC units were owned and operated by public authorities, such as trash disposal agencies. A manufacturer would erect the unit and operate it through a shake-down period. Unit operations would then be turned over to the agency, which would select staff and operate the unit.[1] When unit modifications were required, the equipment vendor or some other contractor might provide advice and/or do the work.

Another public ownership option would be for the agency to contract with a private service organization to operate the unit. Of course, the service organization could be owned by the vendor.

Another option includes having so called "third-party investors" be the owners of the unit. They would contract with public agencies to receive MSW and with a service organization to operate the unit. The service organization could be an independent private company or a vendor-owned service company. This has the advantage of shifting some of the risk-taking from the public to the investors and service organizations. Of course, the contract establishing the pricing structure for cost recovery will have to balance the interest of the public with those of the private parties.

Vendor ownership with operations by a vendor-owned service company is an increasingly attractive organizational structure.[2] The public gains because the expertise of the vendor is available throughout the unit's life. The vendor may have resources which are not available to other organizations. The vendor gains by creating additional revenue and by assuring that the operation of equipment is consistent with its design. Also, information developed through operations can be incorporated into the new designs.

Slide 6-2

```
EVOLUTION OF MWC DESIGNS.

Single Chamber, Flue-Fed
Multiple Chamber
Refractory Wall Incineration
Mass Burn Waste-to-Energy
Modular
RDF Waste-to-Energy
```

There has been a significant evolution in the design of municipal waste combustor equipment.

Slide 6-3

SINGLE CHAMBER FLUE-FED INCINERATOR[3]
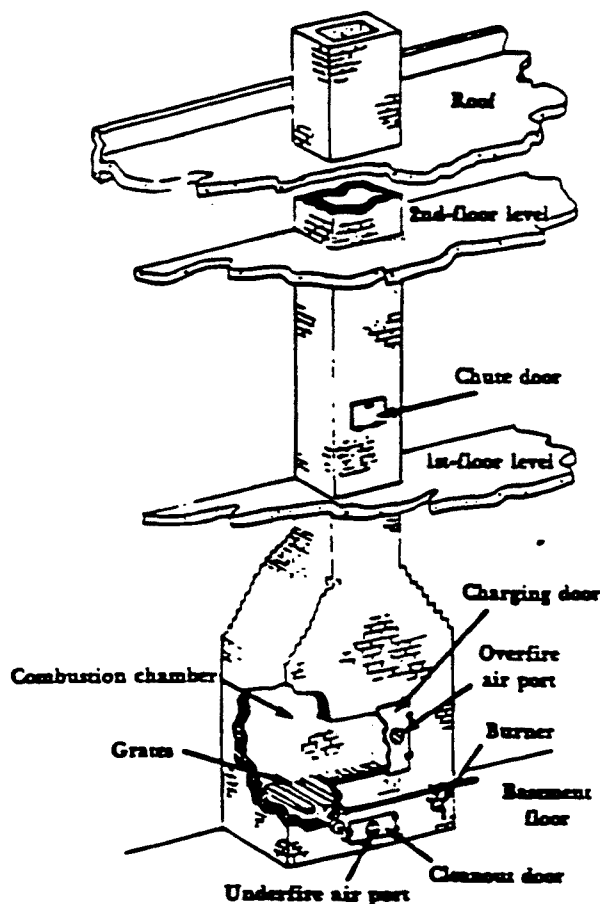
Flue-fed, single chamber incinerators were widely used in apartment houses in urban areas in the 1940s and 1950s. Their performance was hampered by the lack of skilled operators. Various design fixes, for example roof-top afterburners, were initiated to reduce smoke.[3]

Slide 6-4

MULTIPLE CHAMBER INCINERATOR STANDARDS[4]

1. Stack	6. Flame port	11. Cleanout doors
2. Secondary air ports	7. Ignition chamber	12. Underfire air ports
3. Ash pit cleanout doors	8. Overfire air ports	13. Curtain wall port
4. Grates	9. Mixing chamber	14. Damper
5. Charging door	10. Combustion chamber	15. Gas burners
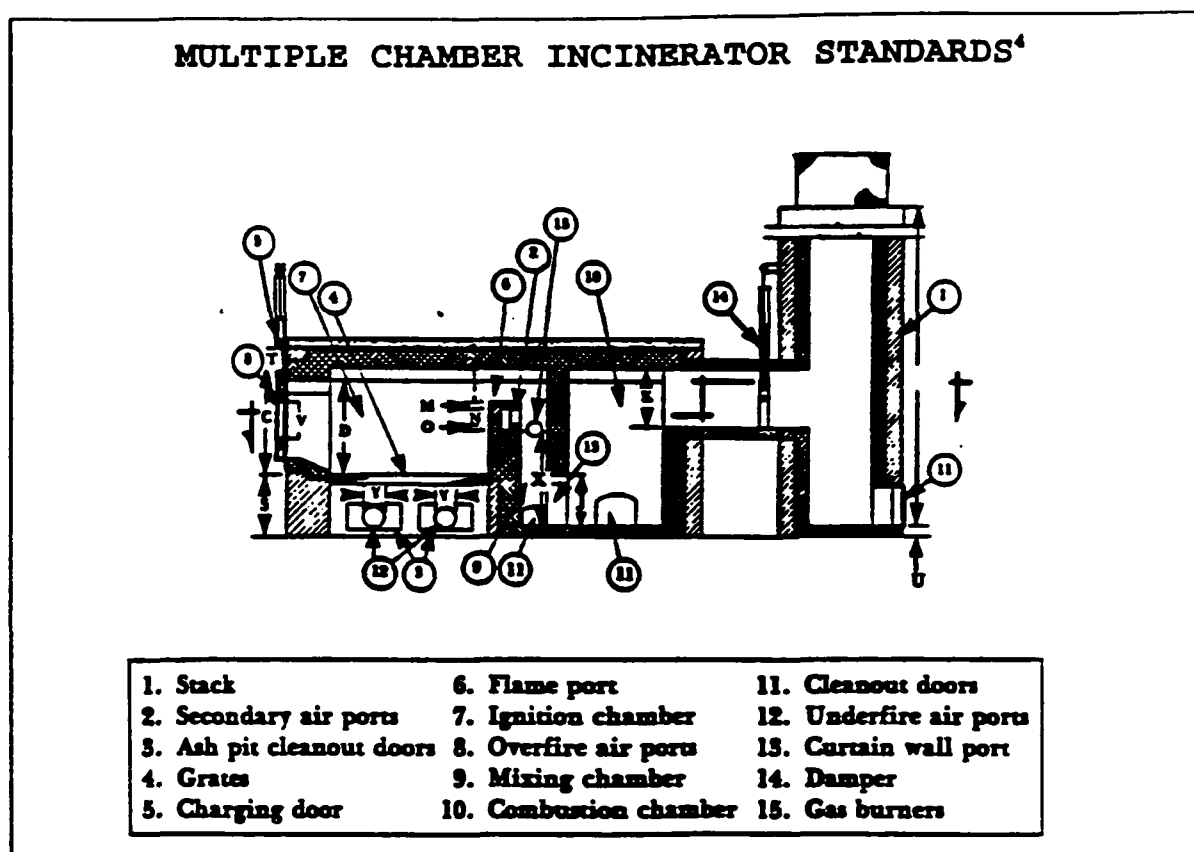
Standards for small, refractory, multiple chamber incinerators were adopted in the 1960s in Los Angeles County, California.[4] Standardized sizes and geometries and provisions for damper controls and auxiliary fuel burners to control combustion chamber temperatures were included. These standards were developed for small batch fired operations, including pathological waste incinerators.

Slide 6-5

REFRACTORY-WALL, MASS BURN

High Excess Air
High Gas Velocities
Particle Entrainment
Smoke
Shut Down in Late-1970s

During the 1940s and 1950s, many refractory-walled, mass burn incinerators were built in the United States. These units are called mass burn units because almost all of the mass picked up by garbage trucks goes into the incinerator. A survey taken in 1965 reported that there were 299 major incinerators operating in the United States.[5] More than 200 of them had been closed by 1979.[6]

REFRACTORY WALL INCINERATOR[7]
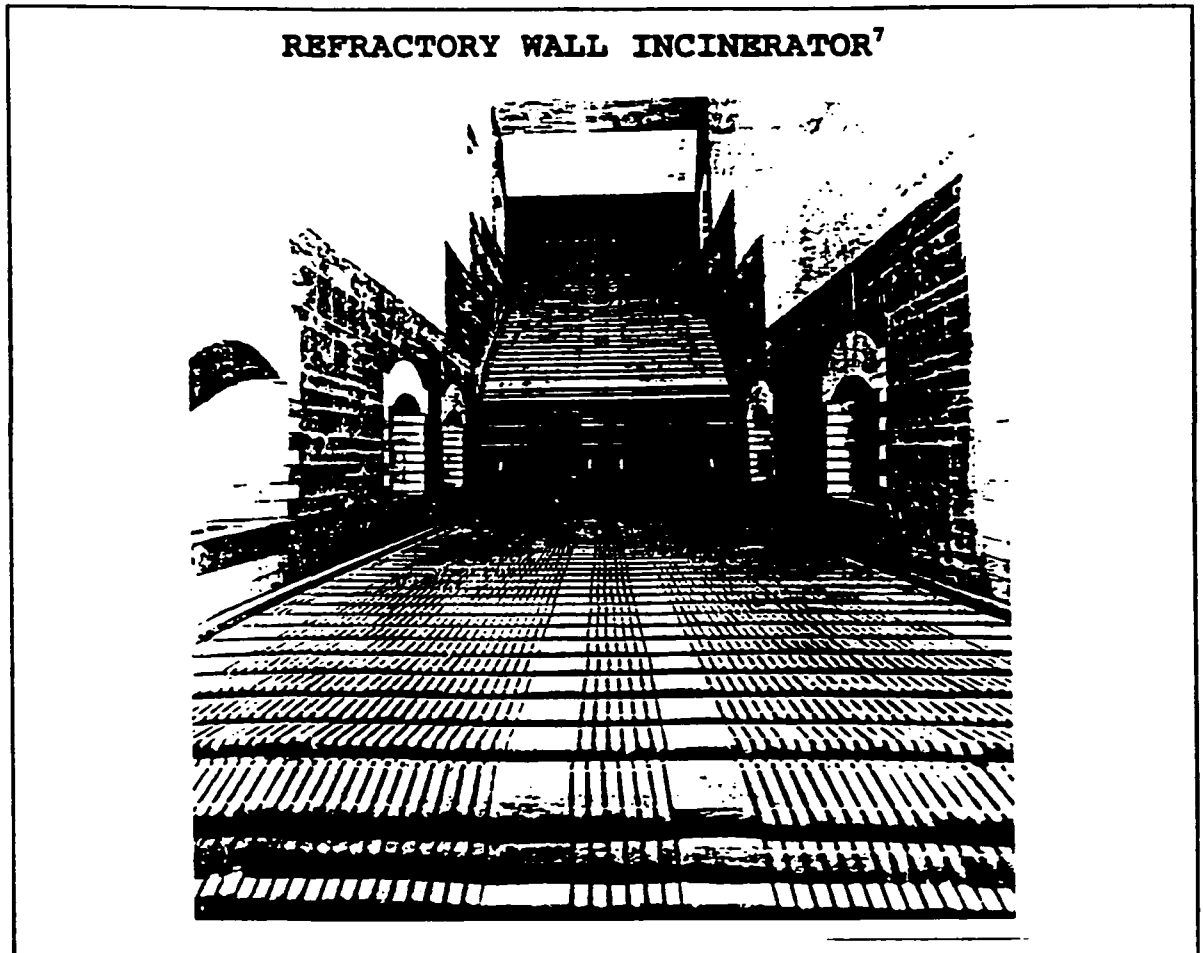
Combustion gases are only moderately cooled by heat transfer to the refractory walls, which provide only incidental heat extraction from the adjacent flaming gases. The temperature of a refractory wall is controlled primarily by regulating the excess air during combustion, with such air acting as a heat sink. Large amounts of excess air are required to keep temperatures low enough to prevent damage to the refractory.

High velocities and poor mixing in the combustion chamber of such refractory wall incinerators has resulted in ash entrainment and smoke emissions.

With the development of smoke ordinances and the Clean Air Act legislation, many municipal incinerators were shut down. For instance, by the mid-1970s about 80 incinerators in New York state were either shut down or required to undergo significant system modifications.[8]

Slide 6-7

```
WATERWALL MASS BURN

Waste-to-Energy
European Designs
ESP for Particulate Control
```

The birth of incineration was in Nottingham, England in 1874, and by 1921 there were more than 200 plants in Great Britain, many producing steam and electric power.[9] Two full scale steam generating plants were built in New York in 1906. However, the waste-to-energy technology became inactive within a few years, because of the auxiliary fuel requirements, poor designs and unskilled operations.

Slide 6-8

EUROPEAN WATERWALL INCINERATOR DESIGNS[10]
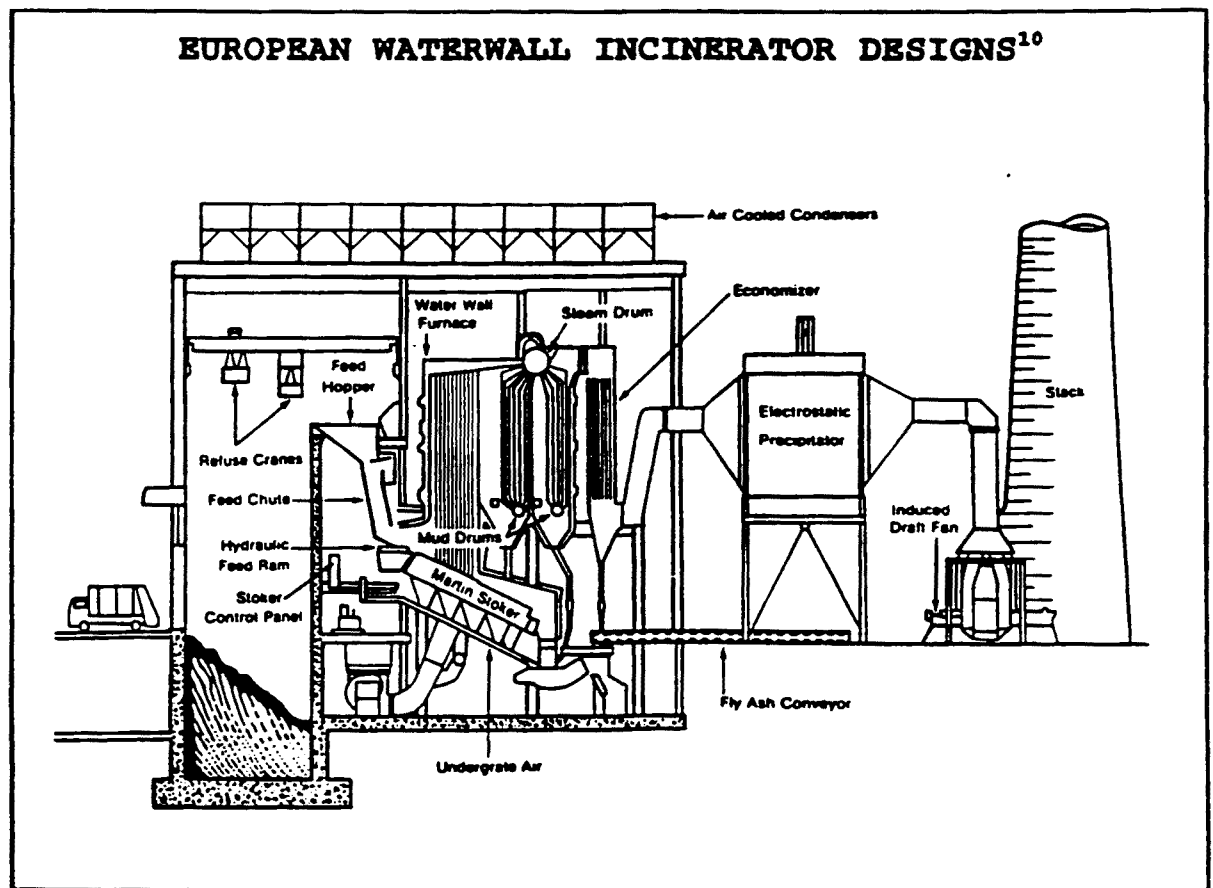
From ASME Journal of Engineering for Power, printed with permission.

In the late 1960s, European technology for grate designs and waterwall incinerators began to be adopted in the United States.[11] A number of different grate designs were developed, including those which vibrate, reciprocate, or translate to agitate the fuel bed. These will be discussed further in Learning Unit 8.

Although steam was produced, large condensers were often provided so that the steam could be recirculated as feedwater when a customer did not need steam.

Slide 6-9

WATERWALL DESIGN CONCEPT[12]
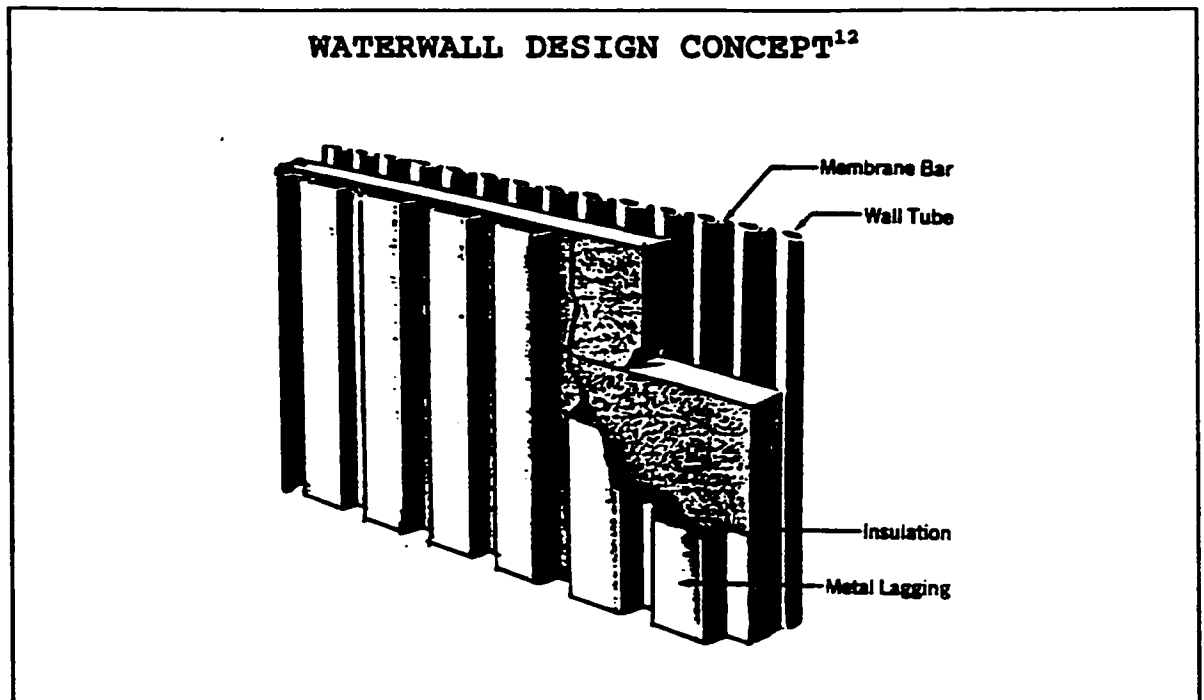
Courtesy of Babcock and Wilcox

The term waterwall or membrane wall relates to the integral boiler design concepts used in most power boilers. Waterwall units have multiple tubes in the form of metal enclosures, which surrounds the ball of flaming combustion gases. The tubes are filled with flowing water, which extracts energy from the adjacent combustion gases.

The region containing the burning gases is called the radiant boiler or radiant furnace section. The overall unit is often called a boiler, integral boiler or steam generator--terms which are often used interchangeably.
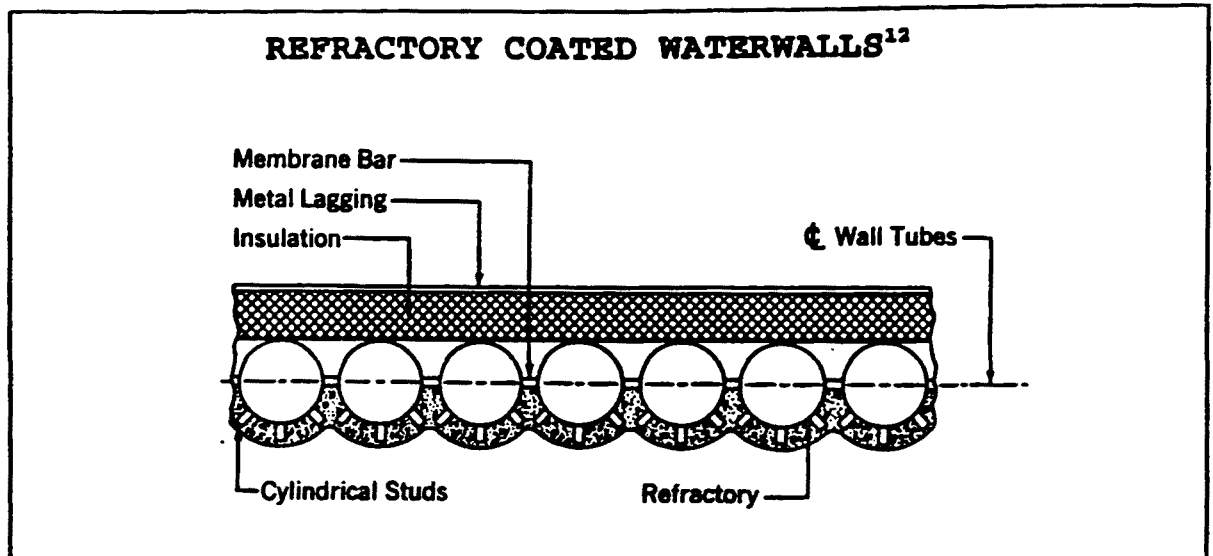
Courtesy of Babcock and Wilcox

Waterwall MWCs with exposed waterwall surfaces have experienced metal wastage from corrosion and erosion. Such metal losses have caused tube failures which require units to be shut down for repair.

Most MWC waterwall units are now using either a highly conductive refractory material (e.g., silicon carbide) or nickel-based alloy overlays on the boiler tubes (e.g., inconel 625), at least in the lower furnace region.[13] These keep the corrosive combustion gases away from the tubes. These barriers also act as insulation, which helps to achieve a more uniform heat extraction rate.

Slide 6-11

ROTARY WATERWALL MASS BURN

Mass Burn or RDF Fired
    Rotary Waterwall Section
    Fixed Waterwall Section
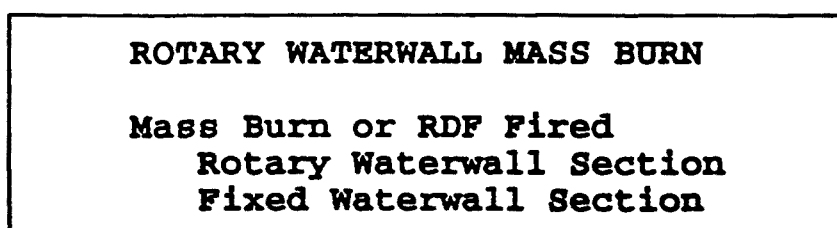
The rotary waterwall technology is an interesting variation on the design of a waterwall MWC unit. The characterizing feature is that the primary grate has rotary action which tumbles the fuel bed. The rotary action is similar to the rotary kiln incinerators, which are used in the cement kilns and hazardous waste incinerators.

ROTARY WATERWALL UNIT[2]
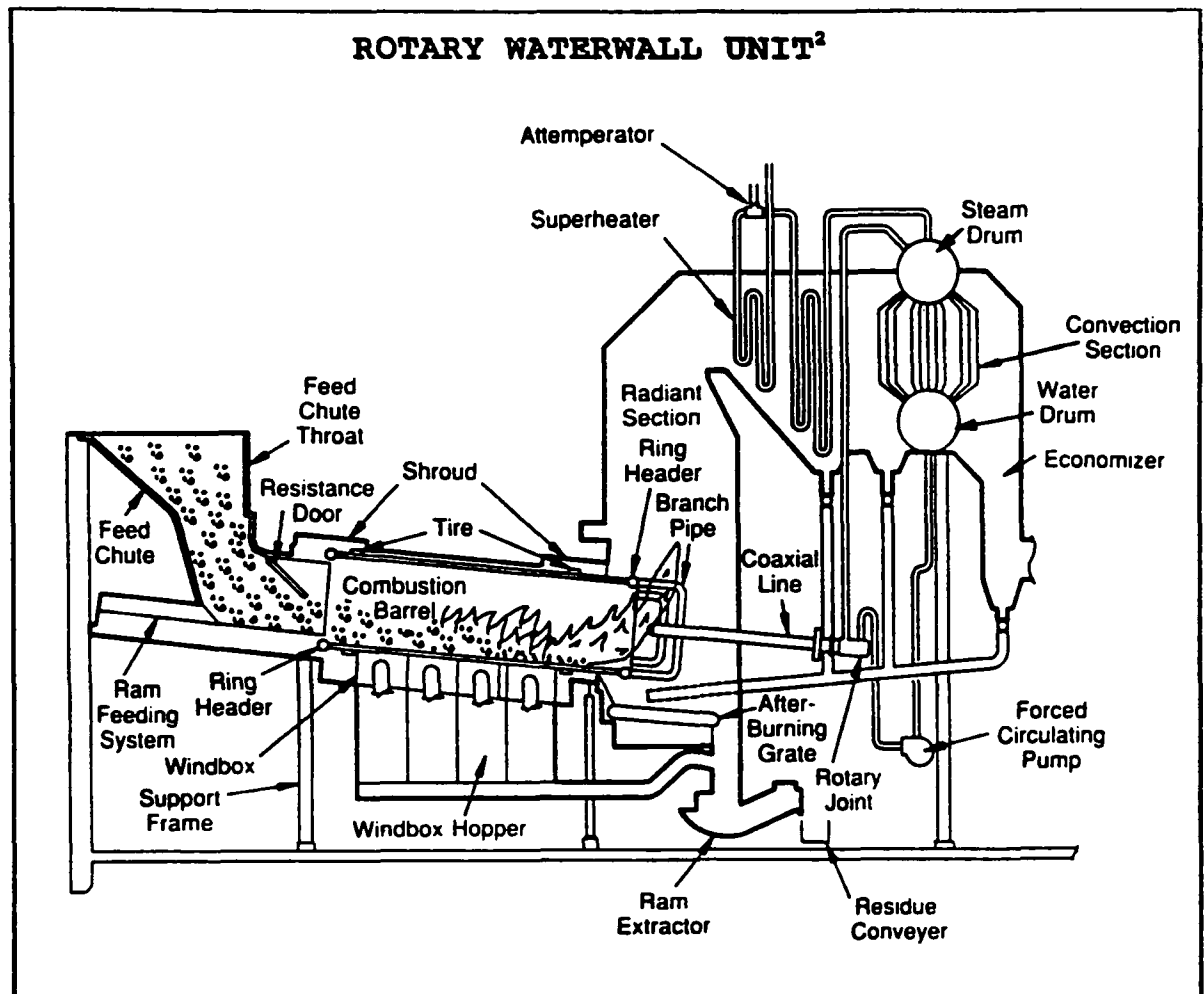
Courtesy of Westinghouse Electric Corporation

In a rotary waterwall combustor, waste materials are exposed to combustion air which also passes through the small air holes in the combustor barrel. As the combustor turns, the tumbling action stirs the waste materials and exposes them to air. The rotary barrel is inclined at a modest angle (e.g., 6 degrees), so that gravity forces help direct the tumbling MSW residues through the unit.

The rotary waterwall combustor has unique piping features which allow water to circulate through the grate and extract thermal energy before being directed to the fixed waterwalls in the furnace area.

Conventional water-cooled grates are provided in a secondary burn-out chamber, which receives the ash from the rotary combustor and holds it in residence for final carbon burn-out before being delivered to the ash pit.

```
┌─────────────────────────────────────────────────┐
│         MODULAR MASS BURN                        │
│                                                  │
│         Factory Manufactured                     │
│         Refractory-Wall                          │
│         Controlled-Air, Starved-Air              │
│         Low Velocity in Primary                  │
│         Low Particulate Entrainment              │
│         Solids Retention for Burn-Out            │
└─────────────────────────────────────────────────┘
```

Modular refractory-wall incinerators were developed in the mid-1960s.[14] These factory manufactured units gained popularity because of their reduced particulate and smoke emissions, without requiring stack gas cleaning equipment. Because standard models were marketed, many installations were permitted based upon the testing of comparable units. Competition from such units stimulated improved combustion equipment and controls in larger MWC units.

Controlled air gets its name from the use of fans to deliver air to strategic locations. Primary combustion conditions can be either rich or lean, starved-air or excess air.

Starved-air is a phrase used to characterize units which maintain sub-stoichiometric or fuel rich combustion conditions in the primary chamber. Starved-air units are also characterized two-stage combustion units: fuel rich in the primary chamber and lean in the secondary. Therefore, the stack gases leave under excess air conditions.

MODULAR CONTROLLED-AIR OR STARVED-AIR UNIT[15]

MODULAR INCINERATOR

AUX. BURNER

SECONDARY CHAMBER

RAM FEEDER
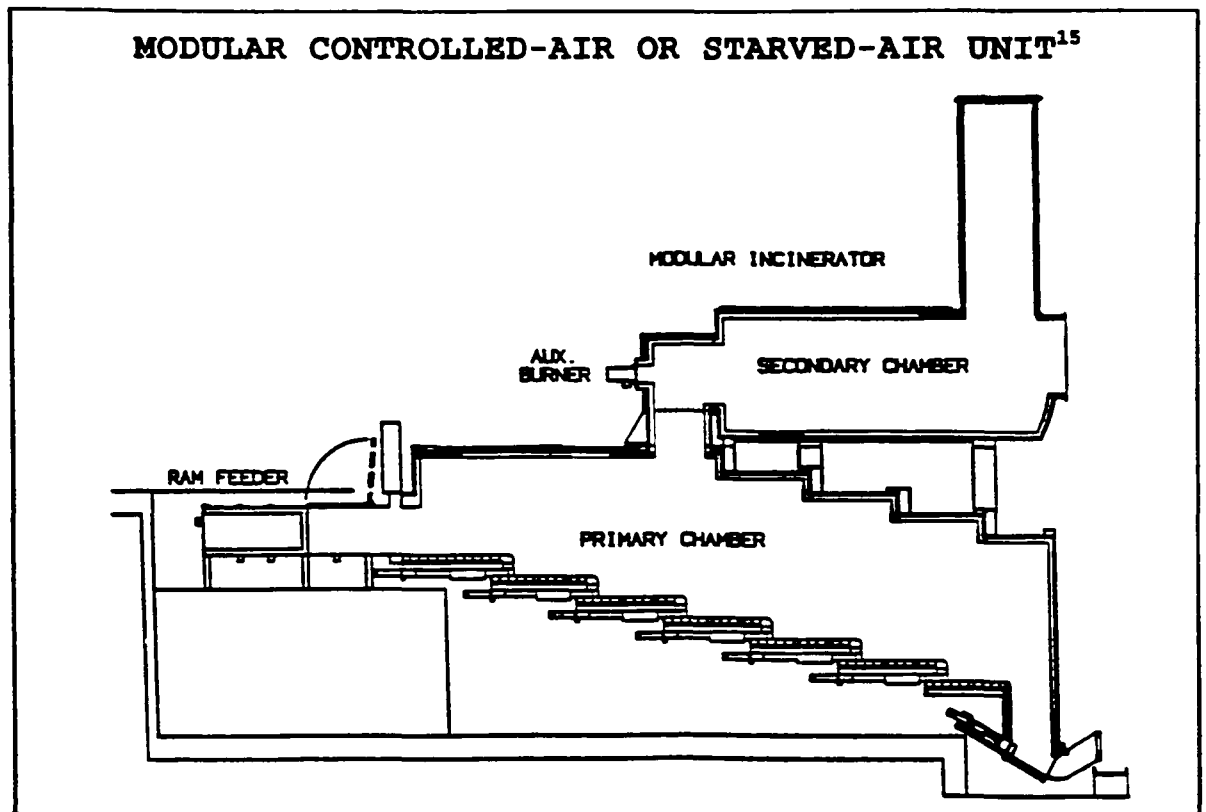
PRIMARY CHAMBER

Courtesy of Joy Energy Systems, Incorporated

Auxiliary fuel burners in the primary chamber are used initially to raise chamber temperatures for enhanced gas volatization.

Under normal conditions, the limited air flow in the primary chamber results in temperatures which are hot enough to drive off the volatiles. A mixture of partially oxidized volatile gases enters the secondary chamber and mixes with additional air for completion of the combustion process.

The amount of ash entrainment is controlled by design features which restrict the air velocities in the primary chamber.

MODULAR INCINERATOR WITH ENERGY RECOVERY[14]

1. Automatic Feed System	5. Steam Generator	9. Exhaust Stack
2. Primary Chamber	6. Steam Separator	10. Emergency By-Pass
3. Transfer Rams	7. Energy Duct	11. Wet Ash Sump
4. Secondary Chamber	8. Emissions Control System	12. Ash Conveyor
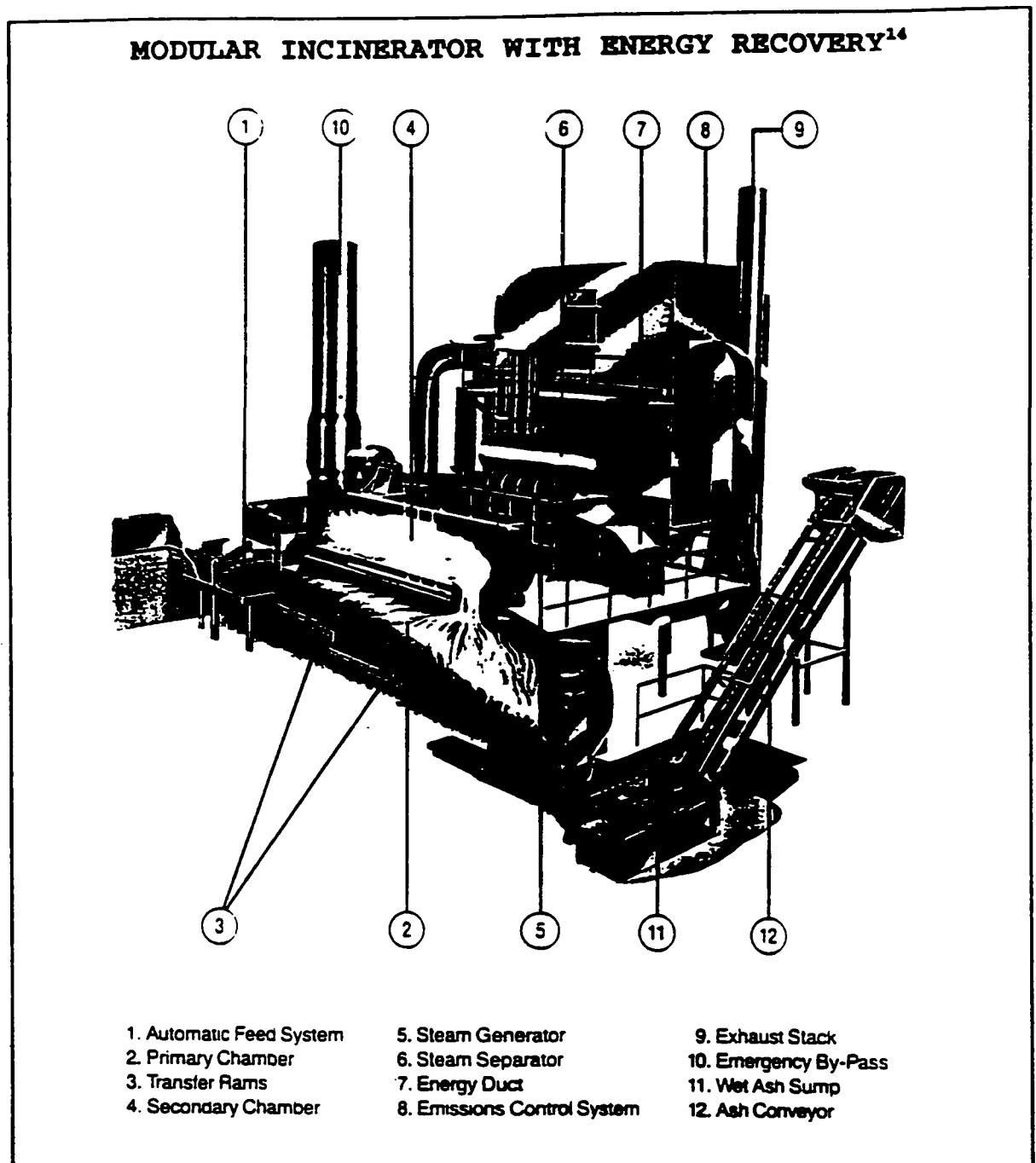
Courtesy of Consumat Systems, Incorporated

Many modular incinerator units function as waste-to-energy units. Energy is extracted in waste heat or recovery boilers, which are located downstream of where the gases leave the secondary chamber. These boilers function basically as air to liquid heat exchangers. Water inside of vertical tubes is converted to steam, which is collected and distributed for commercial purposes.

Waste heat boilers generally extract a smaller fraction of the fuel energy than is possible in waterwall units. This is because waterwall units operate with high temperature, radiant heat extraction in the primary chamber, whereas modular units recover energy from lower temperature flue gases.

Approximately 140 new MWC units were constructed in the USA during the 1970s and 1980s,[2] with about half of the units being modular refractory units with recovery boilers and half being the larger waste-to-energy units.[16] These units were subject to the 1971 NSPS for incinerators having sizes greater than 50 tons/day. During this time period, MWCs generally used electrostatic precipitators to meet the particulate control standards.[11]

The NSPS and EG promulgated for MWCs in 1991 set standards for new and existing MWC units which require new controls for acid gases, products of incomplete combustion, and particulates. Units subject to these regulations typically require dry scrubbers and either fabric filters or electrostatic precipitators.

Slide 6-16

```
RDF UNITS

Waste Processing of RDF
Utility Pulverized Coal Units
    Suspension Firing
Spreader Stoker Units
    Suspension & Grate Burning
Co-Firing with Coal
```

Refuse derived fuel preparation systems and combustion technologies were developed in the mid-1970s.[17] Initially, refuse was prepared for suspension firing in utility boilers burning pulverized coal.

Later modifications included the co-firing of RDF along with coal in spreader stoker units. Today, RDF may be exclusively fired in spreader stoker units, although the option of co-firing with coal is often provided.[18,19]

The main advantage of RDF combustion relative to mass burning of MSW is that the RDF has a higher heating value and has more nearly uniform physical properties.
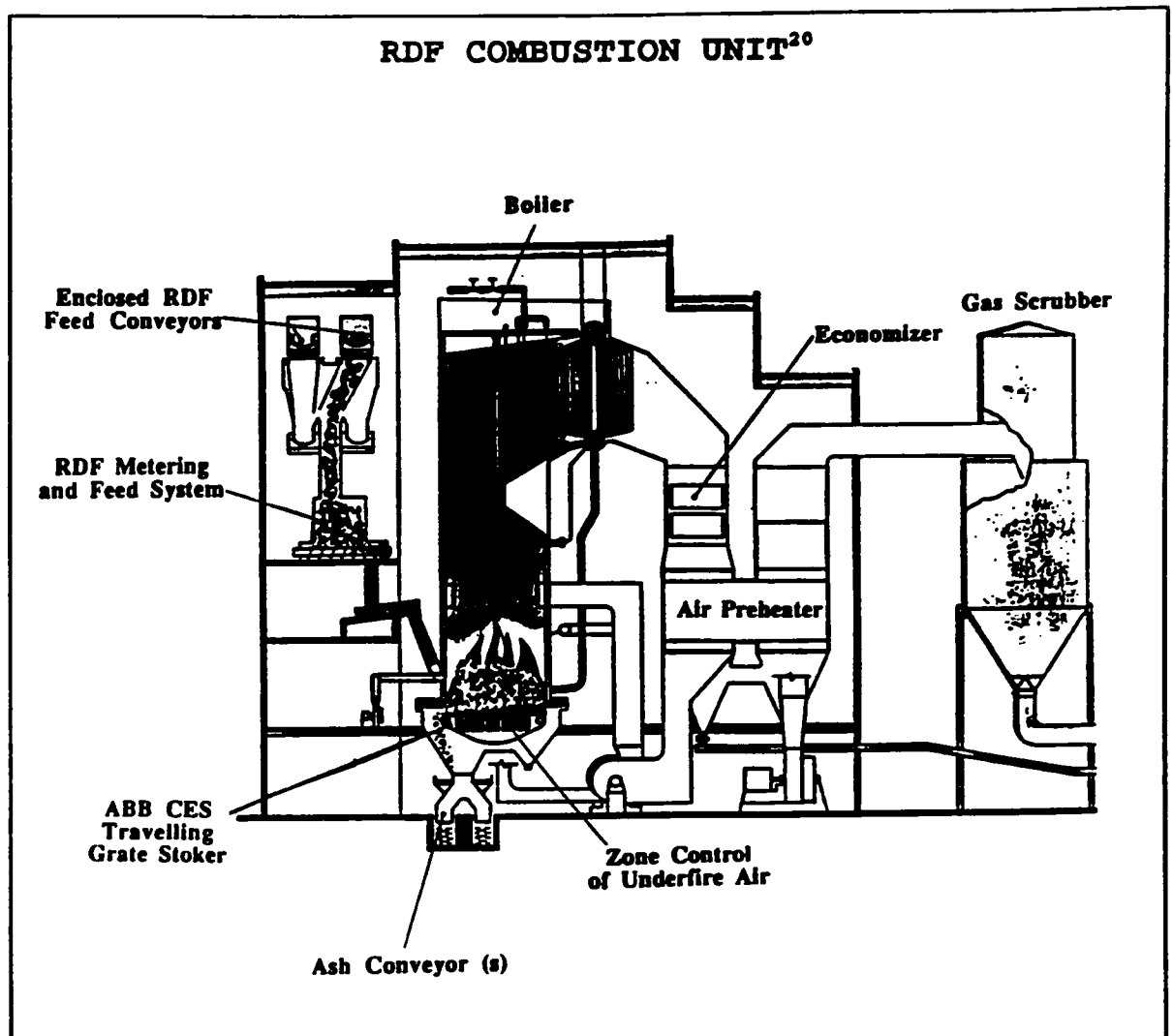
Courtesy of Combustion Engineering, Incorporated

The features of combustion of RDF can be compared to burning coal in a spreader stoker fired unit. Both coarse and fluff refuse derived fuels (c-RDF and f-RDF, respectively) are less dense than coal and tends to be formed as chips which are more easily entrained. A greater fraction of RDF typically burns in suspension, although the residence time may be inadequate for full carbon burnout. Therefore RDF units will have greater soot and particulate loadings than mass-burn systems.

The ash fusion temperature for MSW and RDF is generally lower than that of coal. Special grate designs have been successful in reducing freezing of molten ash on the grates which would otherwise plug the siftings and under-grate air passages.[13] Clinker formation on the grates is generally a concern when switching from coal firing to RDF firing.

In addition, RDF has a lower heating value than coal and requires less theoretical oxygen for complete combustion. Therefore, switching from burning RDF to coal requires some combustion system adjustments.

REFERENCES

1. Christopher Hocker, "Waste-to-Energy Development: Who's Doing What and Why?" Solid Waste and Power, August 1989, pp. 12-19.

2. Scott Siddens, "A Decade of Innovation in WTE Incineration," Solid Waste and Power, April 1990, pp. 16-23.

3. J. A. Danielson, Air Pollution Engineering Manual, AP-40, Second Edition, U. S. Environmental Protection Agency, May 1973, p. 472.

4. J. E. Williamson et al., "Multiple Chamber Incinerator Design Standards for Los Angeles County," Los Angeles County Air Pollution Control District, October 1960.

5. R. J. Alvarez, "Study of Conversion of Solid Waste to Energy in North America," Proceedings of 1976 ASME National Waste Processing Conference, Boston, May 1976, pp. 163-174.

6. R. J. Alvarez, "Status of Incineration and Generation of Energy from Processing of MSW," Proceedings of 1980 ASME National Waste Processing Conference, New York, May 1980, pp. 5-26.

7. Municipal Incineration, A Review of Literature, AP-79, U. S. Environmental Protection Agency, 1971, p. 29.

8. "Energy Recovery from Existing Municipal Incinerators," A Final Report to New York Power Authority, prepared by Chesner Engineering, PC and Black and Veatch Engineers, Nov. 1984, pp S-1 to 3-46.

9. R. C. Corey, Principles and Practices of Incineration, Wiley-Interscience, 1969, pp. 2-4.

10. Georg Stabenow, "Results of Stack Emissions Tests at the New Chicago Northwest Incinerator," ASME J. Engineering for Power, pp. 137-141, July 1973.

11. W. D. Turner, Thermal Systems for Conversion of Municipal Solid Waste, Vol. 2: Mass Burning of Solid Waste in Large-Scale Combustors: A Technology Status Report, Report ANL/CNSV-TM-120, Vol. 2, Argonne National Laboratory, December 1982, pp. 43-168.

12. Steam, Its Generation and Use, 39th Edition, Babcock and Wilcox, New York, 1978, p. 16-3.

13. Joseph G. Singer, <u>Combustion Fossil Power,</u> 4th Edition, Combustion Engineering, Inc., Windsor, CT, 1991, pp. 8-16 to 8-26 and 12-22.

14. "Integrated Waste Services, Information Summary," Consumat Systems, Inc., Richmond, Virginia, Undated Brochure.

15. "Controlled Air Incineration," Joy Energy Systems, Inc., Charlotte, NC, Undated Brochure.

16. <u>Municipal Waste Combustion Study, Report to Congress,</u>" U.S. Environmental Protection Agency, EPA-530-SW-87-021-a, May 1987, pp. vi-viii.

17. Floyd Hasselriis, <u>Thermal Systems for Conversion of Municipal Solid Waste, Vol. 4: Burning Refuse-Derived Fuels in Boilers: A Technology Status Report,</u> Report ANL/CNSV-TM-120, Vol. 4, Argonne National Laboratory, March 1983, pp. 1-166.

18. Daniel F. Moats, J. Mathews, and K. C. O'Brien, "A Performance Update for the Columbus Project," <u>Proceedings of 1988 ASME National Waste Processing Conference,</u> Philadelphia, PA, May 1988, pp. 181-189.

19. Gary L. Boley, "Startup and Operations of the Mid-Connecticut Resource Recovery Project," <u>Proceedings of 1990 ASME National Waste Processing Conference,</u> Long Beach, CA, June 1990, pp. 21-29.

20. "Prepared Fuel Steam Generation System," ABB Resource Recovery Systems, Windsor, Connecticut, Undated Pamphlet.

7. COMBUSTION PRINCIPLES II: THERMOCHEMISTRY

Slide 7-1

```
THERMOCHEMICAL CONCEPTS

Heating Values & Load
Ignition Temperatures
Combustion Temperatures
Temperature Control Methods
```

This learning unit introduces the thermochemical concepts of combustion which have relevance to plant operations. Included are: fuel properties, combustion energy release rates, heat sinks, combustion temperature and temperature control.

Slide 7-2

```
HEATING VALUES

Higher Heating Value (HHV)
        Bomb Calorimeter
        Water Formed is Condensed
Lower Heating Value (LHV)
        Computed from HHV
        Assumes Water Formed is Vapor
```

The higher heating value (HHV) is defined as the maximum combustion energy released by a fuel per unit mass.[1] Heating values for solid fuels can be determined with a laboratory device called a bomb calorimeter. The procedure includes weighing the fuel sample, burning it completely, and measuring the energy absorbed by an adjacent heat sink. Since the combustion products are cooled back down to room temperature, all the water vapor in the produce gases will be condensed. The HHV is obtained by dividing the energy gain of the heat sink by the mass of the sample.

The lower heating value (LHV) is the same as HHV except that the vaporization energy associated with the water in the product gases must be subtracted. If one is able to calculate or measure the amount of water in the product gases and look up the heat of vaporization per unit mass, the LHV can be computed. Of course, if no water is formed in combustion (e.g., as in burning pure carbon) the LHV and the HHV will be the same. The HHV of the example MSW of Slide 4-17 was given as 4,830 Btu/lb; its corresponding LHV was computed to be 4,100 Btu/lb.

Because the water produced by combustion generally leaves the unit in the stack gases as water vapor, the LHV is often used to represent an upper limit for energy recovery. Most combustion unit capacity standards in the United States are based on HHV, but some of those used in Europe are based on LHV.

HEATING VALUES OF SELECTED FUELS[1,2,3]			
FUEL	HHV Btu/lb	BASIS	MOISTURE %
Methane	23,875	Dry	0.0
Fuel Oil, #6	18,300	As Received	0.7
Coal, PA Bitum.	13,800	As Received	1.5
Coal, WY Subbitum.	9,345	As Received	25.0
Wood, White Pine	8,900	Kiln Dried	8.0
Wood, White Oak	8,810	Kiln Dried	8.0
Lignite, ND	7,255	As Received	37.0
MSW, Ames, IA	6,372	Dry	0.0
RDF, Ames, IA	6,110	As Received	6.5
MSW, Ames, IA	4,830	As Received	24.2
Wood, Fresh Cut	4,450	As Received	50.0

The HHVs of various representative fuel samples are presented above. Higher heating values can be reported either on a "dry" basis or on the basis of the total sample "as received" in the laboratory. The HHV is most often reported on an "as received" basis because the moisture influences its combustion. Note that the methane value corresponds to gaseous methane at 60°F and atmospheric pressure.

One should note that the moisture content of RDF is less than that of MSW because some drying occurs during its preparation. The amount of metals recovery in RDF processing affects not only the ash content but also the heating value.

```
UNIT  RATED CAPACITY
      MSW  Charging Rate
           tons/day
           lb/day
           lb/hour

UNIT  OPERATING LOAD
      Gross Energy Input
           Btu/hour
```

The rated capacity of a MWC unit is generally stated in terms of a nominal MSW charging rate, which is generally given in tons/day. By contrast, the phrase "operating load" generally corresponds to the overall energy input, which is based on the fuel charging rate and its HHV. Load is generally presented in units of Btu/hour.

Slide 7-5

```
UNIT OPERATING LOAD =
            FUEL CHARGING RATE x HHV

Example:   500 tons/day Unit
           4,500 Btu/lb HHV

UNIT OPERATING LOAD =
           500 tons/day x 2,000 lb/ton x
           4,500 Btu/lb x 1 day/24 hours

UNIT OPERATING LOAD =  188,000,000  Btu/hr
```

There is a direct relationship between the fuel charging rate, the HHV of the fuel, and the overall rate of energy input. The charging rate times the HHV equals the load. Of course, the units must be properly canceled, as in the above example.

Combustion chambers are generally designed for a given gross energy input rate. Therefore, as the fuel composition and its HHV changes, the charging rate under maximum load conditions can change accordingly. For instance, if fuel enters with a larger heating value, the charging rate should be reduced accordingly.

Slide 7-6

IGNITION TEMPERATURES[5]		
Material	Phase at 60°F & 14.7 psia	Ignition Temp.,°F
Sulfur	Solid	470
Charcoal	Solid	650
Gasoline	Liquid	663-702
Acetylene	Gas	589-825
Fixed Carbon	Solid	765-1115
Hydrogen	Gas	1065-1095
Methane	Gas	1170-1380
Carbon Monoxide	Gas	1130-1215
Benzene	Liquid	1335

Ignition (or auto-ignition) temperatures are presented as general indications of the temperatures required for combustion. Ignition temperature may be defined as the temperature at which rapid combustion in air ignites automatically and becomes self-sustaining.

As illustrated above, ignition temperatures of volatile hydrocarbons vary from acetylene at about 700°F to methane, carbon monoxide and benzene at around 1,200°F or higher. The fixed carbon remains in a solid form and has ignition temperatures as low as 765°F.

Ignition temperatures of paper and plastic materials are not provided because a large fraction of these materials burn as volatile matter, composed of a number of different hydrocarbon compounds.

Note, that actual combustion processes are driven by complex reactions involving presence of radicals (e.g., OH). Therefore, the combustion processes can be self-sustained at temperatures below those listed in Slide 7-6. In addition, combustion depends upon the enclosure design, air-fuel mixture, air velocity and the source of ignition.

Slide 7-7

EXAMPLE OF RDF PROXIMATE ANALYSIS	
	Percentage by Weight
Moisture	26.6
Ash	21.7
Volatile Matter	43.6
Fixed Carbon	8.1
Total	100.0

Our understanding of combustion can be aided by referring to the parameters of the proximate analysis. The moisture fraction is the water which vaporizes as the fuel is heated above ambient conditions. One can assume that the fuel is essentially dry by the time it is heated to approximately 220° F.[5]

Volatile hydrocarbon materials are gaseous materials which burn much like natural gas. These gases are evolved as the MSW is heated. Volatilization begins as a straight distillation process. Light hydrocarbons are distilled first, and heavier hydrocarbons are evolved as the temperature increases. Some heavy or residual fuel hydrocarbon materials will undergo thermal and/or catalytic cracking before being evolved as new hydrocarbon gases. The distillation process is generally completed by the time the fuel temperature reaches around 1,750° F.[5]

Fixed carbon is the solid combustible fraction of the fuel. It undergoes burning on the surface. Solid carbon combustion can occur as the volatile gases are being evolved, since the ignition temperature of carbon is as low as 765° F.

Slide 7-8

```
+----------------------------------------------------+
|                                                    |
|    ADIABATIC COMBUSTION CONDITIONS                 |
|                                                    |
|    Energy Release From Combustion                  |
|             No External Heat Losses                |
|             Heats Combustion Product Gases         |
|             Vaporizes Moisture                     |
|                                                    |
+----------------------------------------------------+
```

Adiabatic combustion conditions are idealized conditions which can serve as a aid for evaluating combustion phenomena. An adiabatic combustion condition is one where all the combustion energy is used either to heat the products of combustion or to vaporize moisture and other materials. As such, adiabatic conditions require that there be no heat loss to the surroundings. Of course, the hot combustion gases produced under adiabatic conditions could be directed into regions where heat transfer could occur. Adiabatic combustion conditions can be approximated in an idealized refractory furnace, with no heat loss.

In general, the maximum adiabatic temperatures correspond to complete burning of stoichiometric air/fuel mixtures. Such conditions are not generally realized in actual combustion conditions and they may not even be desirable. For instance, the maximum adiabatic temperatures would generally be high enough to damage the furnace structure and the heat exchange surfaces. Therefore, controlling furnace temperature is important from the standpoint of protecting the combustion unit.

Slide 7-9

```
+----------------------------------------------------+
|                                                    |
|      COMBUSTION TEMPERATURE CONTROL                |
|                                                    |
|      Fuel Modulation                               |
|      Heat Transfer to Surroundings                 |
|      Heat Sink Materials                           |
|                                                    |
+----------------------------------------------------+
```

Combustion temperatures can be controlled by modulating the delivery of fuel and air, assuming that the heat losses are relatively constant in time.

The rate of heat extraction to the surroundings can be somewhat regulated. For instance, if the flow of feedwater increases in a furnace with an integral boiler, the heat transfer to the waterwalls will increase and the combustion temperatures will drop.

Slide 7-10

```
┌─────────────────────────────────────────────┐
│          HEAT SINK MATERIALS                 │
│                                              │
│          Water in Fuel                       │
│          Nitrogen                            │
│          Excess Air                          │
│          Flue Gas                            │
│          Water Sprays                        │
│                                              │
└─────────────────────────────────────────────┘
```

Heat sink materials have the effect of lowering the effective combustion temperature. They may be considered as either undesirable or desirable. The water in MSW is generally considered to be an undesirable heat sink material, since all the water must be vaporized before combustion can occur.

Temperature control can also be established by the delivery of various heat sink materials. Excess air is the most common heat sink available for operator control. This method is used particularly in the secondary combustion chamber of a modular incinerator. Under excess air conditions, an increase of excess air can be used to reduce combustion gas temperatures and protect the refractory.

The nitrogen in air is a less obvious heat sink material because the combustion temperatures would be considerably higher if pure oxygen were used rather than air.

Combustion temperatures can also be controlled by flue gas recirculation.[6] This method is often used in power plants and in some MWCs because the extra flue gas acts as a heat sink material.

Slide 7-11

```
┌─────────────────────────────────────────────┐
│          WATER SPRAYS                        │
│                                              │
│          Reduce Fuel-to-Air Ratio            │
│          Reduce Temperature                  │
│          Reduce Velocity                     │
│          Reduce Opacity                      │
│          Reduce Fires in the Charge Hopper   │
│                                              │
└─────────────────────────────────────────────┘
```

Water sprays are used as a heat sink in the primary chambers of modular controlled-air incinerators. The lower temperature will retard the volatilization process, thereby decreasing the local fuel-to-air ratio.[7] With lower temperatures, the velocity of the gases are also reduced.

Water can be sprayed onto a fresh charge of waste to slow down the rate of volatilization of plastics. Otherwise, a burst of volatiles would produce a fuel-rich mixture which might not burn completely, resulting in opacity problems.

Water is also sometimes sprayed onto the charging ram to prevent fires in the charging hopper.[8]

Slide 7-12

```
STARVED-AIR UNITS

Two Stage Combustion
Lower Velocities in Primary
Primary Chamber: Gasifier
        More Primary Air
        Higher Primary Temperatures
Secondary Chamber: Excess Air Combustion
```

Starved-air is a phrase used to describe a particular form of two-stage combustion which occurs in modular incinerators. Under starved-air conditions, the primary chamber acts as a gasifier, distilling the volatile gases and mixing them with less air than would be required for stoichiometric conditions. The process of distillation of the volatile components is sometimes considered pyrolysis. Although combustion does occur in the primary chamber, there is not enough air for complete combustion of the volatile gases.

The secondary chambers of modular units are designed to mix additional air with the partially reacted gaseous mixture (fuel) from the primary chamber. Adequate provisions for supplying air and mixing it with the fuel are required to obtain complete combustion in the secondary chamber.

Starved-air incinerators were initially developed because of their inherent feature of low particulate emissions. If more air were to be added in the primary chamber, the rate of combustion would increase, raising the gas temperatures and thereby increasing the rate of gas volatilization. The increased air supply and gas temperatures would cause the velocities to increase, which would increase the amount of particle entrainment.

Slide 7-13

```
┌─────────────────────────────────────────────────┐
│                                                 │
│      EXCESS AIR COMBUSTION                       │
│                                                 │
│      Excess Air - Heat Sink                      │
│      More Excess Air                             │
│              Temperature Reduction               │
│                                                 │
└─────────────────────────────────────────────────┘
```

Excess air combustion is in contrast to starved-air combustion. For example, in an excess air unit, an increase in the delivery of air generally results in a decrease in the combustion temperature. However, the combustion phenomena is much more complicated, as will be discussed later, with under-grate and over-fire air and other considerations.

REFERENCES

1. Joseph G. Singer, Combustion Fossil Power, 4th Edition, Combustion Engineering, Inc., Windsor, CT, 1991, pp. 2-13 to 2-27.

2. Steam, Its Generation and Use, 39th Edition, Babcock and Wilcox, New York, 1978, pp. 5-8 to 5-17 and 6-2.

3. D. E. Fiscus, et al., Study of Existing RDF Co-Firing Experiences, Vol. 2: Appendixes to Phase I Final Report, Report ANL/CNSV-TM-134, Vol. 2, Argonne National Laboratory, October 1983, pp. C-1-14, C-1-15, & C-9-14.

4. Steam, Its Generation and Use, 39th Edition, Babcock and Wilcox, New York, 1978, pp. 6-6.

5. Joseph G. Singer, Combustion, Fossil Power Systems, 3rd Edition, Combustion Engineering, Inc., Windsor, CT, 1981, p. D-5.

6. "Nitrogen Oxide Control For Stationary Combustion Sources," EPA/625-5-86/020, U. S. Environmental Protection Agency, July 1986.

7. W. R. Seeker, W. S. Lanier and M. P. Heap, Municipal Waste Combustion Study, Combustion Control of Organic Emissions, U.S. Environmental Protection Agency, EPA-530-SW-87-021-c, May 1987, p. 7-9.

8. Handbook of Operation and Maintenance of Hospital Medical Waste Incinerators, EPA/625/6-89/024, U. S. Environmental Protection Agency, January 1990, pp. 16-17.

8. MSW HANDLING EQUIPMENT

Slide 8-1

```
SOLID MATERIALS FLOW PATH

1.  Weight Scales
2.  Tipping Floor, MSW Storage Pit
3.  Front-End Processing Equipment
4.  Charge Hopper, Feeder Device
5.  Combustion Chamber Grate
6.  Ash & Fly Ash Collection Devices
7.  Ash Removal System
8.  Ash Disposal at Landfill/Monofill
```

The various elements of the solid materials flow path are listed above. Note that these elements will take different forms at different MWC facilities. For example, the full scale front-end processing equipment for RDF will not be found at a mass burn facility, and the grate in large mass burn units may be replaced by a hearth with a ram device in modular incinerators.

Slide 8-2

```
SCALE OPERATOR FUNCTIONS

1.  Restrict Delivery to Facility
2.  Basis for Tipping Fees
3.  Processed Waste
4.  Unprocessed Wastes
5.  Ash
6.  Recovered Materials
```

Note that the weight scale operation has various important management functions. Certainly, the weight scale provides the basis for tipping fee collections as well as a record of the source and weight of material processed by the MWC facility.

The scale operator may have the duty of restricting the delivery of materials to those which can be appropriately processed by the MWC facility. During periods of shut-down, the scale operator can provide information about the location of alternative disposal sites.

The operators will typically weigh the materials being transported "off site." These can include the ash which is sent to monofills and/or landfills, undesirable materials which are removed from the waste stream before combustion, and recovered materials delivered to recycle and reprocessing operations.

```
┌─────────────────────────────────────────────────────────────┐
│                                                               │
│        UNACCEPTABLE AND/OR UNDESIRABLE MATERIALS              │
│                                                               │
│        1.  Not Permitted - Hazardous, etc.                   │
│        2.  Cause Damage - Explosion, Breakage                │
│        3.  Restrict Operations - Blockage                    │
│        4.  Incombustible                                      │
│                                                               │
└─────────────────────────────────────────────────────────────┘
```

Permit restrictions may include provisions which prevent specified materials from being processed in MWC units. Examples would include hazardous wastes, radioactive wastes, and "red bag" medical waste. Other materials may include construction debris and industrial wastes.

Automotive and rechargeable consumer batteries are undesirable incineration materials because they are sources of some heavy metals emissions. Even with effective gas cleaning, it would be much better if batteries were recycled or alternately disposed, since incineration does not destroy the heavy metals.

Among the materials which can cause damage to the unit are the pressurized gas canister, cans of gasoline, and metal drums of waste oils, solvents, gasoline, and unknown liquids. These items can lead to explosions in the combustion chamber. Some very dry materials, like fine sander dust, are capable of burning violently.

Heavy objects like automotive engine blocks can cause damage to the grates and conveyors. Metal cables and pipes can cause blockages of conveyors and may damage the grates. Large bulky items such as construction, demolition, and land clearing debris (e.g., masonry materials and tree stumps) and industrial wastes (e.g., rolls of plastic and carpet and miscellaneous chemical materials) are generally considered undesirable.

Metals and glass are examples of non-combustible materials which, although detrimental to equipment operations, are often charged into MWC units. Although some metals are basically unmodified by the combustion process, lead melts at around 620°F and aluminum melts at around 1,200°F. These temperatures are below the typical active fuel-bed combustion temperatures.[1] Lead contributes to the metal deposits on heat exchanger surfaces. Melted aluminum can solidify in the air-entry holes in the grate, restricting air flow through the fuel bed and creating uneven burning. Routine maintenance may be required to remove such deposits.

Glass melts at around 2,000°F, a common temperature level in combustion chambers.[1] Much of the clinkering on the grate is related to the melting and solidification of glass.

Slide 8-4

```
┌─────────────────────────────────────────────────┐
│   ISSUES OF FUEL VARIABILITY                     │
│                                                  │
│   1.   Fuel Size                                 │
│   2.   Heating Value                             │
│   3.   Volatility                                │
│   4.   Fuel Moisture                             │
│   5.   Ash (incombustibles)                      │
│                                                  │
└─────────────────────────────────────────────────┘
```

Bulky materials which are combustible include tires, mattresses, and wood furniture. Their large sizes would restrict the air flow to other combustible materials.

The heating values of component materials have considerable variability. For instance, plastics have almost twice the heating value of paper. Plastic materials may appear to undergo pyrolysis instantaneously upon being delivered into the combustion chamber, whereas other materials may require a considerable drying period before their combustible volatiles are evolved.

Some materials have a very low heating value because of their high moisture content. For example, yard wastes have little value as a fuel, although they are organic materials which can be effectively reduced in MWC units.

Slide 8-5

```
┌─────────────────────────────────────────────────┐
│   OPERATING STRATEGIES FOR FUEL VARIABILITY      │
│                                                  │
│   1.   Source Separation                         │
│   2.   Front End Process                         │
│   3.   Mix Wet and Dry Wastes                    │
│   4.   Compensate Through Equipment Design       │
│                                                  │
└─────────────────────────────────────────────────┘
```

Source separation techniques in recycling programs can reduce the amount of glass and metals in the waste charged into MWC units, thereby improving the fuel. Bottle bills have been able to significantly reduce the glass and aluminum in the MSW. Some communities limit the acceptance of garbage to those items which can fit inside a standard container. Separate disposal procedures can be adopted for undesirable, oversized and/or non-combustible materials, such as waste oils, batteries, metals and "white goods" (water tanks, stoves, refrigerators).

The front-end waste processing techniques, presented in Learning Unit 3, can be used to remove undesirable components and produce RDF fuel. RDF processing facilities may have picking stations adjacent to a conveyor to remove undesirable

materials and direct them to alternate disposal sites. TV monitors can help operators review the waste. Manual controls can be used to stop the conveyor when inappropriate items are observed.

Front-end processing at mass burn units focuses on the removal of materials which are untreatable or inappropriate for combustion. Operators of front-end loaders and cranes generally remove such materials from the tipping floor.

The mixing of MSW before the combustion process is one of the most important MWC operations. Overhead crane and front-end loader operators should mix wet and dry materials before they are placed in the charge hopper or feed system. This makes the fuel more nearly homogeneous, reducing swings in combustion heat release rate.

MWCs are designed to compensate for the expected diversity of fuel size and material composition. However, most units will have reduced performance associated with changes in fuel moisture, air flow restrictions, and fuel-bed disturbances. Specific equipment design features will vary by unit size and local conditions.

Slide 8-6

```
RECEIVING AND FEEDING EQUIPMENT

GENERAL:
     Receiving Area (Tipping Floor)
     Storage Pit or Area

MODULAR MASS BURN UNITS:
     Front Loader
     Hydraulic Ram Feed System

LARGER MASS BURN UNITS:
     Overhead Crane & Grapple
     Gravity-Fed Charge Hopper

RDF UNITS:
     Conveyors & Processing Equipment
     Gravity-Fed Charge Hopper
     Air Swept Distributor
```

Modular MWC units have automatic feed systems which include a hatch door, hydraulic transfer rams, and a moveable fire door. The system is sequentially operated by a timer. The hatch opens and a charge is placed in the transfer device; the hatch closes, acting as an air lock; the fire door opens; the ram delivers the charge into the combustion chamber; the ram is retracted; and the fire door closes.

Front loader operators at modular units can generally control the amount of MSW in each charge. The control board operator can establish the dwell time between each charging cycle. A water spray may be used to cool the ram and/or fire doors, thereby preventing the ignition of the MSW in the feed system.

Slide 8-7

GRAVITY FED CHARGE HOPPER[2]
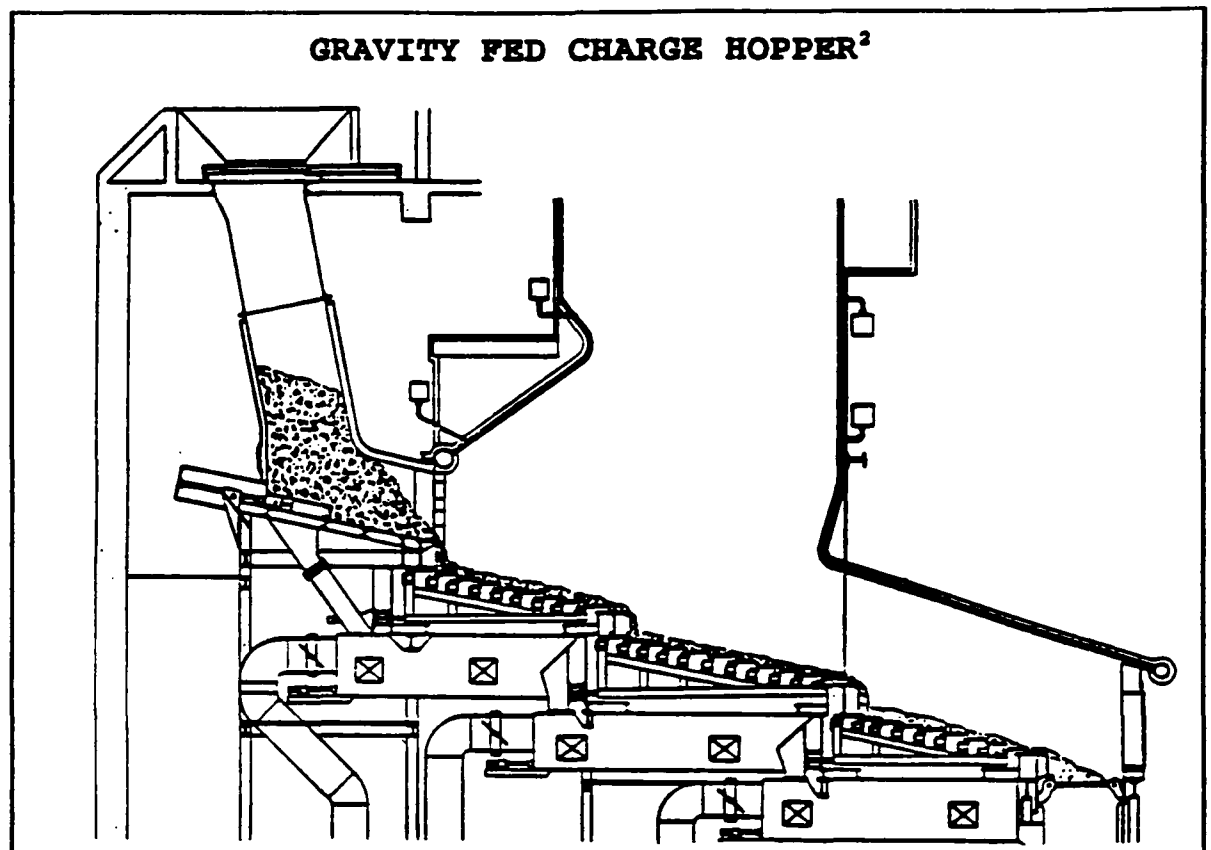
Courtesy of Detroit Stoker Company.

Large MWC units generally have gravity-fed charge hoppers which deliver fuel to the combustion grates on a continuous basis. The crane operators may be required to weigh each grapple of waste that is delivered to the charge hopper. An operator variable is the height of MSW kept in the charging hopper, with higher levels resulting in a denser material on the fuel bed and more mass being charged.

Charge hoppers often include provisions for charging rams, resistance doors, and/or vibrating feed mechanisms. The fresh MSW may act as an air lock between the inside of the combustion chamber and storage area. The control room operator may be able to control the operation of charging rams or other feeder mechanisms, if they are available.

The front-end processing of RDF was discussed in Learning Unit 3. Note that the receiving and temporary storage area can be either a flat tipping floor or a storage pit.

Slide 8-8

AIR SWEPT DISTRIBUTOR SYSTEM FOR RDF

BALANCED
DAMPER

DISTRIBUTOR
SPOUT

AIR FLOW

ROTARY
AIR DAMPER
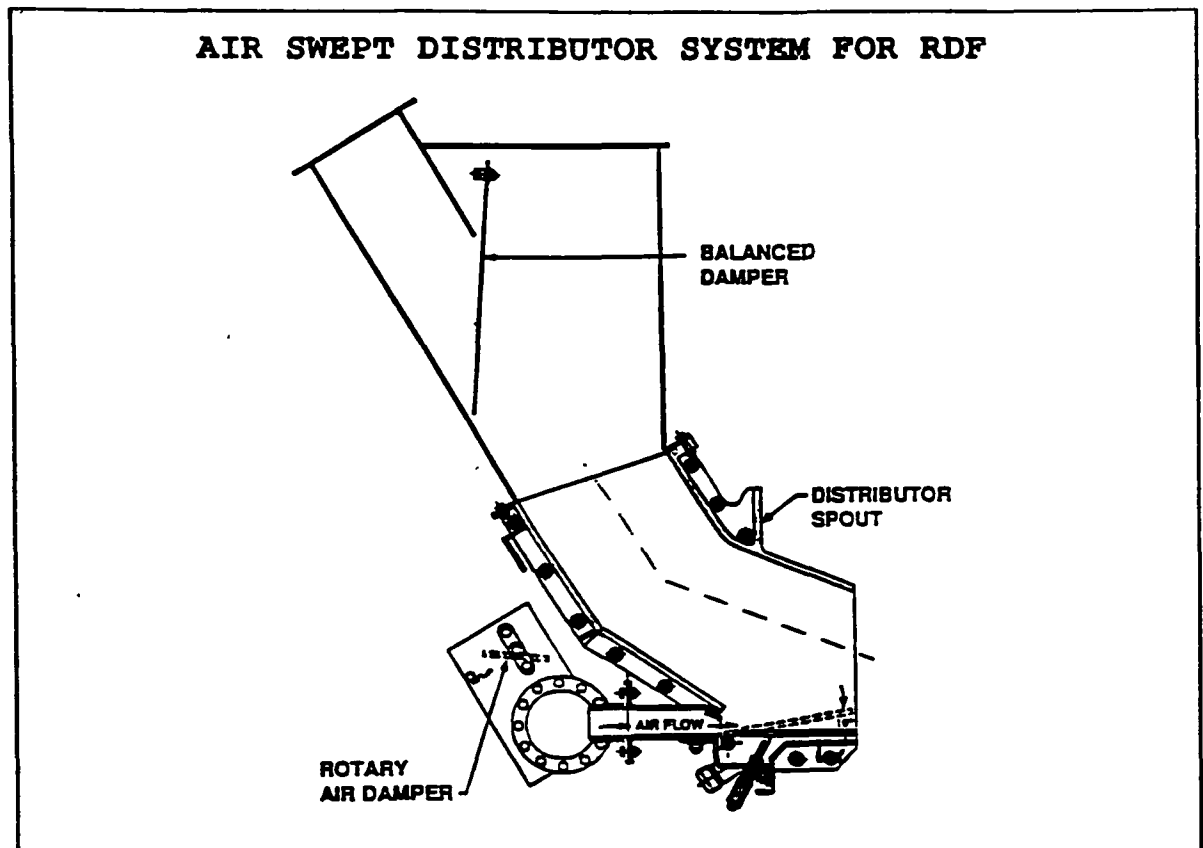
Courtesy of Detroit Stoker Company

The delivery of RDF into the combustion chamber is typically very similar to that used in spreader stoker coal and wood feed systems.[3] The example shown above delivers RDF into the combustion chamber for suspension burning in the overfire air. Most of the fixed carbon is allowed to achieve burnout on a travelling grate at the bottom of the unit.

Slide 8-9

FUNCTIONS OF GRATES & HEARTH

1. Support MSW During Drying
2. Support MSW During Volatilization
3. Distribute Under-Grate Air
4. Stir, Tumble and Mix Wastes
5. Support MSW During Burn-Out
6. Deliver Bottom Ash to Ash Pit

The grate and hearth have the multiple functions indicated above. Radiant heating from the combustion of gases and appropriate rates of air flow must be supplied for the grates/hearth to function properly.

GRATE BURNING COMBUSTION CONCEPT[4]
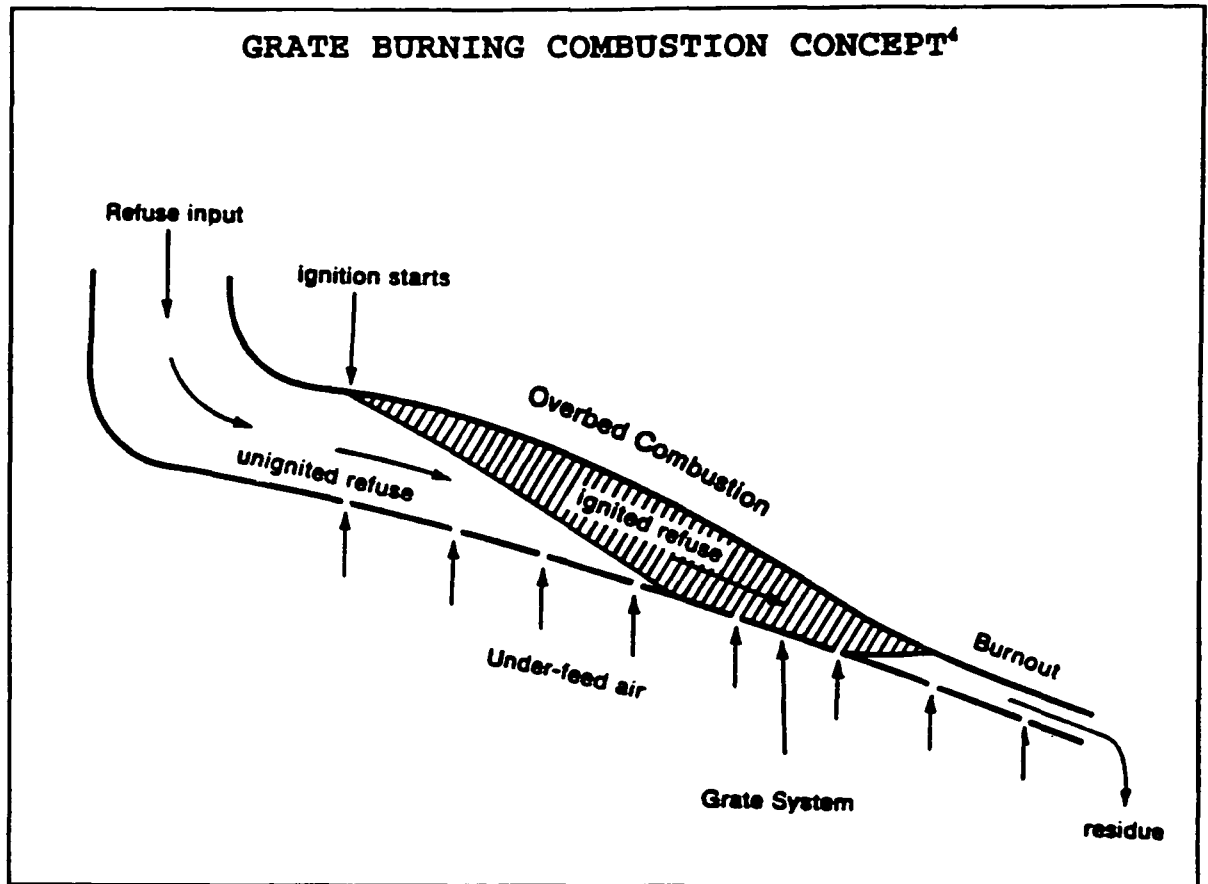
The four principle activities which MSW undergoes in the fuel-bed on a grate are: drying, devolatilization, ignition of volatiles and burning of fixed carbon.[4]

The sketch shows an initial region of unignited refuse. As the MSW is heated, it first undergoes a drying process. The drying process is driven by the heating of the fuel bed by radiant energy from the combustion regions. The moisture is transferred to the under-grate air which diffuses upward through the fuel-bed. Of course, if the air is pre-heated, the drying will occur more quickly.

Subsequent heating of the fuel bed results in the distillation or gasification of the volatile matter. The process proceeds with different gaseous materials being evolved as the bed temperature is increased.

Ignition begins on the top of the fuel bed when the gaseous materials are heated above ignition temperatures. The burning proceeds downward, with the rate being limited by the delivery of under-grate air. Fuel bed agitation is also important because it increases the porosity of the fuel bed. The increased porosity allows more air to mix with the volatiles, increasing the combustion intensity. This, in turn, causes greater rates of heat transfer and distillation of volatiles.

After the volatilization process has been completed, additional surface burning of the fixed carbon can occur until the burn-out process is completed and the ash is delivered to the ash pit.

Other aspects of bed combustion will be presented in the next learning unit.

Slide 8-11

```
GRATE DESIGNS

1.   Reciprocating Stoker Grate
2.   Reversed Reciprocating Grate
3.   Rocking Grate
4.   Vibrating Grate
5.   Roller Grate
6.   Travelling Chain Grate
7.   Refractory Lined Rotary Kiln Grate
8.   Rotating Waterwall Grate
```

A major design consideration for grates is the stirring, tumbling, and mixing of waste, so as to expose fresh MSW surface area to the air. If such actions are inadequate, pieces of waste can stick together, forming an impermeable mat of unburned material. Such unburned material may pass through the combustion chamber and be observed in the bottom ash.

Air-flow passageways in the grates are designed to slowly diffuse under-grate air through the MSW in the fire bed. If the air flow is too great, entrainment of the bed material will occur, leading to increased fouling and particulate carry-over.

If the fuel bed is of uneven depth or has some material constituents which pack differently, the flow of air through the bed will not be uniform. Air flows along the path of least resistance. Under such conditions, the mixing of air and volatile fuel gases will lead to both lean and rich air/fuel gaseous mixtures being evolved along the fuel bed. This may be compensated for in the unit's over-air delivery system design.

Slide 8-12

RECIPROCATING STOKER GRATE[5]

Flow direction

Fixed grates

Moving grates
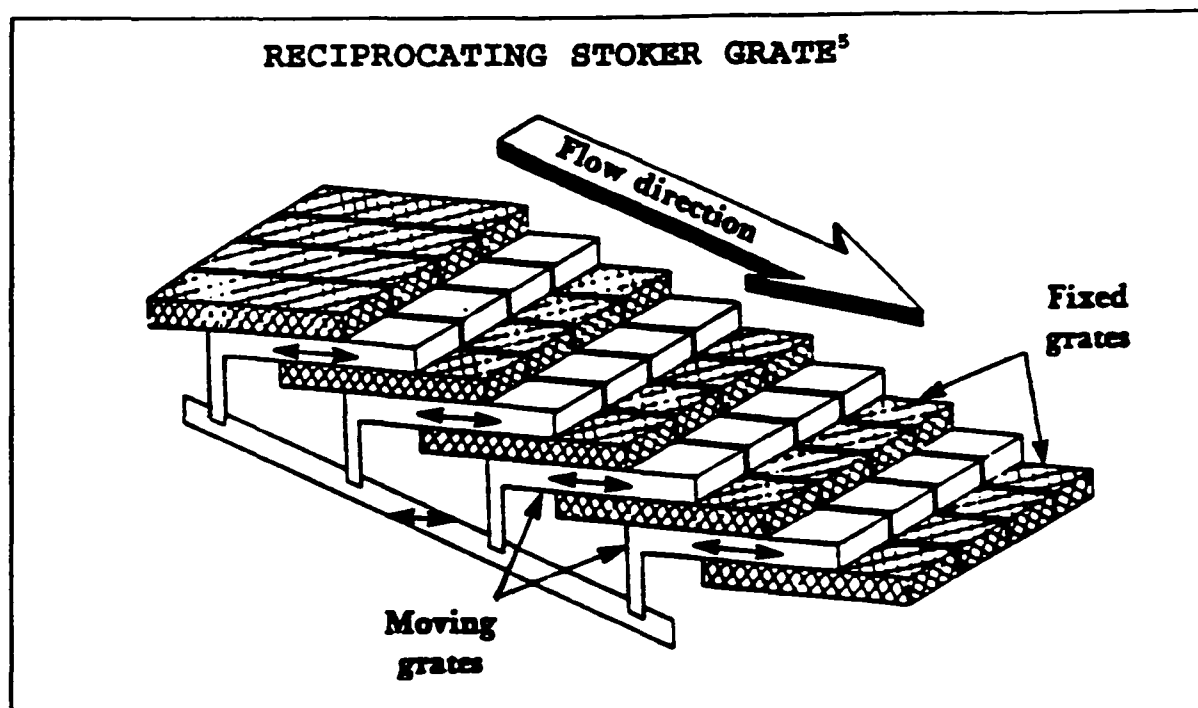
Another purpose of the under-grate air is to cool the grate. Mechanical damage to an overheated grate can include the spot welding of adjacent metal parts. Some grates have design provisions for water cooling with passage-ways through the grate. The rotary waterwall MWC unit is such an example.

Slide 8-13

REVERSED RECIPROCATING GRATE[6]

Fixed Point Pivots

Refuse
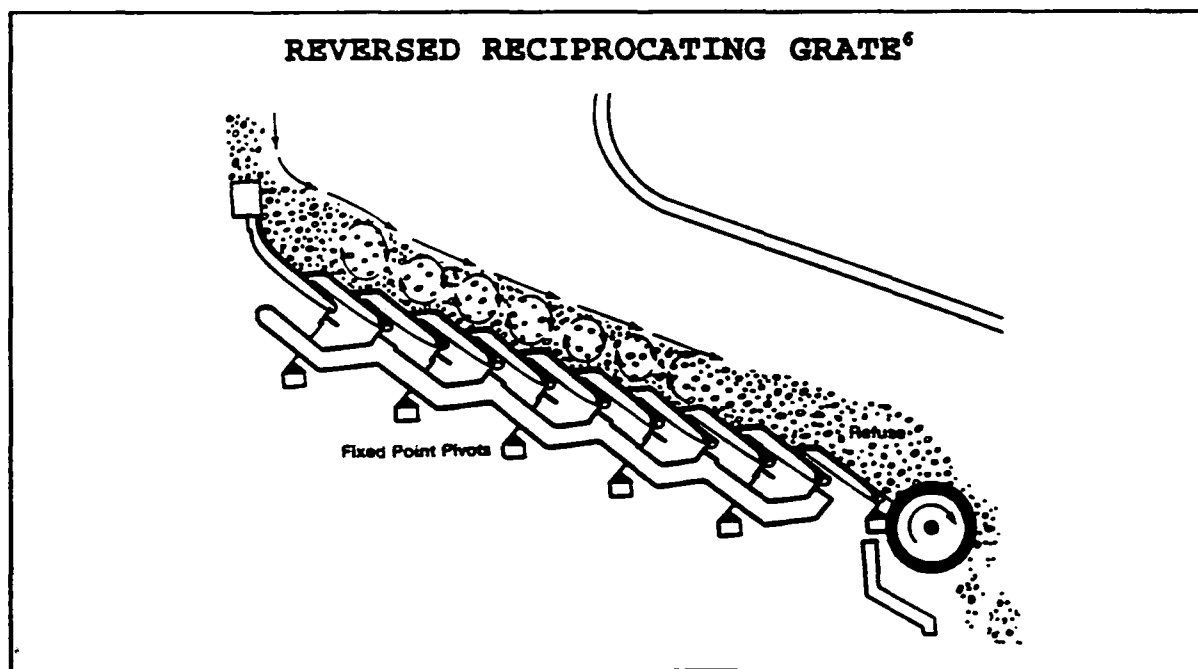
From Proceedings of the 1978 ASME Solid Waste Processing Conference, printed with permission.

Slide 8-14
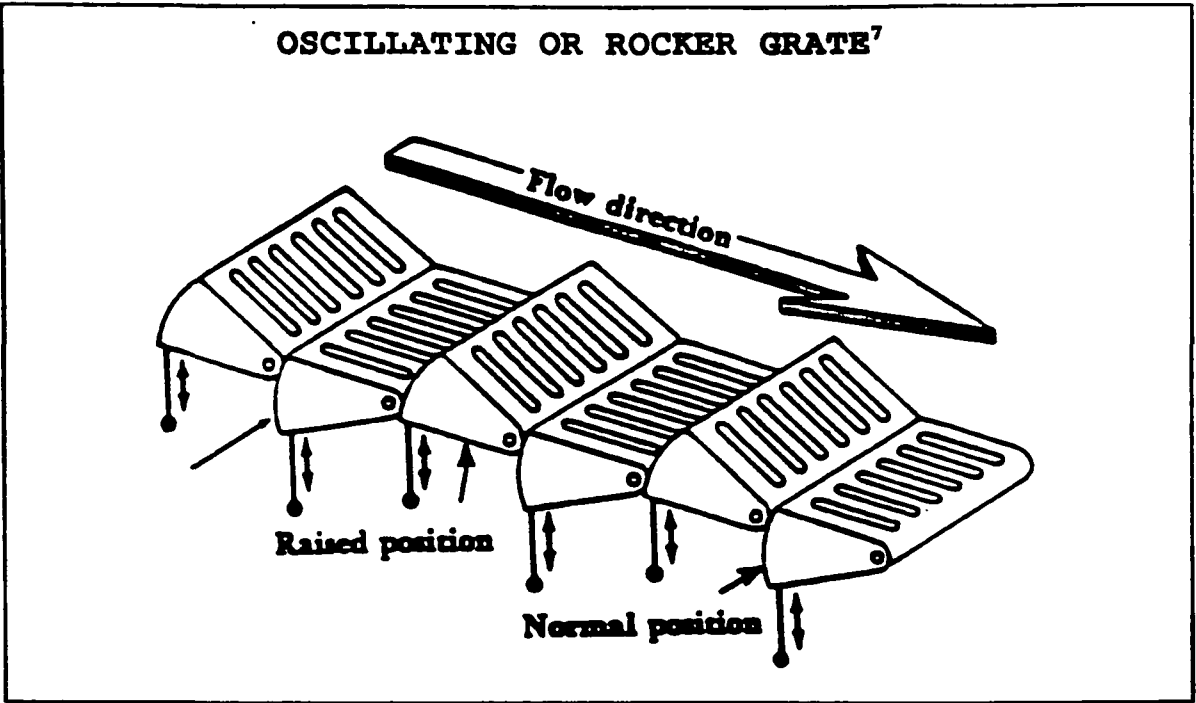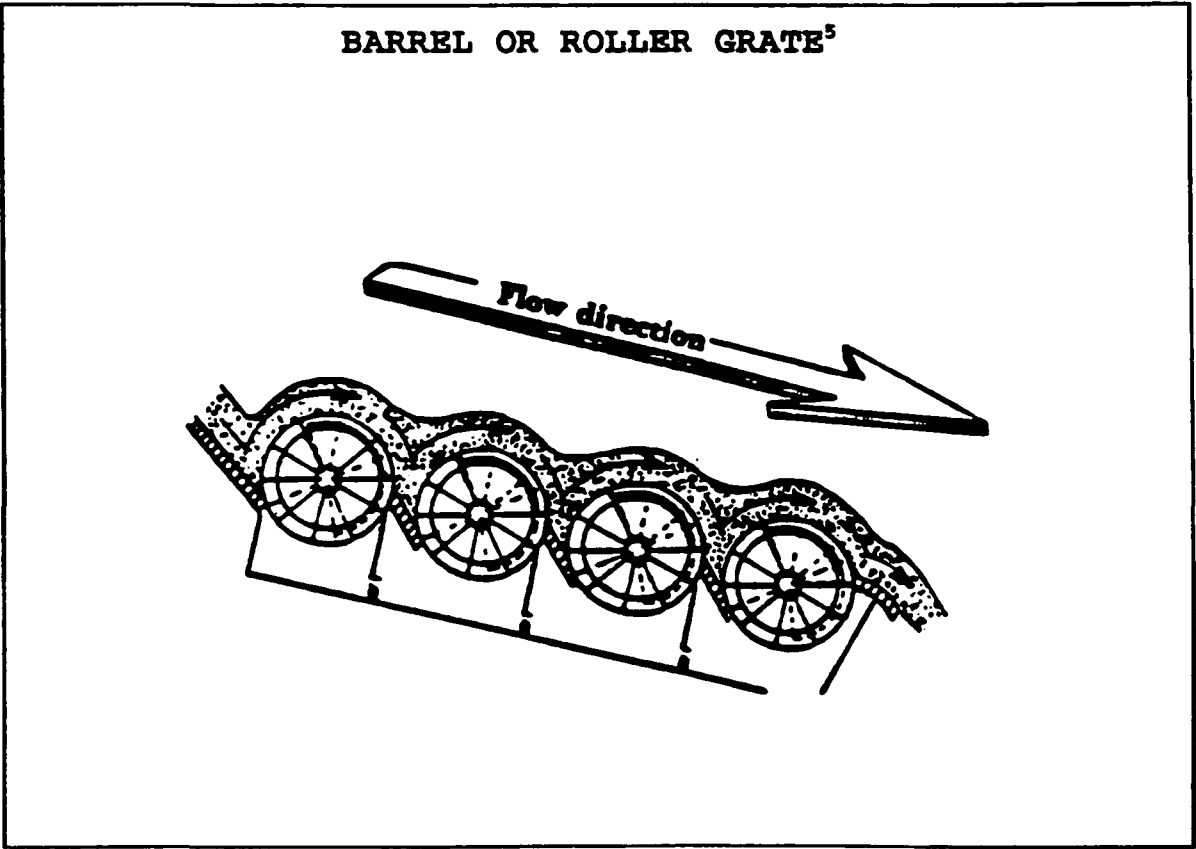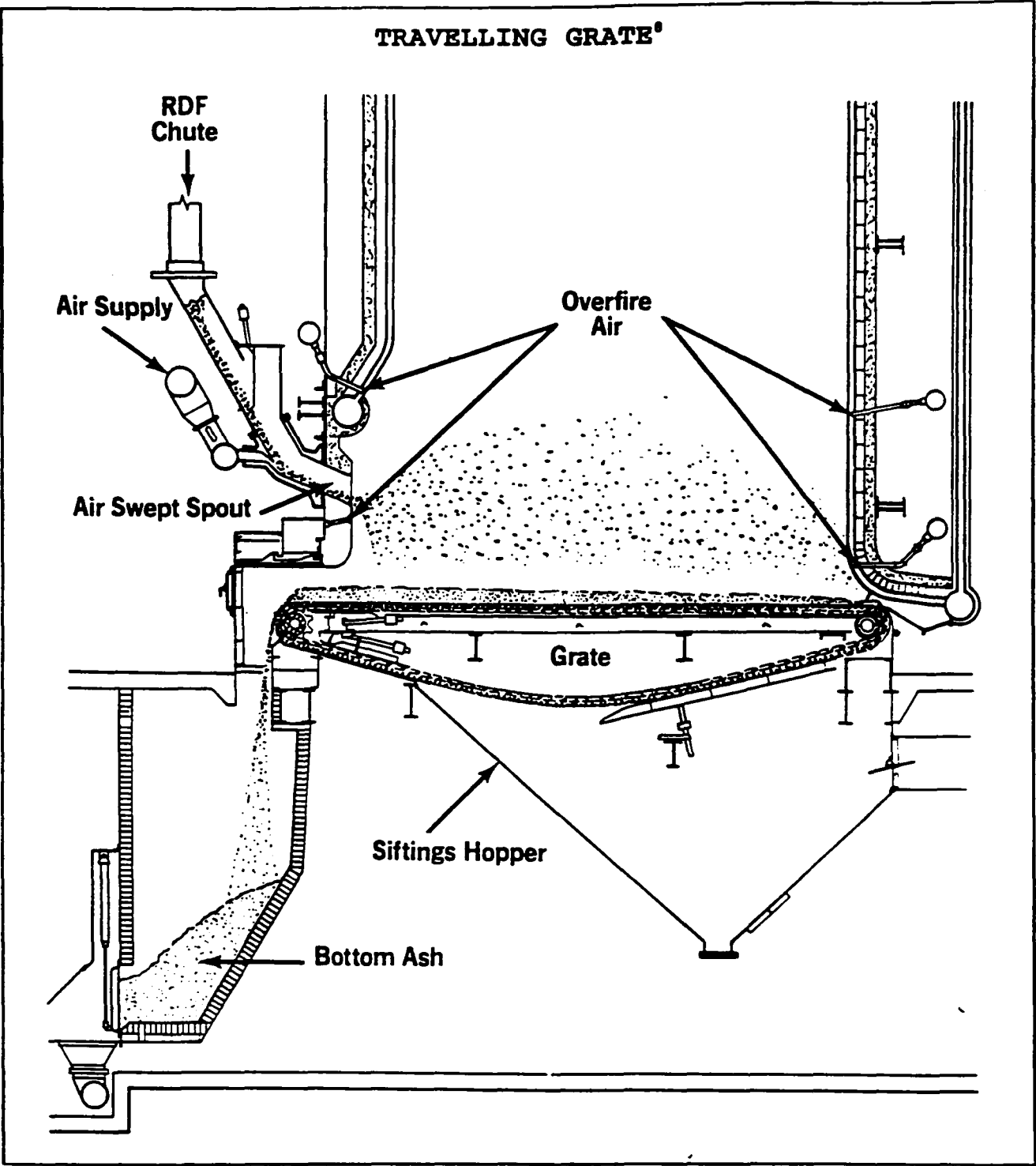
OSCILLATING OR ROCKER GRATE[7]

Flow direction

Raised position

Normal position

Slide 8-15

BARREL OR ROLLER GRATE[5]

Flow direction

TRAVELLING GRATE[*]

Courtesy of Detroit Stoker Company

Slide 8-17

ROTATING WATERWALL COMBUSTOR[2,9]

Courtesy of Westinghouse Electric Corporation

Slide 8-18
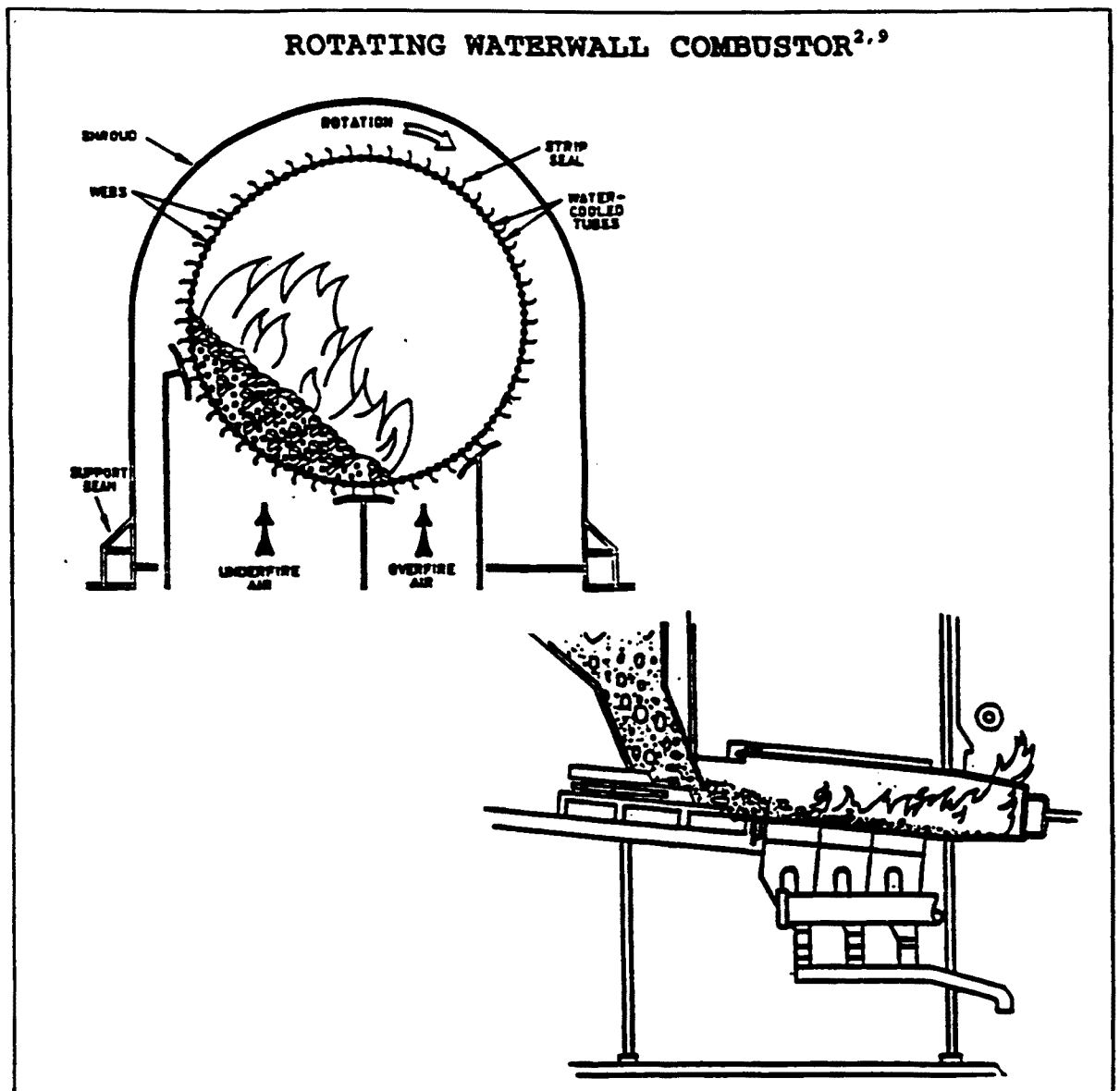
GRATE MALFUNCTIONS

1. Overheating (Thermal Stresses)
2. Corrosion, Erosion
3. Blockage
4. Hydraulic System Problems
5. Deposits from Molten Metal
6. Breakage by Heavy Objects

Malfunctions can also disable the normal movements of grates. These can be due to overheating (thermal stresses), materials changes, blockages, and hydraulic

and/or mechanical system problems. A large bulky item falling on a hot grate can cause mechanical damage, and thermal stresses can cause materials to fail.

Slide 8-19

```
ASH REMOVAL LOCATIONS

1.  Grate Siftings
2.  Bottom Ash
3.  Boiler Ash
4.  Fly Ash
```

Ash or combustion residue material is typically collected from the four above-mentioned areas in waterwall MWC units.[10] Modular MWC units will have their ash collected as bottom ash, boiler ash, and fly ash. Modular units typically do not have provisions for grate siftings, as an impermeable refractory hearth is used instead.

Slide 8-20

```
REMOVAL OF GRATE SIFTINGS & BOTTOM ASH

Water-Filled Quench Tank
        Submerged Drag Chain Conveyor
        Ram Type Ash Discharger
        Grizzly Scalper
        Belt or Vibrating Conveyor
        Magnetic Separator
```

The grate siftings have their sizes limited by the openings and crevices in the grate, typically less than 0.5 inch.

By contrast, bottom ash contains both fine fly ash, unburned pieces of combustible materials like wood and plastic, and the non-combustible materials like metal cans, mattress springs, car wheels, broken glass, and pieces of concrete.

Both grate siftings and bottom ash are delivered into a quench tank located under the combustion chamber. In modular units, the quench tank is at the end of the combustion chamber, and material is delivered there through the action of hydraulic ram devices.

Because of the size diversity in bottom ash, its removal devices must be robust in design. A grizzly scalper is sometimes used to remove oversized items from the conveyor system. Magnetic separation is often used for ferrous metal recovery from mass burn MWC units.

```
┌─────────────────────────────────────────────────────┐
│         REMOVAL OF BOILER ASH & FLY ASH              │
│                                                       │
│    Collection Hopper                                  │
│         Automatically Operated Air-Locks              │
│         Screw or Dry Drag Chain Conveyor              │
│         Pneumatic Conveyor                            │
│         Bucket Elevator                               │
└─────────────────────────────────────────────────────┘
```

Boiler ash is the particulate material which is deposited in hoppers as the combustion gases change directions in the convection sections of the boiler. This material is approximately the size of sand, generally passing a 30-mesh screen.

Fly ash is the fine particulate which is collected in the air pollution control device. Fly ash typically includes both the fine residue from the combustion process and the lime or other scrubber reagent materials which are used for acid gas control.

Boiler and fly ash removal from collection hoppers is accomplished with the use of automatically operated air-locks which are designed to prevent air leakage from the outside into the flue gas. Extraction and removal of ash from collection hoppers is accomplished with various devices, including pneumatically operated double gate valves, screw conveyors, pneumatic extraction, dry drag chain conveyors, and bucket elevators.

Slide 8-22

MOTOR OPERATED ROTARY AIR-LOCK[11]

Slide 8-23
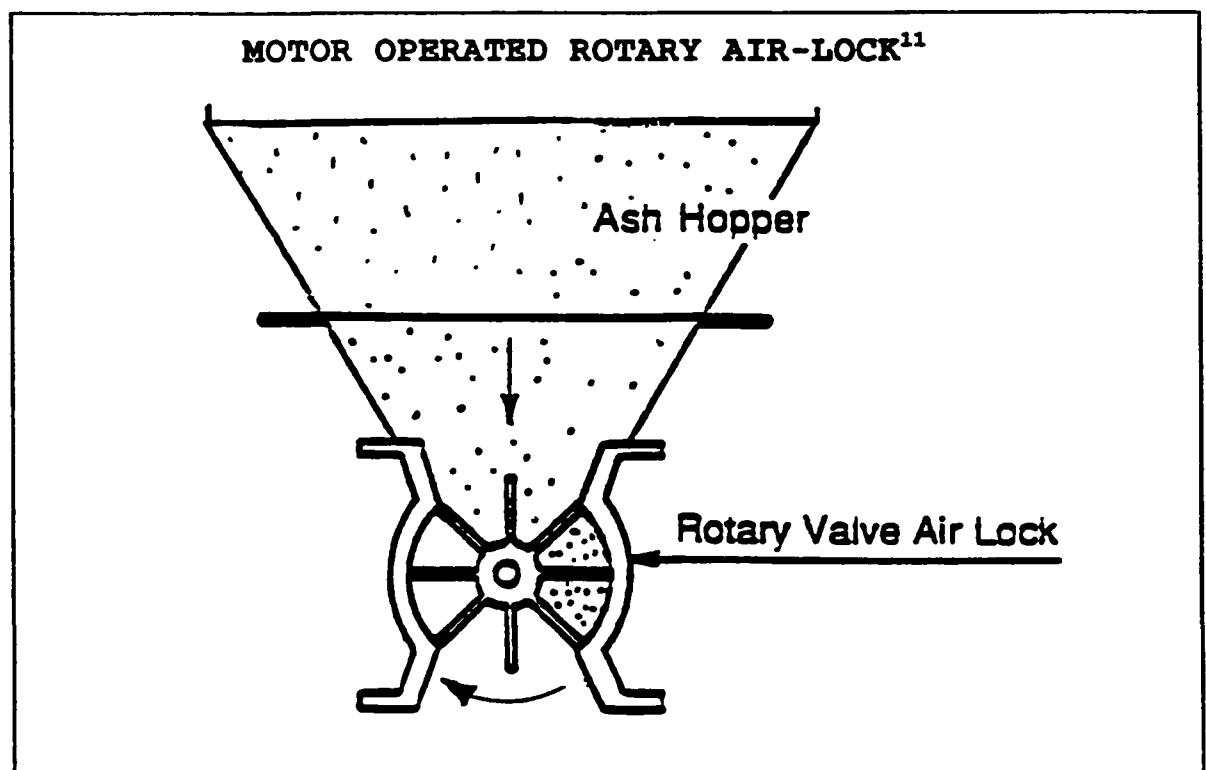
```
ASH REMOVAL SYSTEMS

1.  Continuous Operation
2.  Intermittent Operation
3.  Batch Operation
```

Boiler ash, fly ash and bottom ash removal systems may be operated continuously or intermittently, depending upon the design. Because the quench tank and collection hoppers have substantial capacity, continuous ash removal may not be required.

Slide 8-24

```
ISSUES REGARDING ASH DISPOSAL IN LANDFILLS

Environmental Impact
Landfill or Monofill
Leachate Effect on Groundwater
        Heavy Metals Concentrations
Fugitive Emissions
```

Landfills have been used for ash disposal for many years. However, there have been some very important issues raised about the environmental impact of such disposal practices.

Currently some agencies have regulations requiring ash to be disposed in monofills, which are special landfills which receive only ash, whereas others allow for co-disposal with mixed wastes in modern landfills.[12]

Monofills may have the same requirements as modern landfills, but organic materials are kept out. This would reduce the tendency for the organics to decompose and make acids which would increase the rate of leaching.

Modern monofills require leachate monitoring and treatment as well as groundwater monitoring. It is reasonable to assume that a modern, well-operated monofill can operate without any significant health risk. In fact, some have indicated that the fugitive emissions may be the major public health risk. These can be controlled by proper design and operational considerations.

REFERENCES

1. Elizabeth A. Bretz, "Energy from Wastes," Power, March 1990, S-1, S-2.

2. Municipal Waste Combustors: Background Information for Proposed Guidelines for Existing Facilities, U.S. Environmental Protection Agency, EPA-450/3-89-27e, August 1989, pp. 5-41 and 9-7.

3. Joseph G. Singer, Combustion Fossil Power, 4th Edition, Combustion Engineering, Inc., Windsor, CT, 1991, p. 12-20.

4. W. D. Turner, Thermal Systems for Conversion of Municipal Solid Waste, Vol. 2: Mass Burning of Solid Waste in Large-Scale Combustors: A Technology Status Report, Report ANL/CNSV-TM-120, Vol. 2, Argonne National Laboratory, December 1982, p. 26.

5. "Field and Enforcement Guide, Combustion and Incineration Sources," U.S. Environmental Protection Agency, APTD-1449.

6. Georg Stabenow, "Design Criteria to Achieve Industrial Power Plant Reliability in Solid Waste Processing Plants With Energy Recovery," Proceedings of the 1978 ASME Solid Waste Processing Conference, Chicago, pp. 427-446, May 1978.

7. Miro Dvirka, "Direct Co-Burning of Unprepared Municipal Solid Waste and Sludge," Proceedings of the 1982 ASME Solid Waste Processing Conference, New York, p. 114, 1982.

8. J. D. Blue et al., "Waste Fuels: Their Preparation, Handling, and Firing," Standard Handbook of Power Plant Engineering, Thomas C. Elliott, editor, McGraw Hill Book Co., NY, 1989, pp. 3-134.

9. W. R. Seeker, W. S. Lanier and M. P. Heap, Municipal Waste Combustion Study, Combustion Control of Organic Emissions, U.S. Environmental Protection Agency, EPA-530-SW-87-021-c, May 1987, p. 5-52.

10. Manzoor Alam and David J. Schlotthauer, "Planning for Successful Ash Handling," Solid Waste & Power, August 1990, pp. 30-36.

11. "Control Techniques for Particulate Emissions from Stationary Sources," Volume 1, EPA 450/3-81-005a, U. S. Environmental Protection Agency, September 1982.

12. Marc J. Roggoff, "The Ash Debate: States Provide Solutions," Solid Waste & Power, October 1991, pp. 12-18.

9. COMBUSTION PRINCIPLES III: REACTION PROCESSES

Slide 9-1

```
COMBUSTION REACTION PROCESSES

Oxidation & Reduction
Incomplete Combustion
Reaction Rate Variables
Flame Phenomena
Bed-Burning
Gasification
Oxidation of Carbon Monoxide
```

This learning unit considers the above applications of combustion reaction processes, which have special relevance to MWC plant operations.

Slide 9-2

```
IMPORTANT REACTION CHARACTERISTICS

1.   Multiple Reactions Occur in Combustion
2.   Reactions May Not Go to Completion
3.   Reactions Are Somewhat Reversible
4.   Reaction Rates Increase with Temperature
5.   Reactions Are Influenced by Concentrations
6.   Reaction Are Limited by Mixing
7.   Compositions Vary with Temperature
```

The completeness of combustion depends on the operating conditions in the MWC unit. These conditions could be evaluated by using the analytical concepts of reaction kinetics. However, the details of reaction kinetics are beyond the scope of this training program.

Nevertheless, insight about some of the subtle aspects of the combustion of MSW can be gained by considering factors that influence reaction rates. For example, the features of reaction rates can help explain the formation and destruction of carbon monoxide.

The above list summarizes reaction characteristics which can help operators understand how certain variables influence combustion.

Slide 9-3

```
┌─────────────────────────────────────────────────────┐
│                                                     │
│     REACTIONS OF CARBON AND HYDROGEN IN OXYGEN      │
│                                                     │
│          C + O₂  ---> CO₂                          │
│          H₂ + 0.5 O₂  ---> H₂O                     │
│                                                     │
│          0.5 O₂     ---> O                          │
│          C + O  ---> CO                             │
│          2 H₂ + O₂  ---> 2 H₂O                     │
│          2 H₂O ---> 2 OH + H₂                       │
│          CO + 2 OH ---> CO₂   + H₂O                │
│                                                     │
└─────────────────────────────────────────────────────┘
```
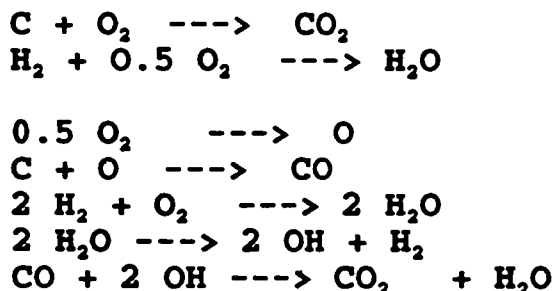
The idealized concepts of combustion were introduced in Learning Unit 5. At that time, we simplified our analysis by assuming that our reactions went to completion. As indicated in the first two equations listed above, carbon and oxygen can react to form carbon dioxide, and hydrogen and oxygen can react to form water.

However, actual combustion reactions are much more complex, as indicated by the other equations listed above. These and other reactions may occur simultaneously, including many which do not go to completion.

Slide 9-4

```
┌─────────────────────────────────────────────────────┐
│                                                     │
│        CONSEQUENCE OF MULTIPLE REACTIONS            │
│                                                     │
│        Not all Reactions Can Go To Completion       │
│        Some Components May Be Depleted              │
│                                                     │
└─────────────────────────────────────────────────────┘
```

The actual burning of hydrocarbons is a multi-step process. For instance, when carbon is burned, carbon monoxide is formed first. The carbon monoxide is then generally oxidized to carbon dioxide. Therefore, the reason for carbon monoxide emissions is incomplete combustion. The destruction of carbon monoxide will be discussed further at the end of this learning unit.

As another example, the nitrogen in the air can react with oxygen if the temperature is high enough. However, the burning of hydrocarbon (fuel) occurs much faster than the burning nitrogen. Therefore, if only enough oxygen is available to burn the fuel, it will be primarily consumed by the fuel. Under such conditions, the oxygen will be essentially depleted and very little will be available for oxidizing the nitrogen, even if the temperatures are very high.

The subject of limiting excess air as a method of controlling the formation of nitrogen oxides will be discussed in more detail in Learning Unit 17.

> **PRODUCTS OF INCOMPLETE COMBUSTION**
>
> **Carbon Monoxide**
> **Dioxins and Furans**

When considering the possibility of incomplete combustion, we might expect various gases to be present in the final mixture. For instance, a simple mixture of hydrocarbon and air could have a final mixture of H_2, CO, OH, O, CO_2 and H_2O.

The products of incomplete combustion from MSW include carbon monoxide (CO) and other reaction products such as MWC organics, including dioxins and furans. These will be considered in more detail in Learning Unit 16.

Slide 9-6

> **REASONS FOR INCOMPLETE COMBUSTION**
>
> 1. Variable Fuel Properties
> 2. Irregular Fuel Feeding Characteristics
> 3. Inadequate Air Supply
> 4. Improper Distribution of Air
> 5. Incomplete Mixing of Oxygen & Fuel
> 6. Inadequate Temperature
> 7. Premature Cooling of Combustible Gases

A number of the operational problems which can contribute to the formation of products of incomplete combustion are listed above.

Slide 9-7

> **REACTION RATES**
>
> Rate of Chemical Change
>   Forward Reaction (Production)
>   Reversed Reaction (Dissociation)

A reaction rate is the rate of chemical change, which might be thought of as the number of new combustion product molecules formed per second.

Every reaction is reversible, to some extent. Therefore, the forward rate is used to signify the production of product gases, whereas the reversed reaction rate relates to the dissociation of product gases back to their original form.

```
OXIDATION AND REDUCTION REACTIONS

Lean Mixture - Oxidizing Atmosphere
         Oxidation Reaction
                 Converts Reactants to Products

Rich Mixture - Reducing Atmosphere
         Reduction Reaction
                 Converts Products to Reactants
```

The knowledge of oxidation/reduction phenomena has important applications in MWC unit operations.

Oxidizing atmospheres are characterized by fuel-lean mixtures. Lean mixtures have more air in the mixture than would occur under stoichiometric conditions.

Reducing atmospheres are characterized by fuel-rich mixtures. A rich mixture has more fuel in a given amount of air than would occur in a stoichiometric mixture. There are a number of combustion situations where reducing atmospheres can cause dissociation to occur.

Fireside corrosion of metal surfaces may be caused by cycling between lean mixture and fuel-rich mixture conditions. Such oxidation/reduction cycling is probably due to variable fuel properties. Under lean mixture (oxidizing) conditions, the metal walls are oxidized. However, under rich (reducing) conditions, oxygen is extracted from the exposed metal oxide on the waterwalls or water tubes, thus destroying the protective metal oxide layer. The unstable chemistry of the wall surface can lead to metal wastage. Various design changes are available to help reduce this problem.

The knowledge of the relative reaction rates of oxygen with nitrogen and fuel has been utilized to develop techniques for nitric oxide control. In particular, a reducing atmosphere can be created by injecting a gaseous fuel. This can cause the gas to be oxidized and the nitric oxide to be reduced back to nitrogen gas.

Slide 9-9

```
REACTION RATE DEPENDS UPON

Temperature
Mixture Concentrations
Stirring Process (Turbulence)
```

Reaction rates increase with temperature because molecular vibrations increase as the temperature increases. As the vibrations increase, the frequency of molecular collisions increases and the molecular binding forces are weakened. When molecules collide at elevated temperatures, the chances of the collision causing the formation of a new compound (combustion product) are increased.

The rates of reaction are limited by the mixing of fuel molecules and oxygen molecules. As the mixing is improved, the rate of reaction increases.

Mixing can be thought of as the process of creating the desired constituent concentrations in the mixture. For instance, the concentration of oxygen needed varies with the type of fuel and its concentration. As indicated in Learning Unit 5, the theoretical air-to-fuel ratio varies from fuel to fuel.

In addition, mixing can be thought of as a stirring or blending process which enhances the rate of collision of oxygen and fuel molecules. This second aspect of mixing is sometimes referred to as turbulence.

Slide 9-10

```
PRE-MIXED GASEOUS FUEL COMBUSTION

Blue Flame Combustion:
    Natural Gas in an Appliance
```

There are two different types of combustion phenomena which are indicated by the observable blue and yellow flames. Understanding flame phenomena can lead to insight about MSW combustion.

Gas stoves feature blue flame combustion, which is produced by burning a mixture of natural gas and air. Blue flame or pre-mixed gas combustion is generally considered to be clean burning, because black deposits are not formed on adjacent surfaces.

After the mixture is heated, the combustion process begins with the oxidation of carbon to carbon monoxide. With appropriate combustion system design and operating conditions, the carbon monoxide can be subsequently oxidized to carbon dioxide.

If the combustion of pre-mixed flames is incomplete, carbon monoxide will be emitted. This can occur when the flames are cooled rapidly and/or if inadequate oxygen is available.

Slide 9-11

```
DIFFUSION-LIMITED COMBUSTION

Yellow/Orange Flame Combustion:
    Inadequately Pre-Mixed Air & Fuel
    Dark Flame Tips
    Black Deposits on Adjacent Surfaces
```

If the air supply of a blue flame, gas burner is constricted, the flame will be transformed into a yellow flame. Yellow flames are called diffusion flames because the oxygen for combustion must be diffused from the air adjacent to the fuel.

In yellow flame combustion, the hydrocarbon gases get hot enough to break their molecular bonds, releasing hydrogen gas which burns readily. Since the oxygen supply is limited, many of the carbon molecules get hot enough to glow with their characteristic yellow color, before they are oxidized.

Such flames are often observed to be long, luminous, yellow flames, whose tips will become dark as the flames cool. The diffusion process occurs relatively slowly, so large combustion chambers may be required to accommodate the long flames.

Black soot is an observable incomplete combustion product associated with diffusion flames. Such black deposits which occur on adjacent surfaces are associated with premature flame cooling or quenching. If a diffusion flame impinges on the wall of the combustion chamber or heat exchanger, the gas temperatures will fall and the combustion process will essentially stop. When this happens, a local puff of smoke and/or soot deposit will be formed.

Slide 9-12

```
BED BURNING PROCESSES

Diffusion Limited Combustion
    Volatile Gases
    Fixed Carbon
Diffusion Limited Flame
```

MSW is a highly variable fuel, composed of incombustible materials, volatile materials which burn as a gas, and fixed carbon (solid) which burns on its surface. Although the actual burning process proceeds through many steps, only the general characteristics will be described.

The actual combustion process occurs with the collision of adequately heated fuel and oxygen molecules. Therefore, molecules which are too cool will not burn. Also, those fuel materials which are trapped inside a piece of MSW cannot be burned until they are either evolved as a gas or become exposed to collisions on the surface.

The volatile gases may burn in the fuel bed if they are adequately heated by the adjacent combustion gases and mixed with the oxygen. These volatile gases will burn with a yellow flame, characteristic of diffusion limited combustion.

Slide 9-13

IDEALIZED FUEL BED REGIONS[1]
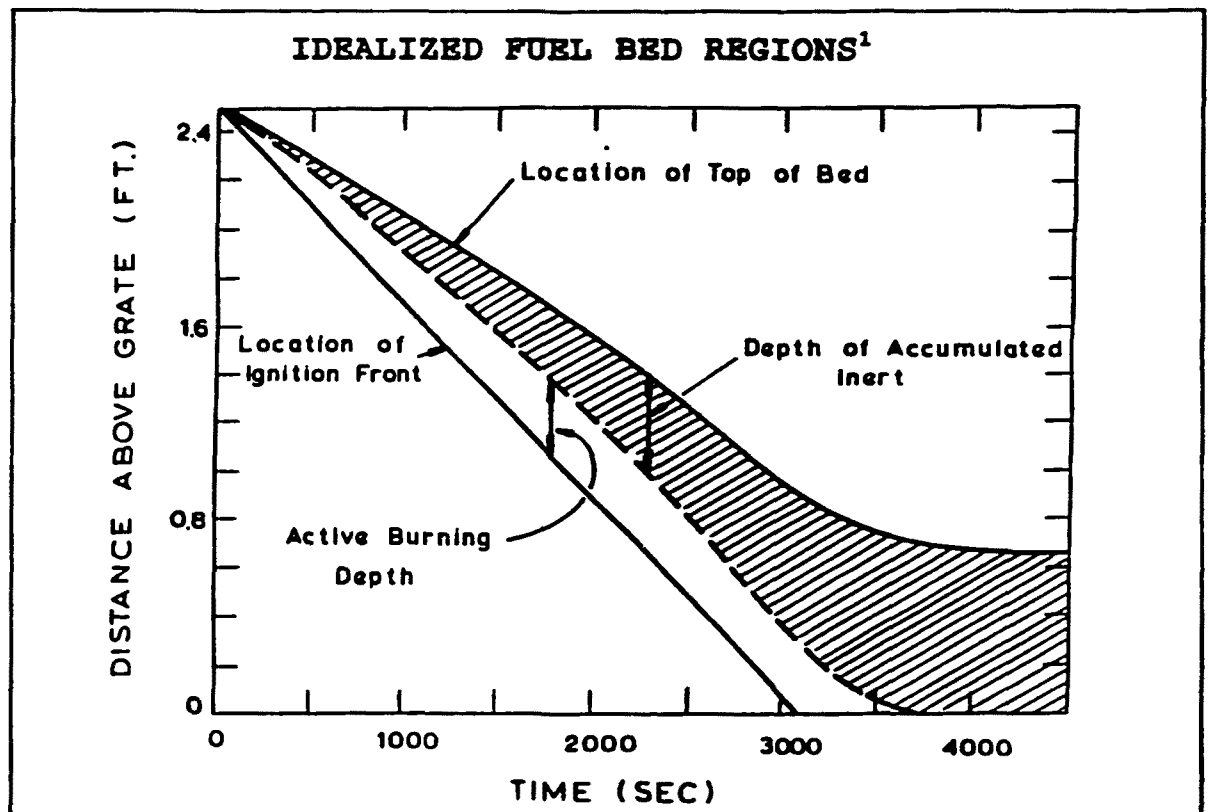
Many MWCs accommodate these combustion features by initially providing a thick fuel bed which slowly moves down the grate. The grate has provisions which enable the diffusion of air through the fuel bed.

The slide illustrates an idealized fuel bed, which becomes thinner as the organic matter is consumed. This is plotted as a function of the residence time on the grate (or the distance down the grate) increases.

The illustration, as well as that of slide 8-10, emphasize that ignition starts on the top of the fuel bed surface. An ignition front moves downward through the fuel bed, acting as a diffusion flame which moves toward the available oxygen in the under-grate air supply. Note that, in the illustration, the ignition front required almost an hour to get to the grate (indicated by 0 ft above the grate).[1]

Adjacent to the ignition front is an active burning region which moves down through the fuel bed. The bed-burning process continues by consuming organic matter deeper and deeper into the bed, leaving a layer of ash of increasing thickness. Ideally, the burnout of the fuel will be completed just prior to its being dropped into the ash collection pit.

The location of the active burning region is controlled by the supply of under-grate air and grate agitation. Movement of the grate can also expose fresh MSW surfaces, which stimulates the heat transfer, volatilization, and the fuel-oxygen mixing processes of combustion.

If an operator were to increase the under-grate air supply, it would cause the burning process to become more intense and lead to additional evolution of volatiles.

Slide 9-14

```
BASIC BED-BURNING PROCESS

Gaseous Products Leaving Fuel Bed
    H₂O, CO₂, CO, Methane, Hydrogen
Solid Products:
    Char (Fixed Carbon)
Solid Residues
    Inorganic Materials (Ash)
```

The MSW fuel bed can be characterized as a gasifier. The active burning region uses up all the available oxygen. As other volatile gases are evolved, they will migrate into the combustion chamber region above the fuel bed. Many of these volatiles will have been heated above their ignition temperatures in the fuel bed, but will lack the oxygen for combustion.

Thus, an oxygen-starved mixture of hydrocarbons and products of complete and incomplete combustion will be formed. The gases flowing from the top of the fuel bed have been found to contain significant levels of methane (hydrocarbon), hydrogen, and carbon monoxide, but are essentially depleted of oxygen.[1] These gases will migrate upward and leave behind the ash and some of the char (carbon).

Therefore, the products of incomplete combustion in the flue gas will tend to be increased when the under-grate air is increased.

However, combustion controls generally provide a simultaneous addition of overfire air along with under-grate air. The overfire air is directed into the combustible gases to supply the required oxygen and to increase their mixing. Therefore, the over-bed combustion zone acts as a second stage of combustion.

```
┌─────────────────────────────────────────────────┐
│  REACTIONS WITH CHAR:                            │
│                                                  │
│  C + O₂  --->  CO₂                      (1)      │
│                                                  │
│  C + H₂O --->  CO + H₂                  (2)      │
│                                                  │
│  C + CO₂ --->  2 CO                     (3)      │
└─────────────────────────────────────────────────┘
```

$$C + O_2 \longrightarrow CO_2 \qquad (1)$$
$$C + H_2O \longrightarrow CO + H_2 \qquad (2)$$
$$C + CO_2 \longrightarrow 2\ CO \qquad (3)$$

The above indicated processes are useful in burning carbon (char) on the fuel bed. The first is the general carbon oxidation reaction. The other two are endothermic (energy extracting) reactions, which occur under high temperature combustion conditions. These reactions occur on the surfaces of the solid materials in the fuel bed, producing carbon monoxide and hydrogen gas.

The fixed carbon on the fuel bed burns with a yellow/orange glow. The migration of oxygen and other gases to the surface is limited by the diffusion process.

```
┌─────────────────────────────────────────────────┐
│  DESTRUCTION OF CARBON MONOXIDE                  │
│                                                  │
│  CO + OH  --->  H + CO₂                 (1)      │
│                                                  │
│  CO + 2 OH --->  CO₂ + H₂O              (2)      │
│                                                  │
│  CO + O   --->  CO₂                     (3)      │
└─────────────────────────────────────────────────┘
```

$$CO + OH \longrightarrow H + CO_2 \qquad (1)$$
$$CO + 2\ OH \longrightarrow CO_2 + H_2O \qquad (2)$$
$$CO + O \longrightarrow CO_2 \qquad (3)$$
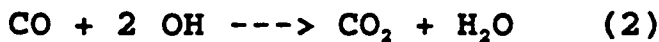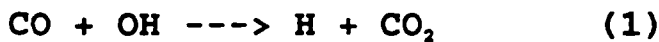
The conversion of carbon to carbon monoxide is a most important process. Carbon monoxide is a very stable molecule which is not easily oxidized. It will not readily react with molecular oxygen, even at high temperatures. The dominant reaction paths for converting CO to CO_2 is shown above. Thus, CO will react with the OH radical and atomic oxygen, which are associated with high temperature dissociation of water and molecular oxygen.

If too much excess air was added to the combustion gases, the temperature could be lowered enough to reduce the OH radical production. The lower temperature would also reduce the rate of CO and OH reactions.

Actually, the combustion processes which occur are far more complex than has been described. Other reactions, including the depletion of some of the important constituents, can take place. For instance, chlorine reacts readily with hydrogen which makes less hydrogen gas and OH radicals available for completion of the combustion process.

REFERENCES

1. G. C. Williams et al., "Design and Control of Incinerators," Final Report to Office of Research and Monitoring, U. S. Environmental Protection Agency, Grant Number EC-00330-03, 1974.

10. DESIGN AND OPERATION OF COMBUSTION EQUIPMENT

Slide 10-1

```
MWC DESIGN OPTIONS

1.  Fuel Processing
2.  Charging Method
3.  Stoichiometric Design
4.  Chamber Wall Construction
5.  Energy Recovery Design
```

There are five overall design options which can distinguish the combustion features of a MWC unit. These are listed above.

As discussed in Learning Units 3 and 4, MWCs are generally distinguished as being either mass burn or RDF units.

Slide 10-2

```
CHARGING METHOD

Direct Bed
Suspension-Fired
Air-Swept Spreader
```

As was discussed in Learning Unit 8, the most common method of delivering raw MSW into the combustion chamber is direct bed charging. The MSW is charged onto the grates or hearth where it goes through a sequence of drying, volatilization, ignition, burning, and burn-out processes.

Suspension firing is the major method used in firing pulverized coal. The coal is ground to a fine powder and then is blown into the hot combustion chamber where it burns in a manner similar to fuel oil. Early attempts at pulverized-type suspension firing of RDF were unsuccessful because of the incomplete burning of the large pieces of RDF. Therefore, suspension burning designs generally have provisions for a travelling grate which can provide an appropriate residence time for the burning of the large pieces of RDF.

Spreader stokers were originally designed to deliver chunks of coal into the over-bed combustion zone, with the small particles burning in suspension and the larger pieces settling onto a fuel bed. The firing of RDF in a spreader stoker unit is very similar. Generally, an air-swept distributer blows RDF into the combustion zone where it is rapidly exposed to hot gases. Drying, volatilization, ignition, and burning appear to occur almost simultaneously. The larger pieces of RDF fall upon the combustion bed, where additional volatilization and carbon burnout occurs.

```
┌─────────────────────────────────────────┐
│   STOICHIOMETRIC DESIGNS                 │
│                                          │
│   Excess-Air                             │
│   Starved-Air (Two-Stage)                │
└─────────────────────────────────────────┘
```

There are two categories of stoichiometric air designs in MWC systems--excess-air and starved-air. The method of construction is also a distinguishing factor. Large units are generally erected through on-site construction and use excess-air designs which feature burning of MSW on grates.

Excess-air, waterwall units have burning on the grates and in the over-bed furnace region above the grates. A relatively high supply of underfire air causes intense combustion on the grates, which aids in carbon burnout and increases the amount of material throughput.

The gases in the over-bed region of an excess-air unit may have local stoichiometries which vary considerably. Such variations are due to both the fuel composition and different gas compositions leaving the drying, volatilization, and combustion regions of the grates. Mixing of the gases is enhanced by the combustion chamber geometry and the over-fire air designs.

About 40 percent of the total air is supplied as over-fire air. Combustion is typically completed in an overall mixture having somewhere between 70 and 100 percent excess air.[1]

Slide 10-4

STARVED-AIR, TWO-STAGE COMBUSTION UNIT[2]
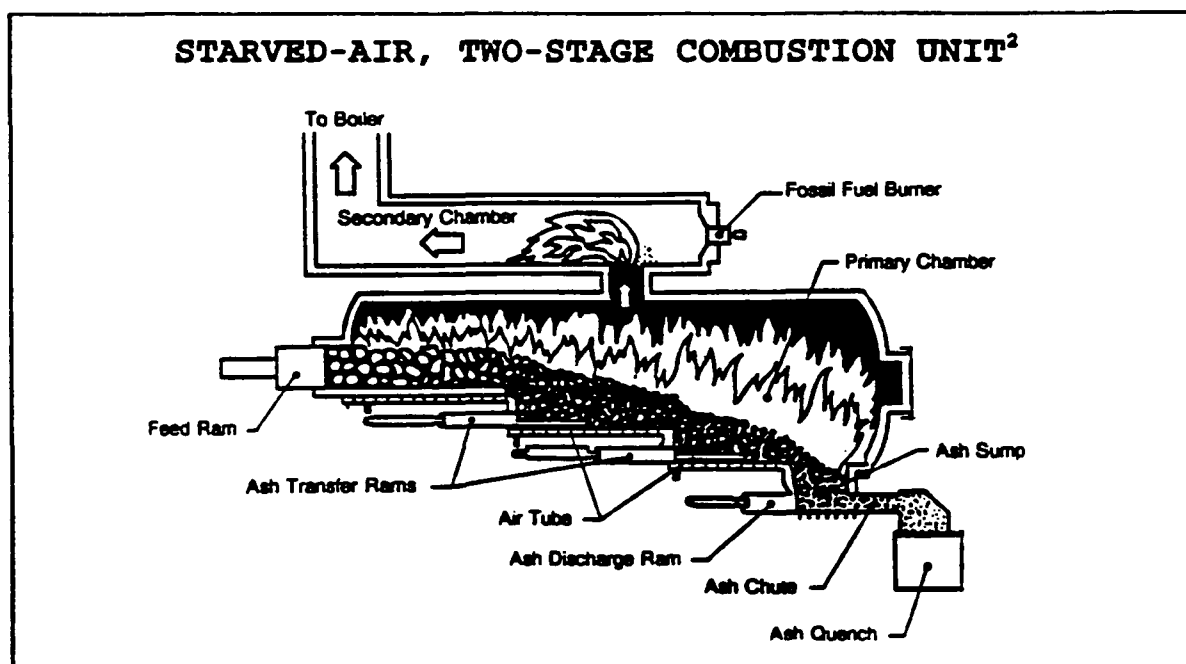
Courtesy of Consumat Systems, Incorporated

Smaller units utilize two combustion chambers which provide for the application of two-stage combustion concepts. These units are often assembled on-site from modular components which are manufactured in a factory.

The primary chamber is designed to operate with somewhere around 40 percent of the air theoretically required for complete combustion.[1] The partial combustion of the volatile gases and fixed carbon is designed to heat the primary chamber gases enough to drive the drying and volatilization processes. Thus, the primary chamber acts as a gasifier.

The secondary chamber receives the fuel-rich mixture and mixes in the secondary air. Secondary air is added so that the overall air supply is from 80 to 100 percent excess air.[1] Additional energy release can be supplied by an auxiliary burner, whose purpose is to maintain secondary combustion temperature requirements.

Slide 10-5

```
ENERGY RECOVERY DESIGNS

Fire-Tube Boiler
Waste-Heat Boiler
Integral Boiler
```

There are three different types of boilers which are widely used in industry.

Fire-tube boilers are the package boiler units which are often used for residential, commercial and light industrial applications. They generally burn natural gas or fuel oil, and are characterized by the combustion gases passing inside tubes, which are surrounded by water. They are generally not used in MWC applications.

Integral boilers designs are those which make use of waterwalls. These are widely used by industries and utilities for the production of steam and electrical energy. The efficiency of conversion of fuel energy (higher heating value) to steam energy varies with the fuel and design application. Example values under baseload conditions are: 88% for pulverized bituminous coal, 75% for RDF, and 70% for MSW.[3] Additional consideration of integral boilers will be included in the following discussion of waterwall units.
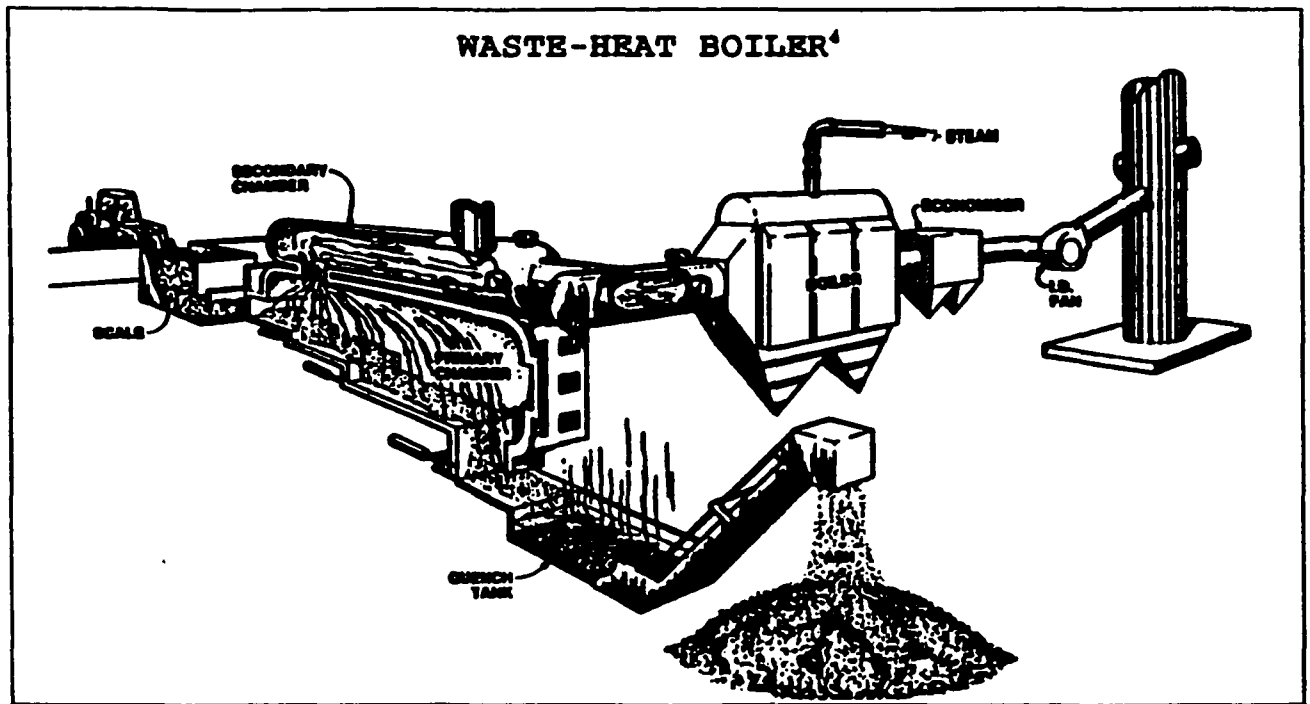
WASTE-HEAT BOILER[4]

A special add-on heat exchanger uses hot flue gas to evaporate water and produce steam. Such boilers are often called waste-heat boilers, since otherwise the energy in the hot flue gases would be wasted. Heat exchange is by convection from the combustion gases which exit the final combustion chamber. As such, recovery boilers are not exposed to gas temperatures as high as those of integral boilers.

Slide 10-7

```
CHAMBER WALL CONSTRUCTION

Refractory-Wall
Waterwall
```

Combustion chamber designs are characterized by their provisions for heat exchange. Walls can be insulated against heat loss or can provide for energy extraction. Refractory walls insulate the combustion gases against heat loss and reflect radiant energy back to the combustion zone and onto the fuel bed. Early refractory-wall incinerators used considerable amounts of excess air to lower combustion temperatures, so as to prevent significant refractory damage.

Modern starved-air refractory-wall units have their secondary chamber temperatures controlled either by limiting the rate of air and/or fuel supplied or by using flue gas recirculation as an inert heat sink material. Gas temperatures in the secondary chambers of modular starved-air units are generally limited to around 2,200°F to prevent damage to the refractory materials.

GRATE/ROTARY KILN REFRACTORY-WALL COMBUSTOR[5]
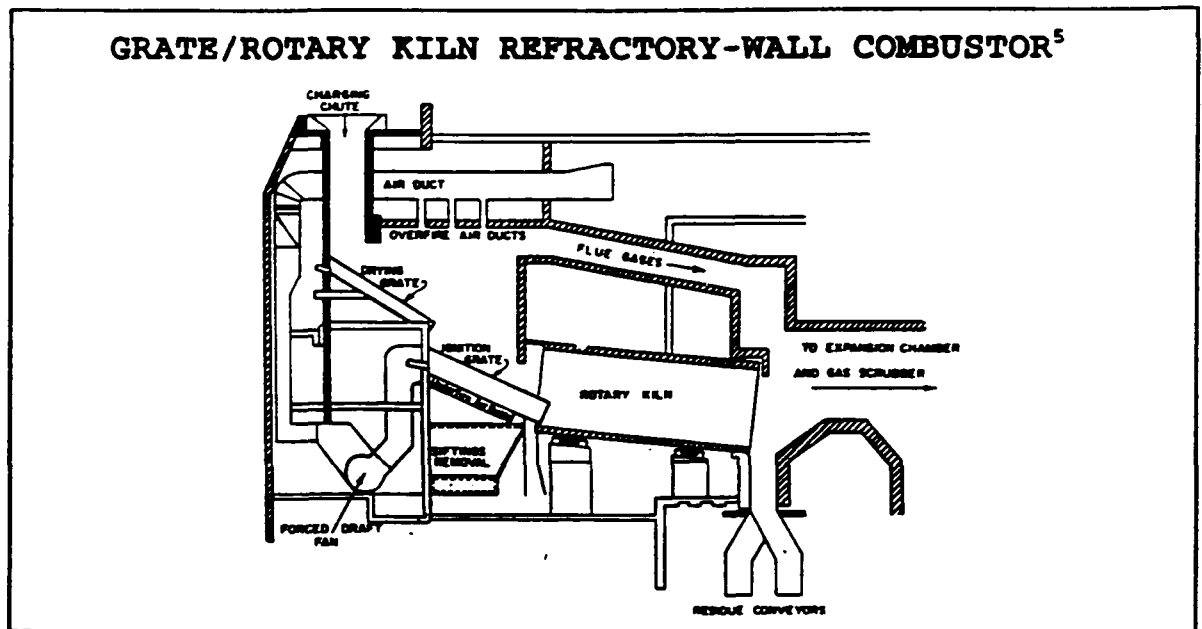
A different design of a refractory-wall incinerator is illustrated above. Although the unit has a rotary combustor, it has many different features from the rotary waterwall units, discussed in Learning Units 6 and 8.

The refractory unit has provisions for drying and ignition of the MSW on a grate, diverting part of the gas flow to a by-pass duct, obtaining final burn-out in a refractory-lined rotary kiln, and using a waste-heat boiler for energy utilization.[6]

Slide 10-9

WATERWALL FURNACE ENCLOSURE[7]
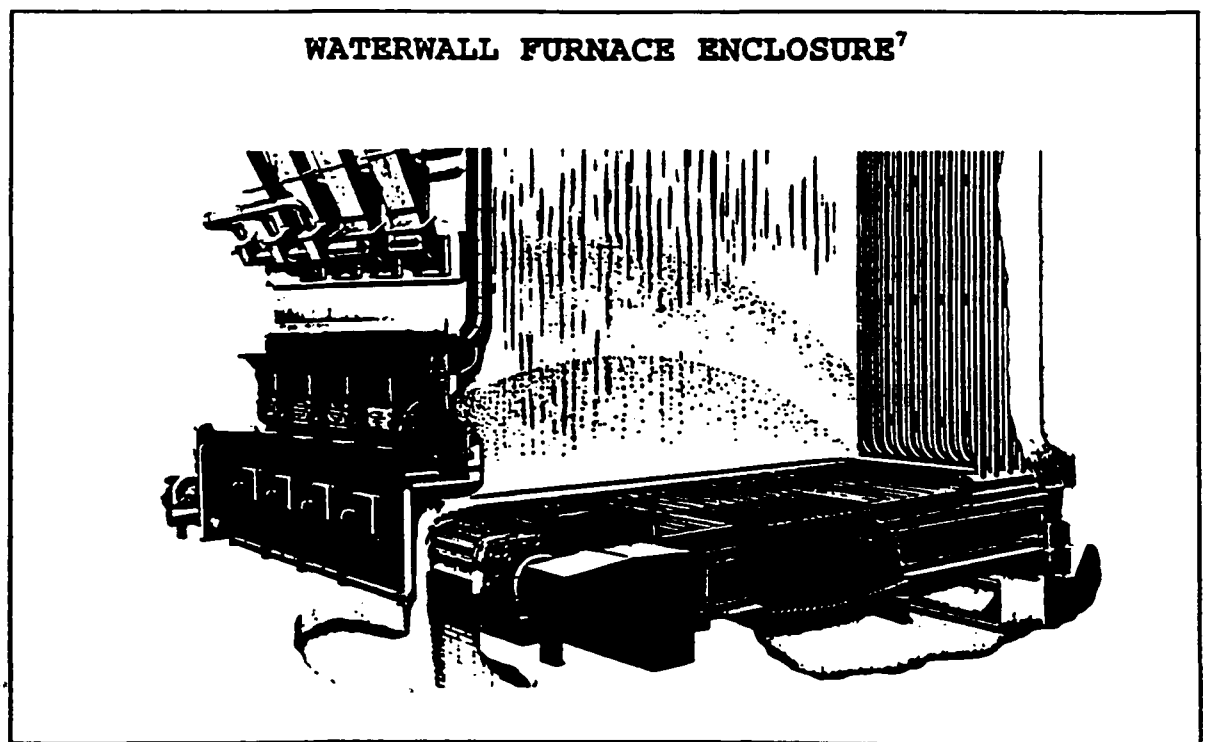
Courtesy of Detroit Stoker Company

Waterwalls are designed to provide for direct heat exchange from the combustion chamber. The heat extraction helps to limit the combustion temperatures. Therefore, less excess air is used than would be required in the refractory-wall incinerators.

The operating temperatures of the waterwalls are generally established by the saturation conditions associated with the boiler pressure. In the early 1960s many waste-to-energy units had waterwall saturation temperatures as high as 500°F (690 psig boiler pressure), with superheat temperatures as high as 875°F.[8] However, many of these units experienced significant waterwall and superheater metal wastage problems, associated with either corrosion and/or erosion.

Slide 10-10
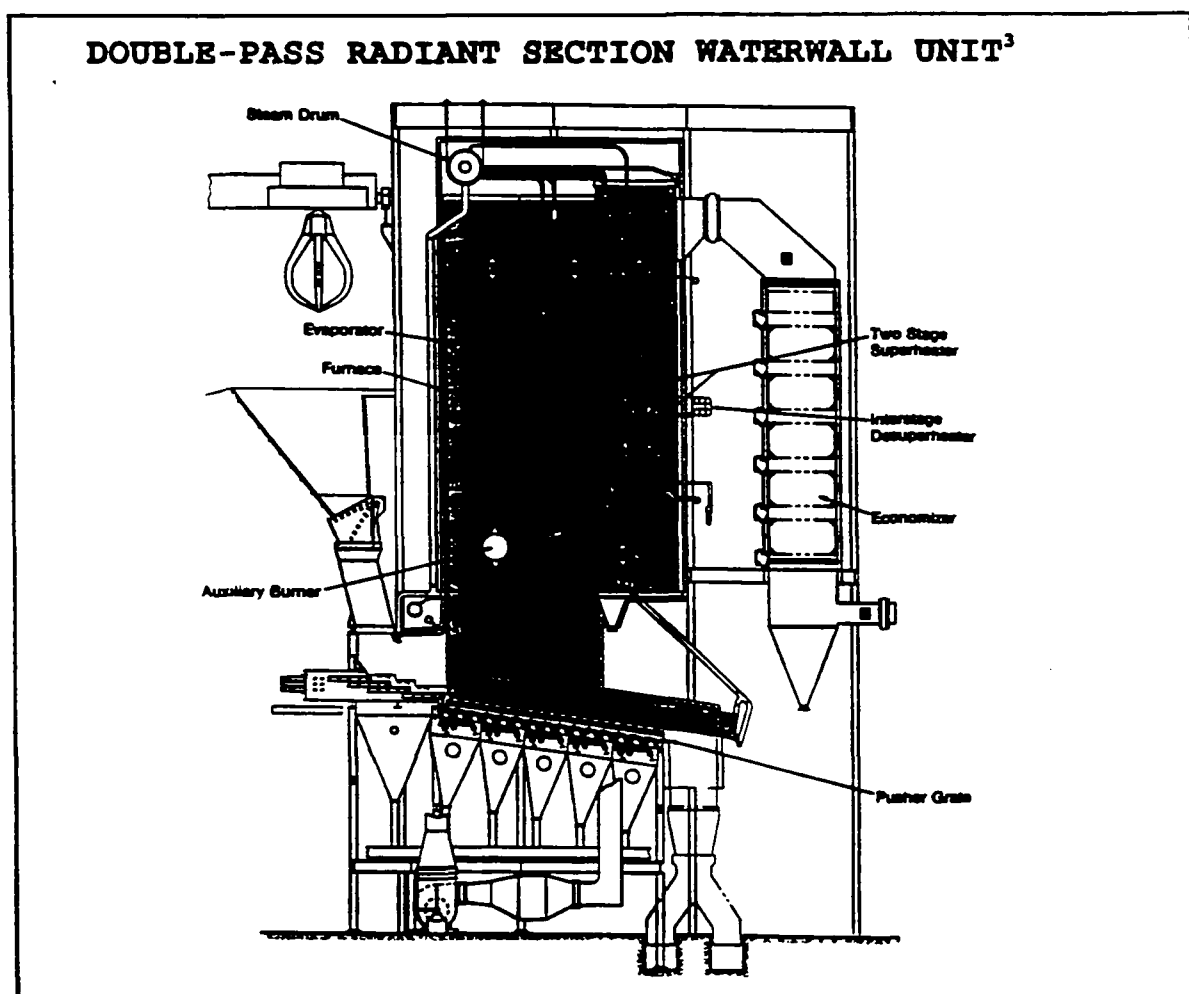
DOUBLE-PASS RADIANT SECTION WATERWALL UNIT[3]

From Joseph G. Singer, Combustion Fossil Power, 4th Edition, 1991, reprinted with permission of Combustion Engineering, Inc.

Waterwalls are typically covered with a special refractory material or nickel-based alloy, particularly in the regions below the overfire air ports. The trend has been to provide waterwall protection and reduce the gas velocities and temperatures. Typical boiler saturation temperatures can range from 500 to 550°F (650 to 900 psig boiler pressure)[3] and superheater temperatures are generally limited to around 900°F.

10-6

The above slide illustrates the design of a furnace with a double-pass radiant heat exchanger. The unit is designed to extract more energy in the radiant section, so as to limit the flue gas temperatures and control superheater metal wastage.

Slide 10-11
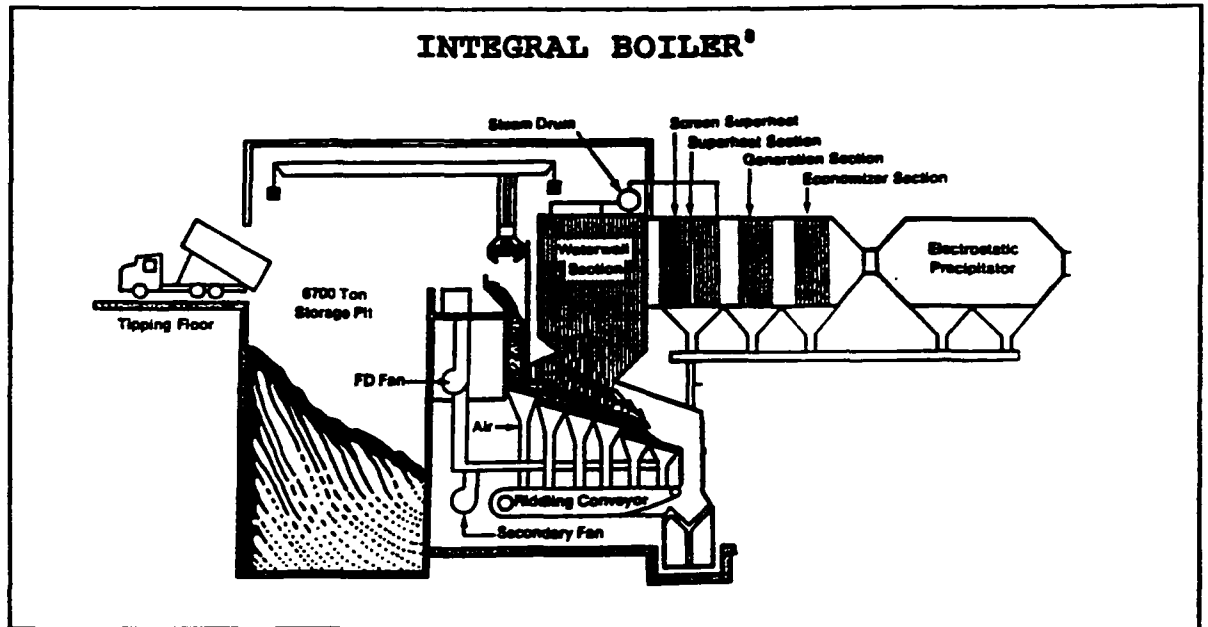
An integral boiler uses the combustion chamber as an integral part of the boiler. The combustion chamber or furnace is also called the radiant boiler section, as radiation heat transfer is its primary mechanism of heat exchange. High temperature luminous gases, glowing with their characteristic yellow color, emit infrared energy which is partially absorbed by the waterwalls and partially reflected onto the fuel bed.

Slide 10-12

```
BOILER COMPONENT EQUIPMENT

Radiant Section
     Feedwater Heating
     Evaporation

Convective Section
     Superheater
     Evaporator
     Economizer
          Feed-Water Heater
```
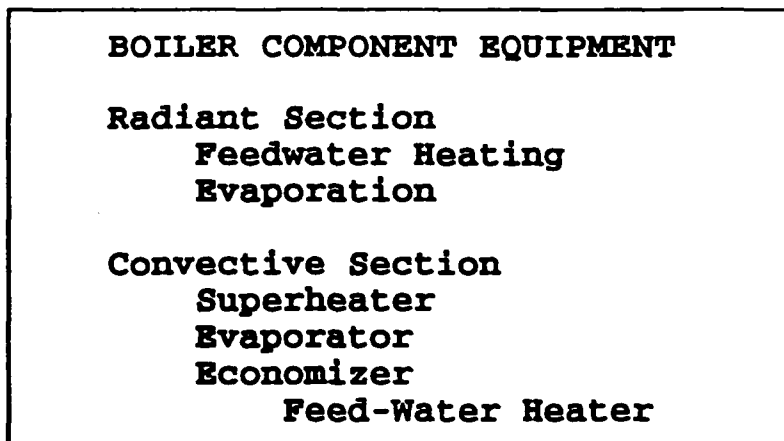
The walls of the furnace heat the feedwater to boiling conditions and provide energy for the evaporation process.

After the combustion gases leave the radiant waterwall section, they pass into the convective section of the boiler. The gases, which are also called flue gases, now pass over the exterior of tubes which contain steam, liquid water, or both. Among the possible boiler components which can be found in convection sections are the evaporator or steam generator, superheater, reheater and economizer.

Boiling occurs in the tubes of the evaporator or steam generator. The evaporator tubes contain steam (water vapor) and liquid water at the saturation temperature. Steam is separated from boiling water in the steam drum, which is generally located at the top of the convection section.

The superheater heats water vapor to temperatures above saturation values, as may be required by the steam turbine or other steam application. A reheater is basically another superheater, which is often found in utility power plants. After steam leaves the high pressure turbine, it can be reheated before it is delivered to the intermediate pressure turbine. Most MWC units do not have reheaters.

The economizer is a heat exchanger in which the feedwater is heated with energy from warm/hot flue gas. The economizer is generally located in the convective section, downstream of the superheater. Prior to this stage, the flue gases have been considerably cooled in the evaporator and superheater, so that additional steam production is not feasible. However, the feedwater temperature is relatively cool so that heat transfer can occur, thereby increasing the overall unit efficiency.

Another heat exchanger, often located in the convection section, is an air preheater. Although at this point the flue gases are too cool to effectively heat feedwater, they are hot enough to preheat the combustion air. Other MWC facilities may use steam for air preheating. Air preheating is important because heated air will aid the MWC drying process and make combustion easier to control.

Slide 10-13

```
FEEDWATER HEATING

Economizer: Energy from Flue Gas
Feedwater Heaters: Energy from Steam

     Closed Feedwater Heater
          Shell & Tube Heat Exchanger
     Open Feedwater Heater
          Deaerating Heater
```

Many MWC units have feedwater heaters which use steam extracted from the turbine to heat the feedwater. Feedwater heaters improve the overall efficiency of the unit. Most feedwater heaters are called "closed feedwater heaters" because the

steam and feedwater are on opposite sides of a "shell and tube" heat exchanger. Typically, steam condenses on the outside of the tubes (shell side), and the feedwater passes through the inside of the tubes (tube side).

Open feedwater heaters, such as the deaerating heater described in Learning Unit 26, have the extracted steam condense and mix with the feedwater.

Slide 10-14

```
┌─────────────────────────────────────────────────────────┐
│        GENERIC TYPES OF COMBUSTION EQUIPMENT             │
│                                                          │
│   Excess-Air Unit                                        │
│        Mass Burn or RDF                                  │
│        Waterwall and Rotary Waterwall                    │
│        Integral Boiler                                   │
│   Starved-Air (Controlled-Air) Unit                      │
│        Mass Burn                                         │
│        Refractory-wall (Modular)                         │
│        Waste-Heat Boiler                                 │
└─────────────────────────────────────────────────────────┘
```

Two generic types of combustion units identified above will be used in order to consider the major operational features which are most often encountered in current practice. The terms excess-air and starved-air will be used to identify the generic types because they relate to the contrasting features of combustion stoichiometry. The commonly used names are "waterwall" units and "modular" or "controlled air" units.

Each vendor will have unique design and operational features, but general operational considerations can be referenced to one of these generic designs.

Slide 10-15

```
┌─────────────────────────────────────────────────────────┐
│           GENERIC COMBUSTION COMPARISONS                 │
│                                                          │
│   Excess-Air Unit                                        │
│        Gasification & Combustion in Fuel Bed             │
│        Complete Combustion in Furnace                    │
│        Relatively High Gas Velocities                    │
│        Relatively High Particle Entrainment              │
│        Good Carbon Burn-Out of Residue                   │
│                                                          │
│   Starved-Air Unit                                       │
│        Gasification in Primary Chamber                   │
│        Relatively Low Gas Velocities                     │
│        Relatively Low Particle Entrainment               │
│        Acceptable Carbon Burn-Out of Residue             │
└─────────────────────────────────────────────────────────┘
```

Because of the differences in the stoichiometric designs of excess-air and starved-air units, their gas velocities are very different. Starved-air units provide less air so that the intensity of combustion and the resulting gas velocities and temperatures are lower than in excess-air units.

This provides a major operational advantage for starved-air units in that they have lower particle entrainment than excess-air units. The disadvantage, however, is that there is considerably more carbon left in the combustion residues. The condition would be much worse if it were not for the fact that the solids' residence time in starved-air units is much greater than for excess-air units.

Slide 10-16

```
OPERATIONAL CONSIDERATIONS

Steady Combustion Temperatures
        Steady Energy/Steam Production
        Steady Heating of the Fuel Bed
        Steady Mixing
        Constant Residence Time
```

In general, the operation of MWC units is improved by maintaining constant and uniform combustion temperatures. But this goal is difficult to achieve due to the diversity of MSW constituent materials and their moisture content. If combustion temperatures vary greatly, there will be corresponding variations in the rates of steam production, MSW gasification, combustion air requirements, mixing conditions, gas velocities, and residence time in the combustion chamber.

Nevertheless, if steady combustion temperatures can be achieved, unit operations will be improved. Steady combustion temperatures lead to steady steam production and steady heating of the fuel bed. Steady fuel bed heating leads to reduced variations in the rates of drying and gasification and in the associated air requirements for mixing and residence times.

THEORETICAL COMBUSTION EQUILIBRIUM TEMPERATURES
MSW WITH DIFFERENT MOISTURE LEVELS
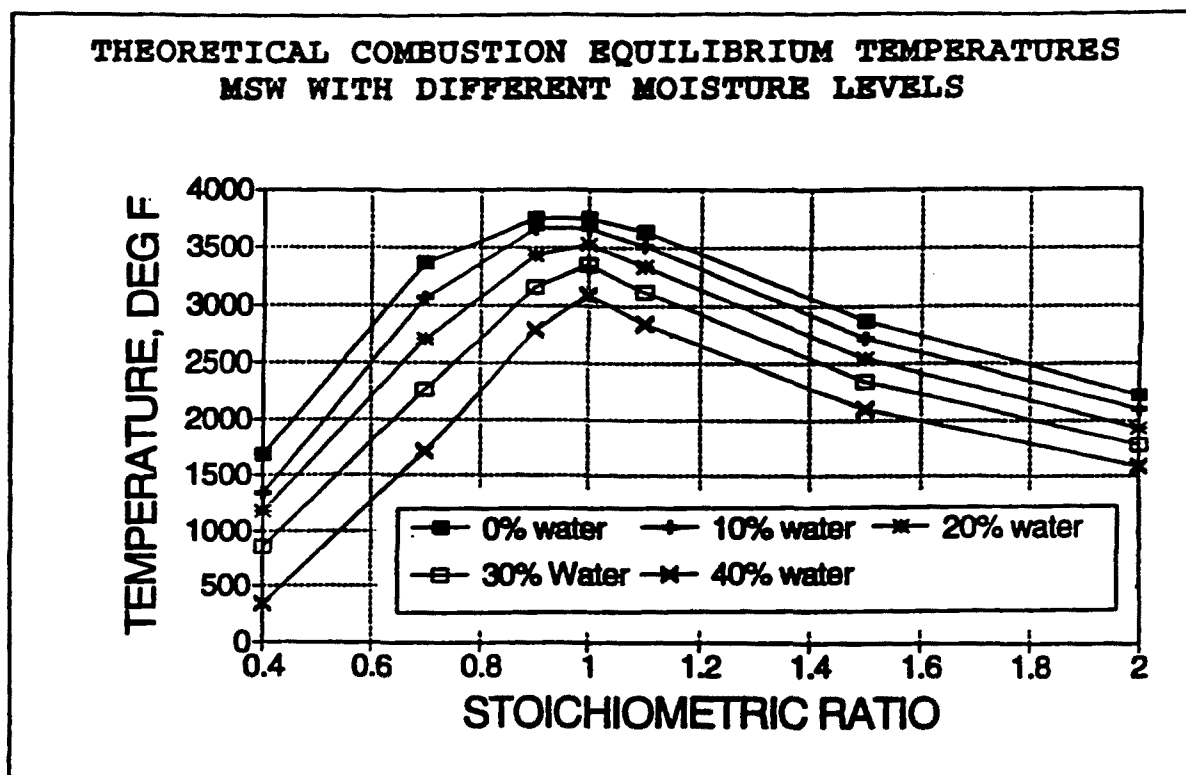
This figure is presented to provide insight about how MSW will burn under different air supply conditions. Theoretical combustion temperatures are plotted as a function of relative amount of air supplied. Various moisture contents in MSW were selected, with the higher curves corresponding to dryer MSW. The temperatures in the slide are maximum values which correspond to combustion without heat loss.

The stoichiometric ratio is defined as the air-to-fuel ratio divided by the stoichiometric air-to-fuel ratio. As indicated in Learning Unit 5, the stoichiometric air-fuel ratio for MSW is about 3 lb-air/lb-fuel. Therefore a unit operating with 100 percent excess air would supply about 6 lb-air/lb-fuel and have a stoichiometric ratio of 2.0.

Generally, an increase in the air supply will directly result in an increase in the stoichiometric ratio, unless the fuel supply rate is changed. Therefore, as the air supply is increased the operating conditions will shift to the right.

It may be interesting to note that an example MSW was assumed and the NASA computer model CET85[9] used for this illustration. The model included provisions for simulating the dissociation of water and other compounds which occurs at high temperatures. This influence gave rise to the unexpected result of the peak temperatures occurring under sub-stoichiometric conditions. If complete combustion had been assumed and the adiabatic flame temperatures displayed, they would reach their maximums with a stoichiometric ratio of 1.0.

```
┌─────────────────────────────────────────────────────────┐
│              OPERATIONAL CONSIDERATIONS                  │
│                                                          │
│   EXCESS-AIR CONDITIONS                                  │
│       Increase in Secondary Air Supply:                  │
│           Decrease in Furnace Temperature                │
│       Increase in Fuel Charging Rate:                    │
│           Increase in Furnace Temperature                │
│                                                          │
│   STARVED-AIR CONDITIONS                                 │
│       Increase in Primary Air Supply:                    │
│           Increase in Primary Gas Temperature            │
│       Increase in Fuel Charging Rate:                    │
│           Decrease in Primary Gas Temperature            │
└─────────────────────────────────────────────────────────┘
```

The previous slide showed that the operating conditions will influence how the temperature will change as the air supply changes. An increase in air supply can cause the combustion temperatures to either increase or decrease. For instance, under excess air conditions, an increase in the air supply (increase in stoichiometric ratio) will result in lower combustion temperatures. This is consistent with the experience of adding more over-fire air and seeing lower combustion temperatures.

The same logic shows that, under excess air conditions, an increase in the fuel supply rate (decrease the stoichiometric ratio) will increase the temperatures. This is consistent with grate agitation causing an increase in combustion temperatures.

By contrast, the primary chamber of a starved-air unit is designed to operate with about 50 percent of the air theoretically required for complete combustion. This corresponds to a 0.5 stoichiometric ratio. If the primary chamber air supply is increased (stoichiometric ratio increased) the primary chamber gas temperatures will increase. This will cause an increase in the volatilization of gases, so that there will be a corresponding increase in the supply of fuel to the secondary chamber.

Alternately, when the fuel delivery is increased (e.g., by fuel-bed agitation) and the air supply is unchanged, the stoichiometric ratio in the primary chamber will be decreased, causing a decrease in primary chamber gas temperatures.

```
STARVED-AIR UNIT OPERATIONAL CONSIDERATIONS

PRIMARY AUXILIARY FUEL BURNER
     Preheat Refractory
     Initiate Ignition
     Increase Gas Temperature
          Increases the Volatilization Rate

SECONDARY AUXILIARY FUEL BURNER
     Preheat Refractory
     Increase Secondary Gas Temperature
          Reduces Smoking
          Reduces Incomplete Combustion
```

Starved-air units make use of auxiliary fuel burners in both the primary and the secondary combustion chambers. The primary burner can be used to preheat the primary chamber and to ignite a fuel charge. It can also maintain adequate gas and refractory temperatures to control the volatilization process.

The auxiliary fuel burner in the secondary chamber is used to assure that the secondary chamber temperatures are adequate. By doing so, the chance of a unit's smoking and emitting products of incomplete combustion are reduced.

Slide 10-20

```
EXCESS-AIR WATERWALL UNIT OPERATIONS

HEAT TRANSFER
        From the Gas Side
        To the Water/Steam Side
```

Many of the operational considerations of MWC units involve maintaining proper combustion conditions and meeting load demands. Meeting a variable steam demand is generally difficult with MSW fuel because of its variable properties and the difficulty in maintaining uniform combustion conditions.

For waterwall units, the operation of the combustion system is closely related to the boiler operation. Heat transfer ties the combustion conditions to the energy recovery system. An upset in combustion will change the steam system. Similarly, a change in the steam demand will cause the combustion system to change. Also, a drop in feedwater temperature will cause greater radiant heat transfer to the waterwalls, which will reduce the combustion gas temperatures.

```
+-----------------------------------------------------+
|        EXCESS-AIR WATERWALL UNIT OPERATIONS         |
|                                                     |
|  TO MEET INCREASED STEAM DEMAND:                    |
|     Increase Grate Agitation & Under-Fire Air       |
|         Increases Fuel Supply & Burning Rate        |
|         Increases Gas Temperatures & Heat Transfer  |
|     Reduce Over-Fire Air (Overall Excess Air)       |
+-----------------------------------------------------+
```

Excess air can be used to control the combustion temperatures, since it is a readily available inert heat sink material. Excess-air units have the ability to independently regulate the underfire and over-fire supplies of air.

If there is an increased demand for steam, the combustion gas temperature will need to be increased to produce the required radiant heating to the waterwalls of the boiler. This will generally be achieved by increasing the combustion intensity through increasing the rate of burning. Increased agitation of the burning section grates and a corresponding increase in under-grate air will increase the bed temperature, volatilization rate and burning rate.

The gas temperatures will also tend to increase if the overall stoichiometric ratio (excess air) is decreased (increased fuel burning rate). This condition will generally cause increased carbon monoxide emissions.

Similarly, a drop in load will need to be controlled by a corresponding drop in the combustion gas temperatures, so that the radiant energy extraction and rate of steam production will be reduced. This may be accomplished with an increase in overfire air and a decrease in fuel supply.

```
+-----------------------------------------------------+
|        EXCESS-AIR WATERWALL UNIT OPERATIONS         |
|                                                     |
|  INCREASED FUEL MOISTURE                            |
|     Gas Temperature Will Drop                       |
|     Gas Temperature Can Be Restored                 |
|         Reduce Air Supply (Excess air)              |
|         Increase Fuel Supply (Grate Agitation)      |
+-----------------------------------------------------+
```

If an increase in the moisture content of the fuel occurs, the extra moisture will act as a heat sink and cause the gas temperatures to drop. The combustion gas temperatures may be restored by reducing the over-fire air supply and increasing the grate agitation.

However, there are limits on the amount of swing which can be tolerated in the air supply or excess air. Control of excess air and the maintenance of combustion stoichiometry are often used to control nitrogen oxide emissions. A design option is to provide flue gas recirculation rather than excess air as the inert heat sink material. These design and control features will be discussed in Learning Units 16, 21, and 22.

Slide 10-23

```
        METAL WASTAGE IN EXCESS-AIR UNITS

   Erosion (High Temperature)
        Temperature Control
        Velocity Control
        Rapping Rather than Soot Blowing

   Corrosion
        Oxidation/Reduction Oscillations
        Chlorine (HCl) Reactions
        Metal Reactions
```

Metal wastage of heat exchange surfaces in MWCs has been a serious operational problem. It generally occurs as a result of corrosion or erosion.

Erosion is the wastage of metal caused by the impact of particulates on metal surfaces. Erosion is particularly problematic under high temperature, velocity, and entrainment conditions. Many design options with reduced gas temperatures and local gas velocities are available.

The metal wastage from corrosion is generally aggravated by the variability of fuel properties, which causes local oscillations between oxidizing to reducing conditions in the regions above the fuel bed and adjacent to the metal surfaces. Under oxidizing conditions, iron oxides will build up on the metal walls. Under reducing conditions, however, the oxygen will be extracted from the wall, exposing pure metal.

Therefore, an important consideration in corrosion control is the improvement of the combustion process. Proper overfire air supply and mixing will aid the completion of oxidation and, thereby, reduce the potential for corrosive attack of the heat exchange surfaces.[3]

Corrosion conditions can also be caused by chlorine and sulfur reactions which appear to catalytically occur within the fly ash deposits on metal surfaces,[3] such as in the superheater. These problems are particularly severe if metal temperatures are above 900 °F.

REFERENCES

1. W. R. Seeker, W. S. Lanier, and M. P. Heap, "Municipal Waste Combustion Study, Combustion Control of Organic Emissions," U.S. Environmental Protection Agency, EPA-530-SW-87-021-c, June 1987, pp. 3-6, 7-8.

2. "Integrated Waste Services, Information Summary," Consumat Systems, Inc., Richmond, Virginia, Undated Brochure.

3. Joseph G. Singer, Combustion Fossil Power, 4th Edition, Combustion Engineering, Inc, Windsor, CT, 1991, pp. 6-13, 8-16 to 8-18.

4. S. E. Sawell and T. W. Constable, "NITEP: Assessment of Contaminant Leachability from MSW Incinerator Ash," Proceedings of an International Workshop on Municipal Waste Incineration, Sponsored by Environment Canada, Montreal, Quebec, October 1-2, 1987, p. 335-336.

5. Hazardous Materials Design Criteria, U.S. Environmental Protection Agency, EPA-600/2-79-198, October 1979.

6. Municipal Waste Combustors: Background Information for Proposed Guidelines for Existing Facilities, U.S. Environmental Protection Agency, EPA-450/3-89-27e, August 1989, pp. 4-84 to 4-118.

7. J. H. Pohl and L. P. Nelson, "Research Required to Generate Power from Municipal Solid Waste," Report to Southern California Edison Company, Rosemead, CA, Submitted by Energy and Environmental Research Corporation, February, 1985, p. 6-47.

8. W. D. Turner, Thermal Systems for Conversion of Municipal Solid Waste, Vol. 2: Mass Burning of Solid Waste in Large-Scale Combustors: A Technology Status Report, Report ANL/CNSV-TM-120, Vol. 2, Argonne National Laboratory, December 1982, pp. 5, 149.

9. Sanford Gordon and Bonnie J. McBride, "Computer Program for Calculation of Complex Chemical Equilibrium Compositions," NASA SP-273, March 1976.

11. DESIGN AND OPERATION OF GAS FLOW EQUIPMENT

Slide 11-1

```
TYPICAL AIR & FLUE GAS FLOW PATH

1.  Forced Draft Fan
2.  Air Preheater (Air Side)
3.  Under-Fire Air
    Over-Fire Air
4.  Furnace (Radiant Section)
5.  Convective Section Heat Exchangers
        Superheater
        Evaporator (Boiler)
        Economizer
        Air Preheater (Flue Gas Side)
6.  Air Pollution Control Devices (APCDs)
        Scrubber (Wet or Dry)
        Fabric Filter (Baghouse) or
        Electrostatic Precipitator (ESP)
7.  Induced Draft Fan
8.  Stack
```

A representative sequence of equipment which comprises the air and flue gas flow path is illustrated above. Note that the air preheater is listed twice. Combustion air, after leaving the forced draft fan, is sent through the air preheater. Later the flue gases pass through the air preheater and provide energy to the combustion air.

As was indicated in the previous learning unit, some MWCs have steam operated air preheaters, whereas others may not have air preheaters.

Early MSW incinerators operated without fans like open fireplaces. They achieved the delivery of air through the phenomena of natural draft. A column of hot air in a chimney is less dense than the adjacent air. Therefore, natural circulation causes the hot air to rise and be replaced by cooler air.

Natural draft systems have gas velocities which are hard to control, as they are directly related to combustion temperatures. A change in operating conditions, such as the entrance of wet MSW, can cause a reduced combustion temperature and after a time delay, the air supply will respond to the cooler gas temperatures. Natural draft systems are also very difficult to control during unit start-up.

Although a tall stack will provide some natural draft, modern MWC units use both forced draft and induced draft fans. These are required to deliver a controlled amount of air flow and achieve proper mixing, which are required for complete combustion.

AIR & FLUE GAS FLOW PATH OF A RDF UNIT[1]
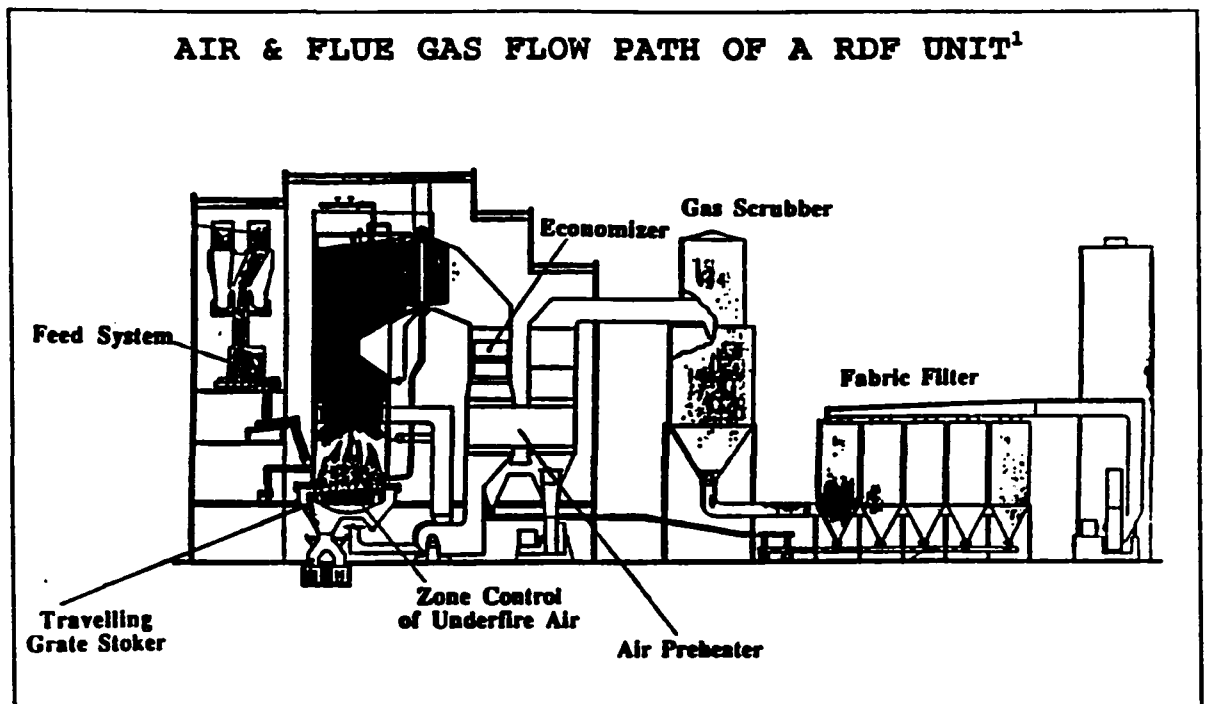
Courtesy of Combustion Engineering, Incorporated

Both forced draft and induced draft fans are typically used in MWC applications. If the fan is upstream of the furnace, it is called a forced draft fan. A forced draft fan can be considered as one that drives air into the furnace. Forced draft fans are attached to ducts which lead to plenum chambers and distribution passageways into the furnace. Depending upon the design, more than one forced draft fan can be used to supply the under-fire and over-fire air.

Induced draft fans act to draw flue gases out of the furnace, past the convective heat exchangers and air pollution control devices (APCDs). Induced draft fans are located upstream of the stack, so they also effectively force flue gases up the stack. If an induced draft fan is not used, the furnace will generally have to operate with a positive pressure. Such furnaces would be called pressurized.

Balanced draft systems are those with both forced draft and induced draft fans in the air and flue gas flow path. In general, the forced draft fan provides for the pressure drop associated with moving air into the furnace, and the induced draft fan provides for the flue gas pressure drop from the furnace to the stack exit. The pressure inside the furnace of a balanced draft system is generally slightly below atmospheric pressure.

Note that in the RDF illustration, the forced draft fan was shown drawing fresh air from the air preheater and blowing it through separate ducts into the under-fire and over-fire regions of the furnace. Air preheaters are often used in RDF units. Some mass burning units do not use air preheaters because of the more intense burning in the fuel bed which requires that cooler air be supplied to cool the grates.

AIR & FLUE GAS FLOW PATH OF A MASS BURN UNIT[2]
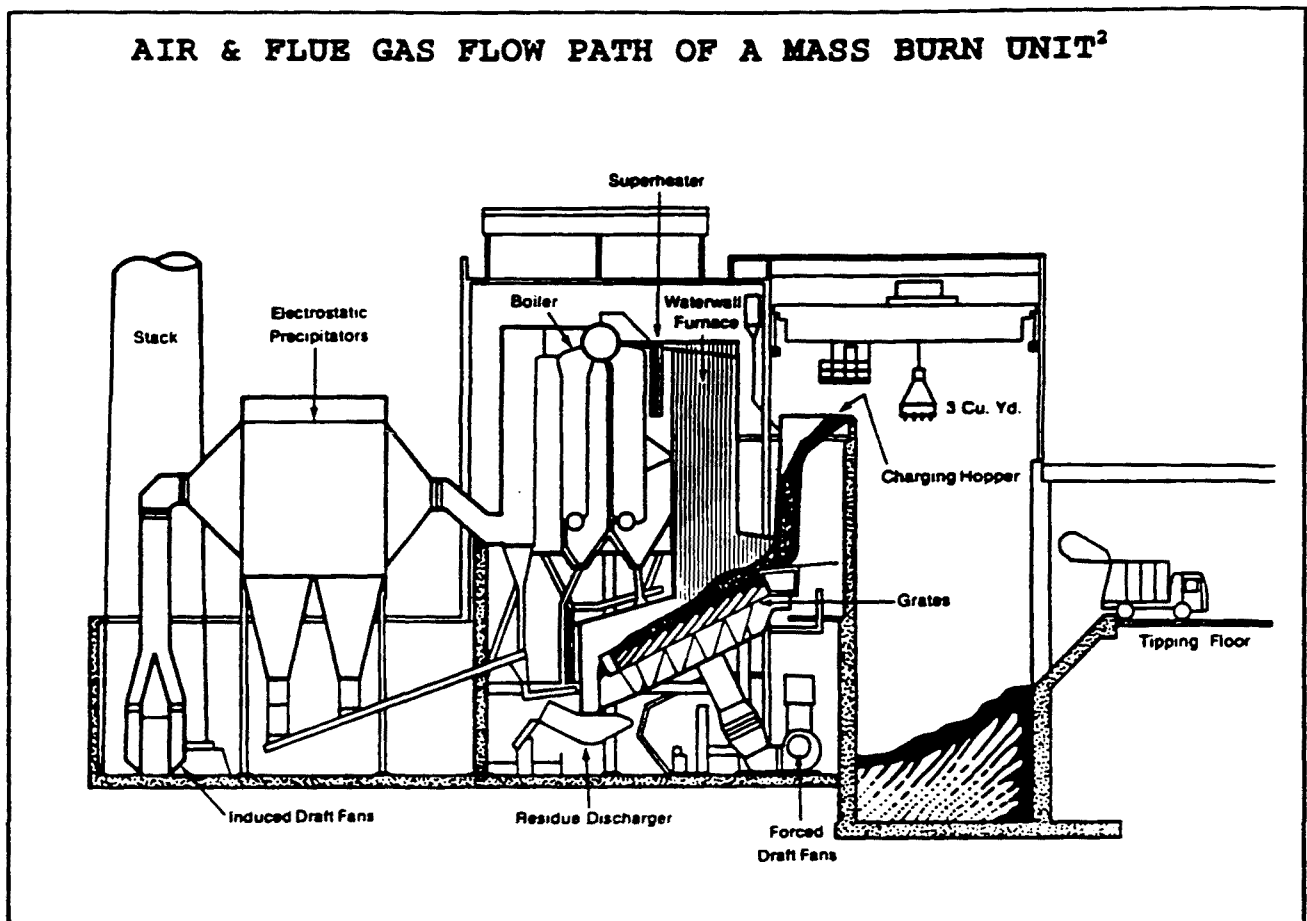
The mass burn unit sketch is typical of many MWC units. Although not shown explicitly in the sketch, most obtain combustion air from the MSW storage pit area in order to control odors.

After the combustion process is completed, the flue gases pass across the various tubes which make up the boiler, superheater, and economizer, and air preheater. Flue gases then flow into the APCDs. Most of the frictional losses are associated with moving the gases through the heat exchangers in the convective section and the flow restrictions of the APCDs (e.g., fabric filters). The pressure drops along the flow path must be overcome by the induced draft fan, which is typically located near the base of the stack.

CENTRIFUGAL FAN WITH INLET VANE DAMPERS[3]

Single-Width Rotor

Backward Curved Blades

Inlet Vane Control
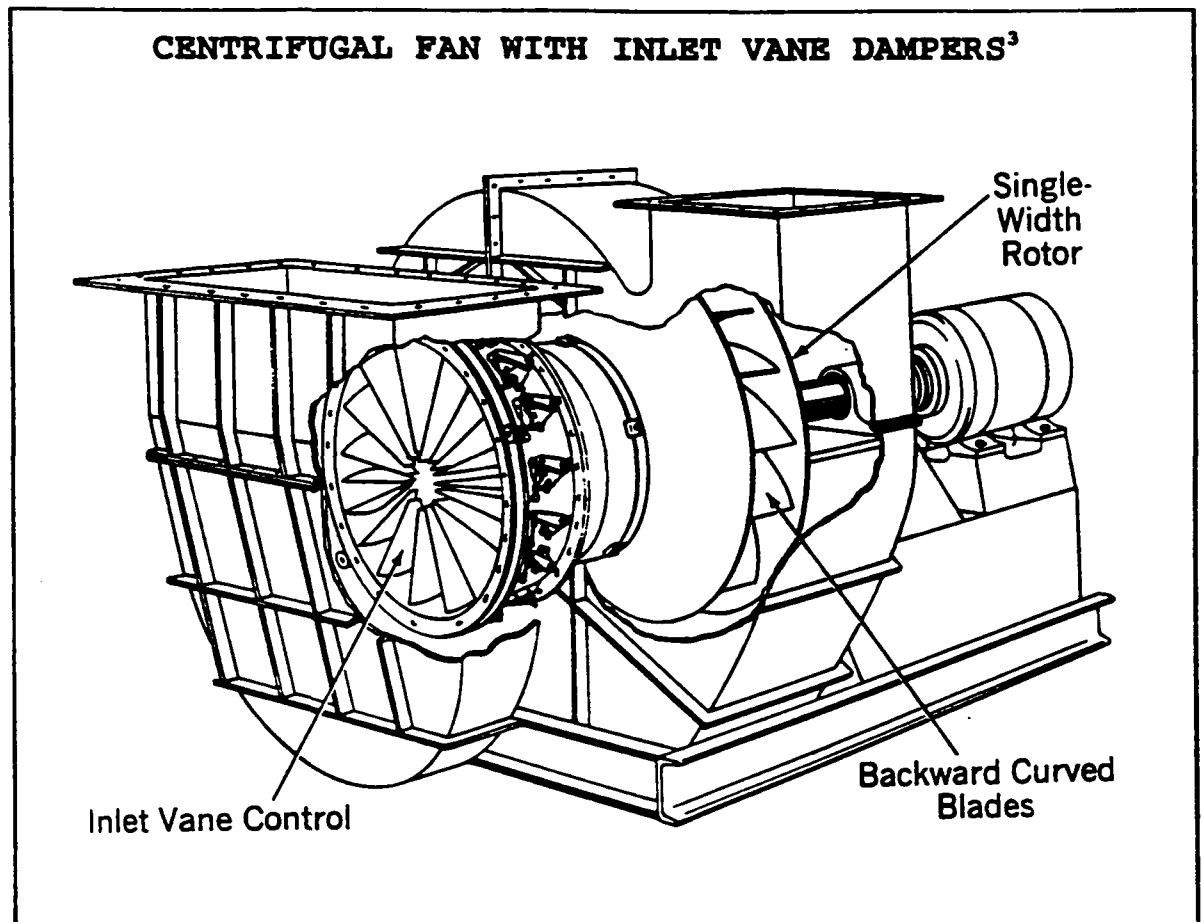
Courtesy of Babcock and Wilcox

Centrifugal fans, such as that illustrated in the slide, are most often used for both forced draft and induced draft fans in power plant operations.

There are a number of different fan designs available, including centrifugal and axial fans. Centrifugal fans can have blade designs with forward curved, radial or backward curved impellers. The design of the fan determines its performance characteristics, which are provided by the manufacturer as a fan curve. Some fans are capable of delivering a fairly large range of flow rates with a modest drop off in pressure, whereas others have their delivery pressure vary considerably with flow rate.

Fans with backward curved blades tend to have high energy efficiencies and are able to produce a flow which is not highly dependent upon the delivered static pressure.

Axial fans are characterized by a window fan in which the air flows along the direction of the axis of the fan. Axial fans are much less often used than centrifugal fans. Some axial fans are controlled by variable pitch fan blades, which can lead to improved fan efficiencies at low flow rates.

Slide 11-5

```
┌─────────────────────────────────────────────┐
│        METHODS OF CONTROLLING AIR FLOW       │
│                                              │
│     1.   Variable Speed Fan                  │
│     2.   Damper in Duct                      │
│     3.   Variable Inlet Vane Damper          │
└─────────────────────────────────────────────┘
```

Air flow through centrifugal fans can be controlled by modulating the speed of the fan, the position of a duct damper or the angle of a variable inlet vane damper. Automatic controls are typically used to automatically increase or decrease the control variable and thereby deliver the desired flow rate.

Variable speed fans have some advantages in terms of high fan efficiency, but have some limitations in terms of performance under modulated flow conditions. Variable operation can be obtained by using variable speed motors or steam turbine drives. In addition, a fixed speed motor could be fitted with a mechanical or magnetic coupling device which turns the fan at different speeds for air flow regulation. Variable speed motors are fairly expensive, and variable drive units may have undesirable frictional losses.

A duct damper is a variable restriction which is placed in the duct. Dampers are often used to control the delivery of under-fire air to the various sections of the grate. Note that because under-fire flow through the grate sections is divided into parallel paths, a changed damper setting in one section which restricts air flow will cause some additional flow in the other sections.

Slide 11-6

VARIABLE INLET VANES FOR CONTROLLING SWIRL[4]
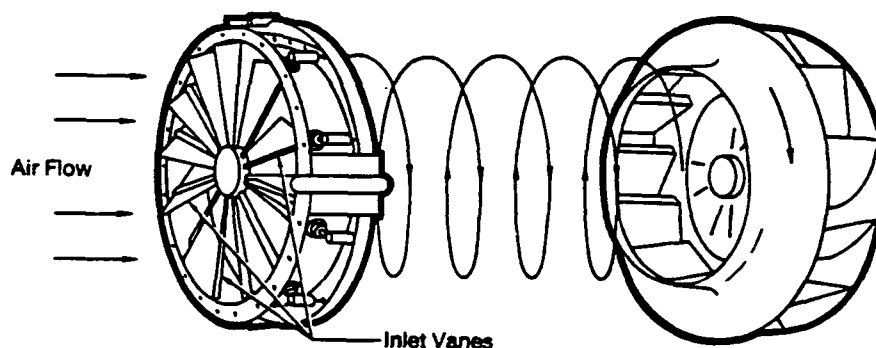
Air Flow

Inlet Vanes

From Joseph G. Singer, Combustion Fossil Power, 4th Edition, 1991, reprinted with permission of Combustion Engineering, Inc.

Many forced centrifugal fans are primarily controlled by varying the blade angle on the inlet dampers. This change acts to modify the swirl or aerodynamic behavior of the flow. In addition, it restricts the effective open area at the inlet.

In general, fans must be designed to meet both the flow and pressure drop requirements of the air and flue gas flow path. The fan must provide the pressure to overcome the frictional forces associated with moving the gas through its flow path. Generally, as the flow rate increases the fan energy requirements go up considerably. Also, the frictional forces are increased as gas temperature increases.

Slide 11-7
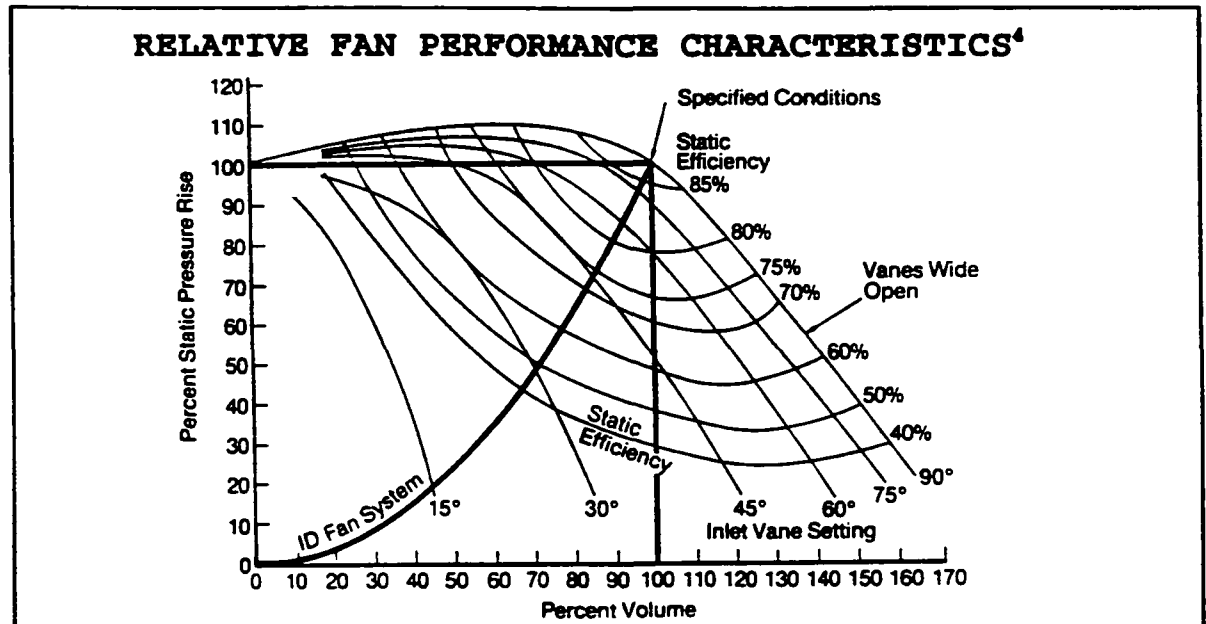
RELATIVE FAN PERFORMANCE CHARACTERISTICS[4]

From Joseph G. Singer, <u>Combustion Fossil Power</u>, 4th Edition, 1991, reprinted with permission of Combustion Engineering, Inc.

The designers who select fans must know the required pressure drop associated with the air and flue gas system. This is generally plotted as a "system curve," which indicates the amount of pressure drop required to deliver various amounts of flow. In the slide, an example system curve is plotted with the origin at the lower left corner. The nonlinear curve illustrates the greater static pressure rise required for flow increases near the rated flow (100%). System curves are typically plotted on a manufacturer's fan curve. Designers can correct system curves to accommodate anticipated changes in gas density or gas temperature by the application of the general fan laws.[5]

A family of "fan curves" is shown above, going from left to right with a concave downward shape. Each fan curve indicates the performance associated with a specified vane angle. As the vanes close down from 90° the flow will be restricted, as indicated by a lower intersection with the system curve. The fan curve also indicates that the fan efficiency deteriorates fairly rapidly (from 87% to 40%) as the vanes are closed from the wide open (100% flow) to a restricted flow (70% of design flow rate).

```
┌─────────────────────────────────────────────┐
│                    DRAFT                      │
│                                               │
│        Negative Pressure (Vacuum)             │
│        Measured in Inches of Water            │
│        Must be Maintained in Furnace          │
└─────────────────────────────────────────────┘
```

Draft is defined as the difference between atmospheric pressure and the absolute pressure at a point. Furnace draft indicates the amount of vacuum on the inside of a combustion chamber. Likewise, draft can provide useful information about the suction capability of a fan. Draft is generally measured with an inclined manometer or other instrument, with typical units being inches of water column.

A modest amount of furnace draft (furnace under slight vacuum) is the general design condition of MWC units, with values typically being between 0.05 and 0.5 inches of water. If the furnace pressure becomes greater than atmospheric, hot combustion gases will leak out through cracks and openings. If this occurs, the surrounding work environment may accumulate fly ash. Personal injury may also occur, and the unit could sustain structural damage.

Draft is routinely monitored in a control room to assure safe operating conditions, particularly in the event that a hatch needs to be opened for inspecting the furnace wall or combustion conditions. If the combustion unit swings to a positive pressure when a hatch is open, hot combustion gases could suddenly burst through the hatch and cause injury.

A unit which is operated with considerably more draft than specified in its design will probably have higher gas velocities, less mixing, and less complete combustion than under normal operating conditions.

The restoration of normal draft may be accommodated through use of a damper or a change in fan operation. Either using a more restrictive damper setting on the exit side of the furnace or opening the damper on the air supply side could be considered to restore proper draft conditions. Automatic draft controls are included in most pneumatic and electronic combustion control systems, as discussed in Learning Unit 22.

```
┌─────────────────────────────────────────────────┐
│                   DEW POINT                     │
│                                                 │
│        Threshold Condensation Temperature       │
│                                                 │
│        Typically Value is Around 300° F         │
│             Fuel Moisture Dependent             │
│             Ambient Air Moisture Dependent      │
│             Water Spray Dependent               │
└─────────────────────────────────────────────────┘
```

Dew point is the temperature at which condensation begins to occur as the mixture of gases is cooled. Dew points are often in the range of 225 to 300°F,[6] which compares with the typical values 280 to 320°F for coal firing.[4].

Dew points are dependent upon the concentrations of moisture and acid gases, including those formed by combustion and the moisture from the waste and ambient air. Dew points are also influenced by evaporation from water sprays and scrubber liquids.

When flue gas is cooled to its dew point, condensation will begin. Generally, water will condense and absorb acid gases. These acid solutions can cause corrosion of metal ducts and hoppers and other materials. Corrosion can lead to holes in metal enclosures, allowing ambient air to leak into the unit. If this occurs, the system performance will generally deteriorate and the cool air will lead to additional condensation and corrosion.

Acidic droplets can cause deterioration and blinding of fabric filters. If lime scrubbing systems are used, condensate formed on the collected filter cake can cause reactions which lead to blinding of fabric filters (material solidification within fabric filters which prevents normal gas flow). Removal of such solids is very difficult, so fabric filter replacement may be the only remedy.

Dew point problems are particularly troublesome during unit start-up and shut-down, when the unit temperatures change between ambient and operating conditions. Intermittently operated units require special care, as they are cooled to ambient temperatures each day.

Standard procedures include maintaining flue gas operating temperatures above the dew point range to avoid corrosion problems. Also, they often call for the burning of auxiliary fuel until the acidic gases have been purged.

```
SLAG AND SOOT DEPOSITS

Slag on Combustion Chamber Walls
Soot on Heat Exchanger Surfaces
```

A routine problem with all power plants is the control of slag and soot deposits. Slag deposits on waterwall surfaces are caused by deposits of liquid fly ash which solidify on the relatively cool wall surface. In fossil-fuel fired power plants, the composition is primarily silicon dioxide, a common inorganic material.

The slag composition in MWC units also includes glass. Significant slag deposits can occur if particle entrainment is high, fly ash composition is unfavorable, and gas temperatures are very high. Physical removal of deposited slag can be accomplished during outage periods for scheduled maintenance. In some units with considerable slagging problems, some breaking off of slag deposits can occur during system operations.

Soot is the name given to the solid deposits which routinely accumulate on the convective heat exchange surfaces. Soot acts as an insulating material, restricting the useful energy extraction by the heat exchanger. The soot is generally deposited as a solid, so it is fairly easy to dislodge.

Soot removal is often obtained by routinely operating either pressurized steam or air operated soot blowers. High pressure jet should not directly impact the surfaces, however, as they would effectively "sand blast" the surfaces and cause metal wastage and tube failures.

Many MWC units now use mechanical rappers or acoustic horns. These cause the metal surfaces to vibrate enough to effectively remove soot deposits, without the metal wastage problems caused by soot blowers.

Soot should be removed before it accumulates enough to significantly limit unit performance. The condition of accumulated soot on a heat exchanger can be monitored by measuring the change of temperatures across the gas side of the unit. For instance, consider the flue gas which normally has a 150 °F temperature drop as it passes through a heat exchanger. If the temperature drop deteriorates to 75 °F, there would be reason to suspect that soot deposits had caused a 50% reduction in the energy extraction.

Sequential soot removal of the various heat exchanger sections is typically provided. This allows the entrained soot to be at a low enough concentration so that the air pollution collection device can handle the extra particulate loading without causing an opacity violation.

REFERENCES

1.	"Prepared Fuel Steam Generation System," ABB Resource Recovery Systems, Windsor, Connecticut, Undated Pamphlet.

2.	W. D. Turner, Thermal Systems for Conversion of Municipal Solid Waste, Vol. 2: Mass Burning of Solid Waste in Large-Scale Combustors: A Technology Status Report, Report ANL/CNSV-TM-120, Vol. 2, Argonne National Laboratory, December 1982, p. 86.

3.	Steam, Its Generation and Use, 39th Edition, Babcock and Wilcox, New York, 1978, p. 17-6.

4.	Joseph G. Singer, Combustion Fossil Power, 4th Edition, Combustion Engineering, Inc, Windsor, CT, 1991, pp. 14-12 to 14-15, 14-36.

5.	George Clifford, Modern Heating, Ventilating, and Air Conditioning, Prentice Hall, Englewood Cliffs, NJ, 1990, pp. 535-536.

6.	Municipal Waste Incinerator Field Inspection Notebook, U.S. Environmental Protection Agency, EPA-340/1-88-007, July 1988, p. 169.

12. NSPS: GOOD COMBUSTION PRACTICES

Slide 12-1

```
┌─────────────────────────────────────────────────────────┐
│   NEW UNITS:   NEW SOURCE PERFORMANCE STANDARDS           │
│   EXISTING:    EMISSION GUIDELINES                        │
│                                                           │
│               Emission Limitations                        │
│               Good Combustion Practices                   │
│               Continuous Monitoring Systems, CEMs         │
└─────────────────────────────────────────────────────────┘
```

The NSPS and EG set federal limits for maximum allowable air pollutant emissions and require that good combustion practices (GCP) be followed.[1,2] GCP requires the continuous monitoring of emissions and combustion conditions. The measurement principles and the operation, calibration and maintenance requirements for continuous monitoring systems (CEMs) are presented in Learning Unit 14.

Slide 12-2

```
┌───────────────────────────────────────────┐
│   TECHNOLOGY-BASED EMISSION GROUPS         │
│                                            │
│        MWC Metals                          │
│        MWC Organics                        │
│        MWC Acid Gases                       │
└───────────────────────────────────────────┘
```

The federal NSPS and EG include standards which are technology-based, rather than based on health effects. Technology-based emission limits are based on the best demonstrated control technology.

The regulated pollutant, MWC emissions, is categorized into three sub-classes of emissions from MWC units by the NSPS.[1] MWC metals include the pure metals, organometallic compounds, and inorganic metal compounds emitted in the exhaust stack. Such metals of concern include: mercury, lead, cadmium, chromium, nickel, and beryllium. These are commonly referred to as "heavy metals".

MWC organics include the products of incomplete combustion (PICs) which are organic compounds. These include dioxins and furans which are carcinogenic materials. Federal regulations are based on the total of tetra-through octa-chlorinated dibenzo-p-dioxins and dibenzofurans.

MWC acid gases include sulfur dioxide and hydrogen chloride. Such acid gases are controlled by acid gas control equipment presented in Learning Unit 20.

Slide 12-3

```
SURROGATES

For MWC Metals:
        *    Particulate Matter, PM
        *    Opacity
For MWC Organics:
        *    Dioxin/Furan (PCDD/PCDF)
        *    Carbon Monoxide
For MWC Acid Gases:
        *    Sulfur Dioxide
        *    Hydrogen Chloride
```

Surrogates are substitutes which are used because the emissions of interest can not be directly measured. Values of surrogates are directly related to the emissions of concern. The NSPS and EG specify surrogates for MWC metals, MWC organics and MWC acid gases.

Slide 12-4

NSPS/EG Emission limits[1,2]			
Emission	New Unit >250 tpd	Existing Unit >250 tpd	Existing Facility >1100 tpd
MWC Organics (PCDD/PCDF)			
ng/dscm	30	125*	60
MWC Metals (PM)			
mg/dscm	34	69	34
Sulfur Dioxide			
% Removal	80	50	70
ppm-volume	30	30	30
Hydrogen Chloride			
% Removal	95	50	90
ppm-volume	25	25	25
Nitrogen Oxides			
ppm-volume	180	NA	NA

* Note: Limit for RDF Stoker Unit is 250 mg/dscm

For the annual stack test, particulate matter (PM) is used as the surrogate for the MWC metals, with the exception of mercury. During unit operations opacity is the continuously monitored surrogate for MWC metals. The opacity limit is generally 10 percent, based on a six-minute averaging period.[1]

Sulfur dioxide and hydrogen chloride are the surrogates for MWC acid gases. They can be monitored continuously. The control of SO_2 and HCl can be satisfied by either limiting the emissions to the ppm levels indicated or by removing the indicated percentage of the upstream gas. All concentrations are to be corrected to 7% oxygen and standard conditions at 68°F and 14.7 psia.

The federal NSPS and EG do not require monitoring of HCl, but HCl control is to be demonstrated during the annual performance test. The federal EG do not set standards for NOx emissions from existing units and do not require monitoring of NOx. However, some state regulations require both HCl and NOx monitoring at existing as well as new units.

Slide 12-5

NSPS/EG Carbon Monoxide Limits, ppm[1,2]		
Type of MWC Unit	New	Existing
Modular	50	50
Mass Burn Waterwall	100	100
Mass Burn Refractory	100	100
Mass Burn Rotary Waterwall	100	250
RDF Stoker	150	200
Coal/RDF Co-Fired	150	150
Bubbling Fluidized Bed	100	100
Circulating Fluidized Bed	100	100

Dioxins and furans are the surrogate for MWC organics, as they can be measured directly during an annual stack test. During unit operations, carbon monoxide, opacity, load, and APCD inlet temperature are used as its continuous monitoring surrogate.

Carbon monoxide emission limits depend upon the type of unit, which is illustrative of a technology-based standard. Carbon monoxide is also a toxic material, but the above emission limits are more restrictive than would be required on the basis of the health effects of carbon monoxide alone. The above CO limits are based on a 4-hour averaging period, except for RDF stokers and mass burn rotary waterwall units, whose limits are based on a 24-hour average.

Slide 12-6

GENERAL COMBUSTION SYSTEM CO - O₂ RELATIONSHIP³

A - INSUFFICIENT AIR

B - APPROPRIATE OPERATING REGION

C - "COLD BURNING"

CARBON MONOXIDE CONCENTRATION

OXYGEN CONCENTRATION
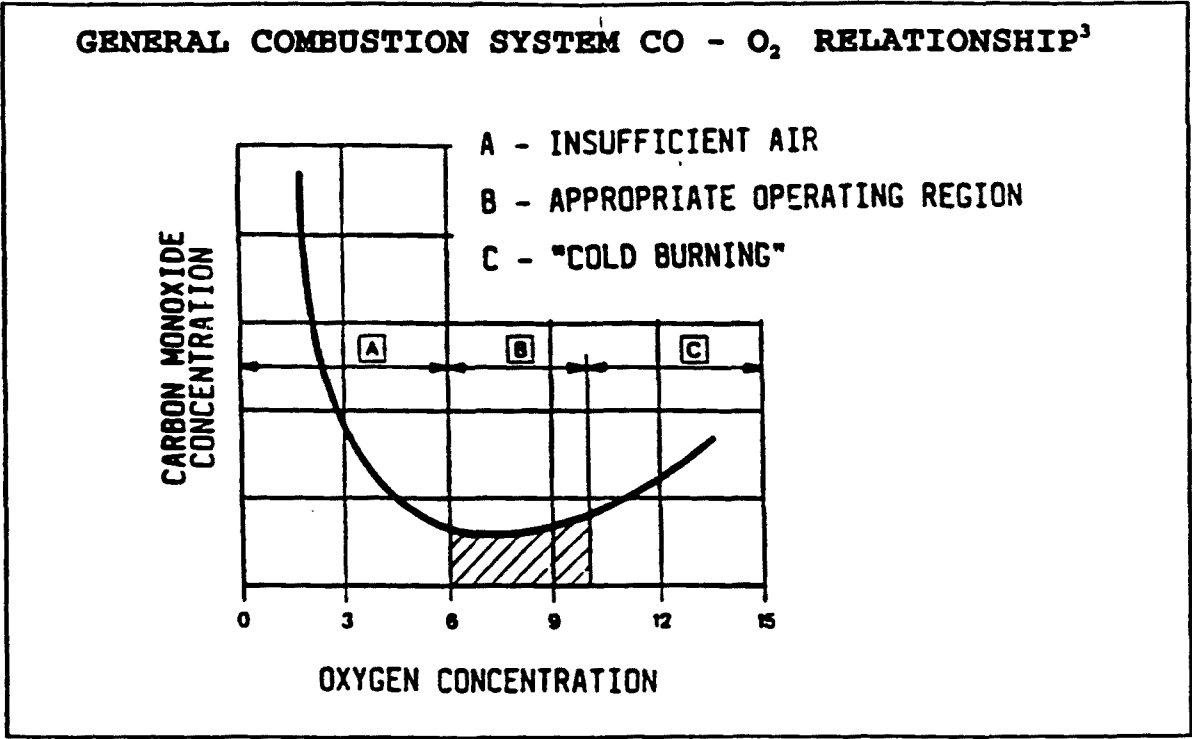
For each combustion system, there is a general relationship between the emissions of carbon monoxide and the amount of excess air.[3] The excess air is generally indicated by oxygen measurements in the flue gas. The recommended operating practice is to maintain the oxygen level in the zone where the carbon monoxide is minimized.

Slide 12-7

EXAMPLE CO - O₂ RELATIONSHIP FOR RDF UNIT⁴

CO (ppm @ 7% O₂)

O₂ (%)
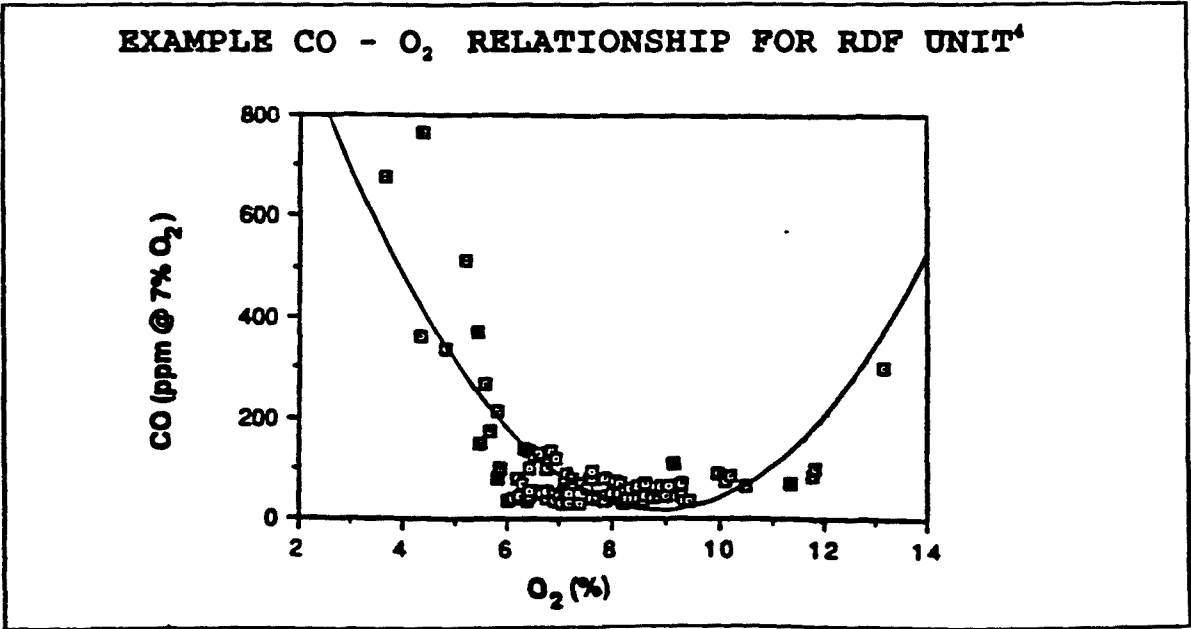
CEMS instrument readings can be plotted to show the relationship between CO and O_2. Slide 12-7 was obtained at an RDF unit. Note that the CO concentrations corrected to 7% oxygen,[4] using computational techniques which will be developed in Learning Unit 15.

Slide 12-8

```
PARAMETERS MONITORED FOR GCP

Carbon Monoxide
Opacity: Not to Exceed 10%
Load:    Not to Exceed 110% of Load
         of Most Recent Dioxin Test
Temperature of Flue Gas into APCD
         Not to Exceed by 30° F
         That of Most Recent Dioxin Test
```

The NSPS and EG set the operating requirements for good combustion practices (GCP) to assure that MWC organic emissions are acceptable. Good combustion practices are satisfied by MWC units which operate under specified limitations for carbon monoxide, opacity, load, and flue gas temperature at the entrance of the air pollution control device (APCD) which removes particulates.

The load limit is keyed to the annual stack test for dioxins. There is evidence that dioxin and furan emissions tend to increase if units are overloaded. This condition may be related to the air supply operating at full capacity. By increasing the load, more fuel-rich pockets of gas can pass through the combustion chamber without complete combustion.

The load limit is monitored as steam flow rate at waste-to-energy units. At the smaller MWC units or refractory MWC units which do not have provisions for energy recovery, a load limit is not required. This is primarily because of the difficulty in monitoring load or heat release in such units.

The temperature requirement at the entrance of the particulate air pollution control device (APCD) is based on evidence that dioxin and furan emissions are catalytically formed on the surface of fly ash. Such catalytic reactions increase with temperature and are also time dependent. If the collected fly ash is held at too high a temperature in the APCD, dioxin and furan emissions have been demonstrated to increase. Maintaining a temperature limit is more practical than controlling the retention time of fly ash in the APCD.

Slide 12-9

```
COMBUSTION CONDITION INDICATORS

     Opacity
     Temperature
          Furnace or Primary & Secondary
          Flue Gas Entering APCD
     Draft
     Carbon Monoxide
     Carbon Dioxide
     Oxygen
     Steam Flow Rate (Load)
```

Combustion conditions can be evaluated through use of a number of measurable parameters. The specific set of CEMs will vary from one unit to another. Small units tend to have fewer monitored parameters than larger units would have.

For example, flue gas monitors for carbon dioxide, carbon monoxide, and/or oxygen can be used to provide relative indication of the amount of excess air in the combustible mixture. Some small combustion units will measure only carbon dioxide, whereas the larger units typically will be required to monitor oxygen.

The oxygen level can also be used as a control signal in an oxygen trim control unit which controls air flow to a desired amount of excess air. Such units should be able to provide adequate air for combustion without either causing a significant increase of pollutant emissions or impairing the unit's operating efficiency.

Slide 12-10

MODULAR UNIT COMBUSTION INDICATOR RANGES[3]		
PARAMETER	LOW	HIGH
Opacity, %	0	10
Primary Temp., F	1,200	1,400
Secondary Temp., F	1,800	2,200
Draft, in w.g.	0.05	0.15
APCD inlet Temp., F		450
Oxygen, %	6	12
Carbon Monoxide, ppm	0	50

The above range of parameters are often indicators of acceptable combustion conditions in modular starved-air MWC units. For example, a modular starved-air

12-6

unit operating with 15 percent flue gas oxygen would have *too* much excess air. Unless very dry MSW was available, auxiliary burners would be required to achieve the recommended temperatures under such excess air conditions.

Slide 12-11

MASS BURN WATERWALL COMBUSTION RANGES[3]		
PARAMETER	LOW	HIGH
Opacity, %	0	10
Furnace Temp. at Fully-Mixed Height, °F	1,800	2,000
APCD Inlet Temp., °F		450
Oxygen, %	6	12
Carbon Monoxide, ppm	0	100

Slide 12-12

RDF WATERWALL COMBUSTOR RANGES[3]		
PARAMETER	LOW	HIGH
Opacity, %	0	10
Furnace Temp. at Fully-Mixed Height, °F	1,800	2,000
APCD Inlet Temp., °F		450
Oxygen, %	3	9
Carbon Monoxide, ppm	0	150

Mass burn and RDF fired MWC units have somewhat similar combustion operating ranges. Note that RDF units typically uses less excess air (oxygen).

REFERENCES

1. U. S. Environmental Protection Agency, "Standards of Performance for New Stationary Sources; Municipal Waste Combustors," Federal Register, Vol. 56, No. 28. February 11, 1991, pp. 5488-5514.

2. U. S. Environmental Protection Agency, "Emission Guidelines; Municipal Waste Combustors," Federal Register, Vol. 56, No. 28. February 11, 1991, pp. 5514-5527.

3. W. R. Seeker, W. S. Lanier, and M. P. Heap, "Municipal Waste Combustion Study, Combustion Control of Organic Emissions," U.S. Environmental Protection Agency, EPA-530-SW-87-021-c, June 1987, p. 1-7 to 1-9, 3-13, and 7-8.

4. James D. Kilgroe et al., "Combustion Control of Organic Emissions from Municipal Waste Combustors," Combustion Science and Technology, Vol 74, 1990, p. 237.

13. INSTRUMENTATION I: GENERAL MEASUREMENTS

Slide 13-1

```
┌─────────────────────────────────────────────────────┐
│            PURPOSE OF INSTRUMENTATION                 │
│                                                       │
│    1.   Supervision of Operations                     │
│    2.   Automatic Control Signals                     │
│    3.   Management Data                               │
│    4.   Pollutant Emissions Surveillance              │
└─────────────────────────────────────────────────────┘
```

Instruments are installed in combustion systems to provide data about the state of the unit's operating conditions. Such measurable information is vital to the operator who must evaluate various aspects of unit performance, including the identification of problem areas. Operators are routinely required to change manual and/or automatic control system settings, consistent with accepted operational procedures.

Predictions about the effect of possible operational changes can be aided by examining the magnitudes of current data and past records. Operational parameter data from various instruments may be required to develop a logical and consistent picture of what is happening and what should be done.

Instruments also provide information used to drive automatic control systems. Both the traditional pneumatic control systems and modern microcomputer-based control systems are designed around the use of control signals from sensors or instruments.

Access to selected operating data is required by corporate management. Recorded data is used by management in determining unit production performance, the need for equipment maintenance, and measures of cost accountability. For example, flue gas temperature data can be used to estimate the degree of boiler fouling and to establish proper boiler cleaning intervals.

In addition to written reports, some environmental control agencies require access to the readings of selected continuous emission monitoring systems(CEMS) through use of a continuous data telemetry system.

Slide 13-2

```
GENERAL MEASUREMENTS

1.  Temperature
2.  Pressure
3.  Flow Rate (Velocity)
4.  Weight
```

The basic instrumental measurement techniques used in MWC unit operations are presented in this learning unit. The focus will be on the equipment operating principles used in general measurements.

The measurement of gas concentrations by continuous emission monitoring devices will be presented in Learning Unit 14, and the use of such measurements in automatic control systems will be presented in Learning Unit 22.

Slide 13-3

```
TEMPERATURE EQUIVALENTS

°C = (5/9)(°F - 32)

°F = (9/5) °C + 32

°K (Kelvin) = °C + 273.15

°R (Rankin) = °F + 459.67
```

Temperatures can be expressed in different units: Fahrenheit, Celsius, Rankine, and Kelvin. The conversion factors for these units are given above.

Slide 13-4

```
TEMPERATURE MEASUREMENTS

Thermometer - Expansion of a Liquid
Dial Thermometer - Expansion of Metals
Thermocouple - Thermoelectric Potential
Thermistor/RTD - Electrical Resistance
Infrared Temperature Probe - Infrared Energy
Optical Pyrometer - Infrared Energy
Acoustic Temperature Probe - Speed of Sound
Temperature Paint - Change of Color
```

The mercury-in-glass thermometer has been commonly used for many years. As the temperature increases, the mercury in the bulb expands and rises in a thin capillary calibrated stem. Mercury thermometers can range from -30 to +900° F.

Thermistors are often used for low temperature applications. Thermistors are made from semiconductor materials whose electrical resistance varies inversely with temperature, and RTDs are made from conductors whose resistance increases with temperature. Appropriate probes and read-out devices are available which directly indicate temperatures. The devices usually include circuits for automatic calibration.

Infrared temperature probes and optical pyrometers utilize the characteristic dependence of infrared energy on the temperature of the surface. These are often used to indicate the effective temperature of hot surfaces such as refractory, molten metal, and fuel beds.

Temperature paints make use of the phenomena, which some materials exhibit, whereby their color is dependent upon their temperature. An object coated with such a paint will change colors upon being heated above a certain temperature range.

Slide 13-5
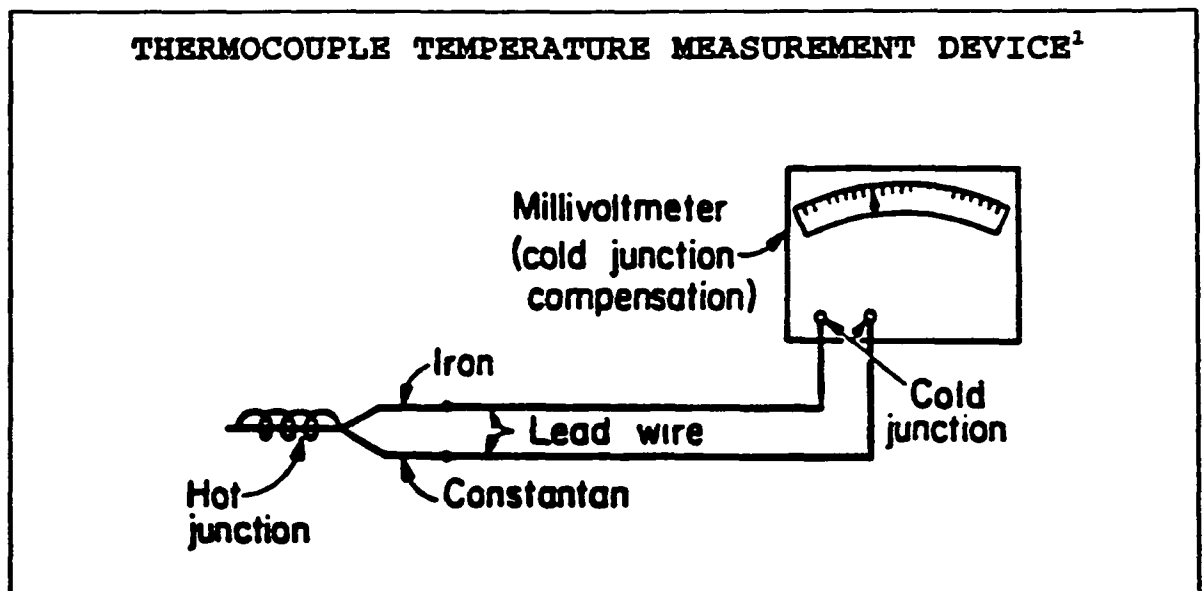
THERMOCOUPLE TEMPERATURE MEASUREMENT DEVICE[1]

From Robert T. Corry et al., "Instruments and Control", Mark's Standard Handbook for Mechanical Engineers, Eighth Edition, Edited by T. Baumeister, et al., McGraw Hill Book Company, NY, 1978, reprinted with permission.

Thermocouples are commonly used because of their high temperature and rapid response capabilities. When the ends of two different metals, such as iron and constantan, are joined together, a small electrical voltage is produced which is proportional to the "hot junction" temperature. Combinations of other metals can be selected depending upon the junction temperature range and the desired accuracy.

The thermocouple's voltage can be measured by a special millivoltmeter in a read-out instrument. A typical read-out device provides an electrical circuit which requires the opposite ends of each thermocouple wire to be attached to special "lead wires" (extension wires) which are connected to the "cold junctions" or reference junctions of the read-out unit. The "cold junction" temperatures must be properly compensated in the unit's circuit to determine the thermocouple's temperature.

Thermocouples can be obtained in protective sheathes which protects the hot junctions from corrosion and/or oxidation. In MWC applications, they may routinely fail after extended exposure to combustion gases or rapidly changing temperatures.

Boiler furnace temperature is commonly measured with a modified thermocouple device called a water-cooled suction pyrometer. Due to the large radiation heat loss from a hot junction to the surrounding cold wall, an unshielded thermocouple will measure temperatures several hundred degrees lower than the actual gas temperatures, particularly if gas temperatures are above 1,500°F. To minimize the loss, the hot junction is shielded and flue gas is rapidly aspirated through the measuring device, so that heat transfer from the hot gas to the thermocouple is greatly increased. The entire probe is generally water-cooled to protect the probe and to prevent it from sagging when it is inserted into the furnace.

Slide 13-6

ACOUSTIC TEMPERATURE PROBE APPLICATION[2]
(Typical Arrangement for 6 Port Mapping)

Processor Controller Unit

Furnace

Wave-Guide Transducer Units

Acoustic temperature probes employ the effect of the speed of sound being influenced by the temperature and composition of the gas through which it passes. Once calibrated, it can measure an average temperature of the gas in the path of sound travel. The acoustic probe usually consists of a microphone and a receiver arranged on opposite sides of the furnace. The acoustic temperature probe technology is still being developed, but when fully operational, it promises to be a very useful device for mapping the temperature patterns of a boiler.

Slide 13-7
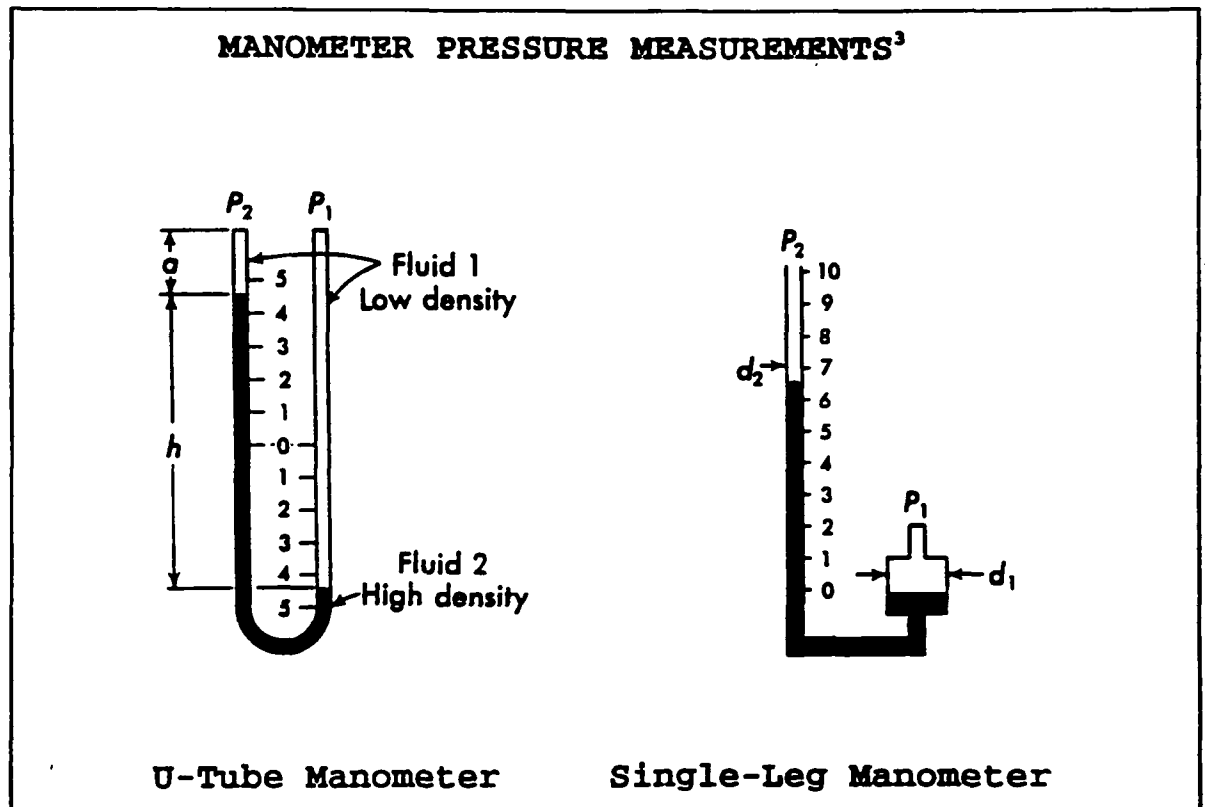
MANOMETER PRESSURE MEASUREMENTS[3]

U-Tube Manometer   Single-Leg Manometer

From Edgar E. Ambrosius et al., <u>Mechanical Measurement and Instrumentation</u>, Ronald Press, New York, 1966, printed with permission.

Pressure is the force per unit area exerted by a fluid, which is typically indicated in units of [lb/in^2]. Pressure is generally measured with a gage relative to the atmospheric pressure. Therefore, absolute pressure, which can be indicated as "psia", is equal to gage pressure, "psig", plus atmospheric pressure, "patm". Traditionally, the gage pressure is the positive amount of absolute pressure above atmospheric conditions, whereas the vacuum pressure is used to indicate the negative gage pressure associated with an absolute pressure below atmospheric pressure.

The simplest pressure measuring instrument is the U-tube differential manometer. The U-tube manometer directly indicates the difference between a pressure in two low density fluid regions as the vertical height of a column of high

density, indicator liquid. When pressure differences are measured, one leg of the manometer will have more liquid than the other, and the height difference is referred to as the "height of the column."

Note that water is the liquid most often used in power plant pressure measurements. The corresponding pressure difference is expressed as "inches of water column", which can be abbreviated as "in. wc." Although mercury has often been used in the past, its use is discouraged because of concern about spillage.

Single-leg and inclined manometers operate on the same basis as a U-tube unit, but the construction is such that all the height differential occurs in one tube. This is particularly true if the diameter of the well, d_1, is much greater than the diameter of the leg, d_2. An inclined manometer operates as a single-leg manometer with an extra horizontal displacement that provides for greater accuracy.

Slide 13-8
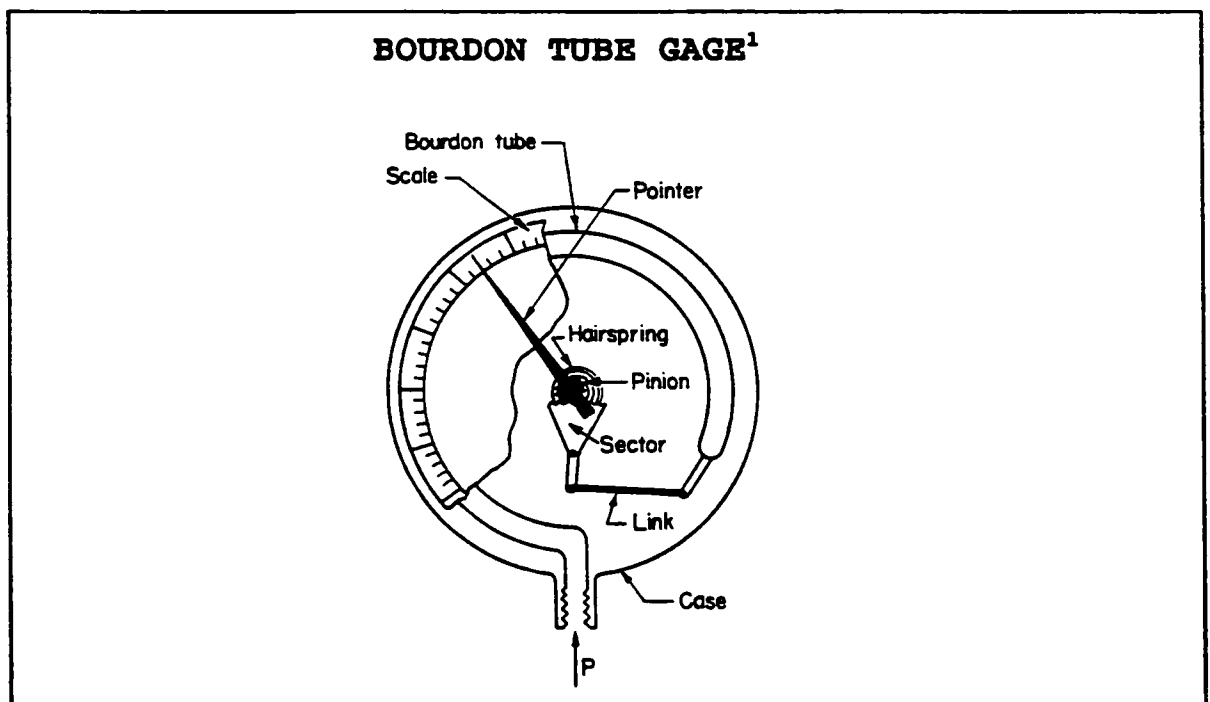
BOURDON TUBE GAGE[1]

From Robert T. Corry et al., "Instruments and Control", Mark's Standard Handbook for Mechanical Engineers, Eighth Edition, Edited by T. Baumeister, et al., McGraw Hill Book Company, NY, 1978, reprinted with permission.
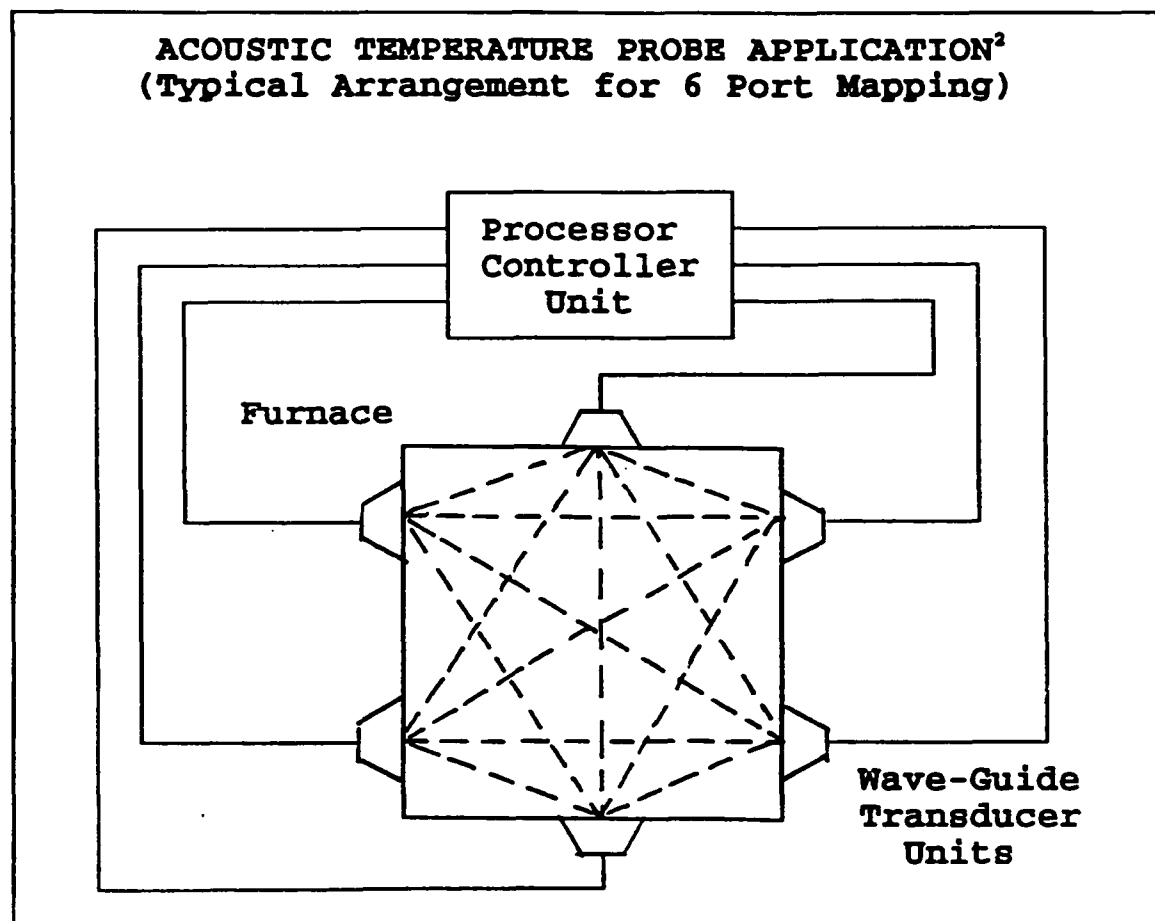
A Bourdon tube pressure gage is the most common pressure measuring device. There are various designs of these gages, but the operating principle is that flattened and curved tubes will change their curvature as internal pressure increases. As one end of the tube is fixed, the displacement of the other end is transmitted through mechanical linkages to a pointer. Pressure readings are proportional to the pointer displacement, so that, after calibration, the units make reproducible measurements.
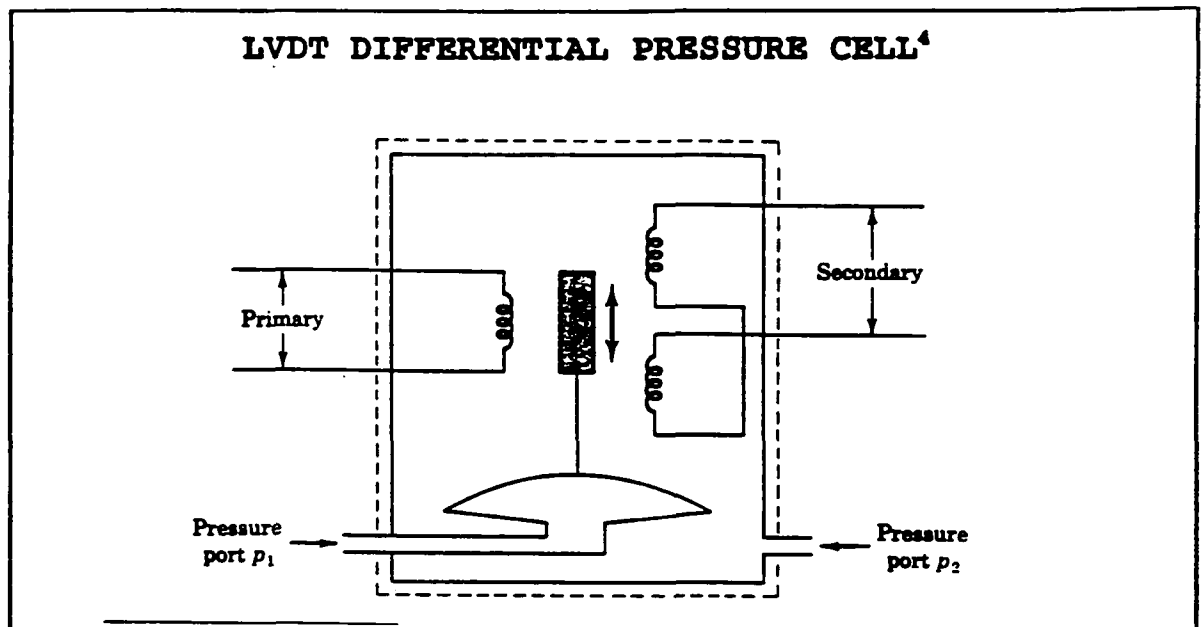
From J. P. Holman, Experimental Methods for Engineers, McGraw Hill Book Company, New York, Fifth Edition, 1989, printed with permission.

Differential pressure (DP) cells, diaphragms and bellows gages are very similar in their basic measurement concept and have design options of producing mechanical analog readings or electrical signals. Diaphragm and bellows devices will expand upon an increase in pressure in much the same way as the elastic metal tube of the Bourdon gage.

Mechanisms can be used to translate the linear expansion into an indicator displacement. These instruments are particularly applied in low pressure applications. Properly selected springs are required to restore the devices to a zero reading for atmospheric pressure or no pressure difference.

A DP cell may use a linear variable differential transformer (LVDT) circuit, as shown in the illustration. The LVOT provides an electrical signal which is proportional to the diaphragm displacement. Other units may have a capacitance pick-up designed to provide a linear signal of pressure variations.

Slide 13-10

13-7
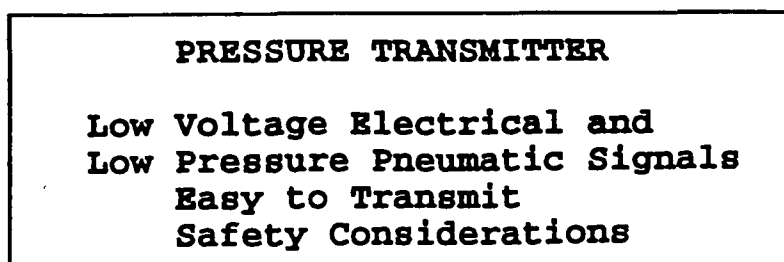
The previously described Bourdon gages may be used to measure high pressures of pumps and other equipment.

However, safety and operational considerations dictate that either a low pressure or low voltage device be used to transmit high pressure signals to control panels.

Low pressure pneumatic devices were very popular in the past, but today's trend is to use low voltage electrical pressure transducers to transmit an analog signal to a control panel's read-out device.

Slide 13-11

```
MEASUREMENT OF FLUID FLOW

MEASURING DEVICE              APPLICATION

Pitot Static Tube            Combustion Air Flow

Orifice Plate                High Steam & Water Flow
                               (Large Pressure Drop)

Venturi                      High Steam & Water Flow
                               (Small Pressure Drop)

Propeller-Type               Medium Air & Water Flow

Rotameter                    Low Water Flow
```

There are a number of different methods available for measuring the flow of fluids. The instruments generally measure some disturbance to the fluid which is proportional to the velocity.
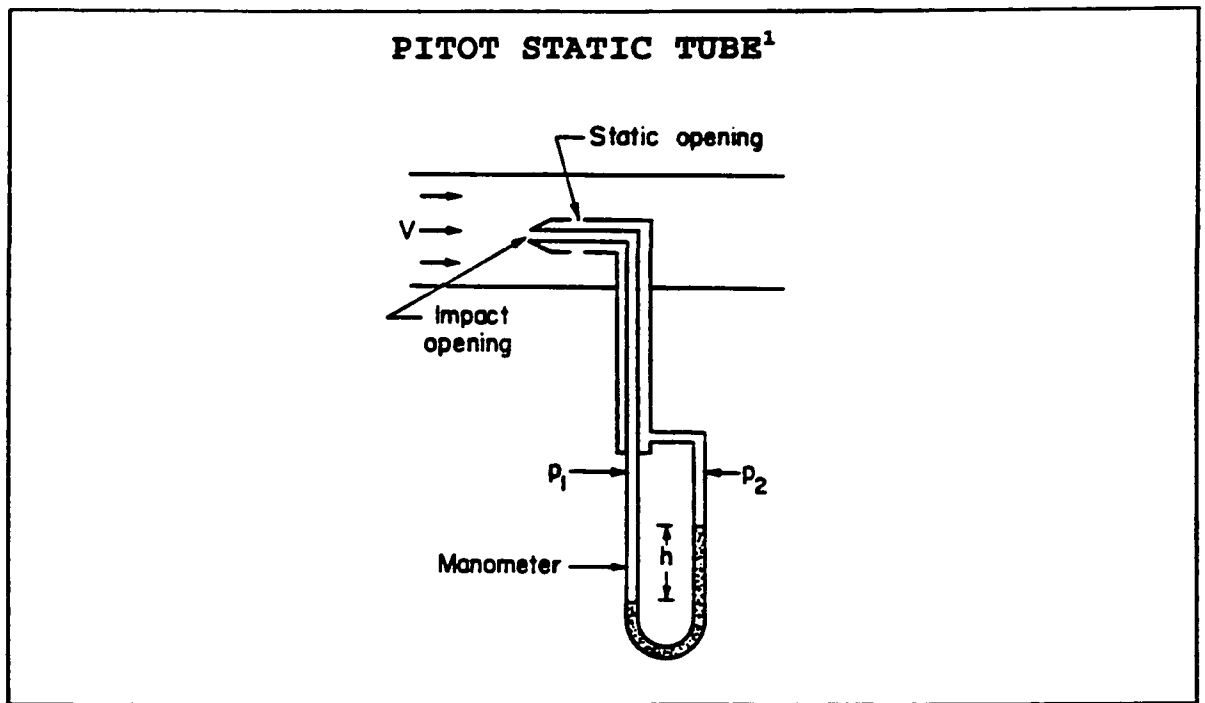
PITOT STATIC TUBE[1]

From Robert T. Corry et al., "Instruments and Control", Mark's Standard Handbook for Mechanical Engineers, Eighth Edition, Edited by T. Baumeister, et al., McGraw Hill Book Company, NY, 1978, reprinted with permission.

The pitot static tube is a device which uses a manometer to measure the difference between the dynamic pressure and the static pressure at a point. Fluid flow theory can be used to establish that this pressure difference is directly related to the fluid velocity at the point of measurement.

The major disadvantage of the pitot tube is that the velocity indicated is the local velocity at a point, rather than the average fluid velocity which is generally more useful for combustion control.

A slight modification of the pitot tube device is used as part of the standard EPA Method 5 stack sampling equipment.

From Robert T. Corry et al., "Instruments and Control", Mark's Standard Handbook for Mechanical Engineers, Eighth Edition, Edited by T. Baumeister, et al., McGraw Hill Book Company, NY, 1978, reprinted with permission.

Average flow rates can be measured with orifice plates, flow nozzles, and venturi tubes. Each of these will cause a disturbance in the flow which can be measured as a pressure drop between upstream and downstream locations. As the flow increases, the pressure drop increases.

A differential manometer or pressure transducer can be used to provide the flow rate, which can be indicated as a velocity (e.g., ft/sec), volumetric flow rate (e.g., cu-ft/min), or mass flow rate (e.g., lb/hr).

Some form of calibration is generally required because the pressure differences for a given flow will depend upon the installation as well as the type of flow restriction. Steam flow is often measured with orifice plates designed to conform to an ASME design standard. When specified measurement locations are provided, standard calibration curves and correction factor relationships may be used.
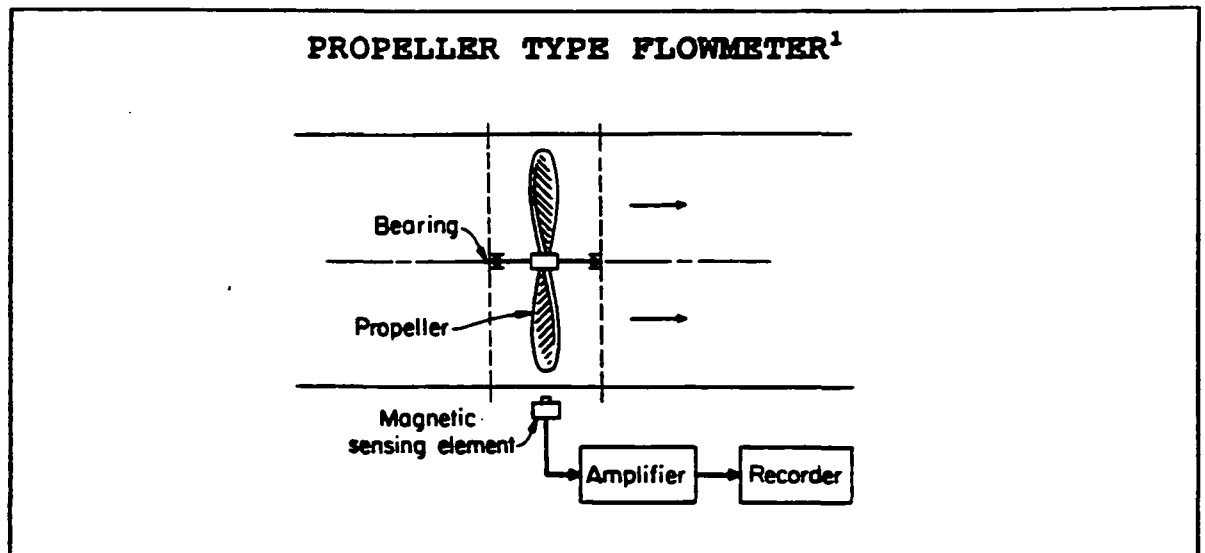
PROPELLER TYPE FLOWMETER[1]

From Robert T. Corry et al., "Instruments and Control", Mark's Standard Handbook for Mechanical Engineers, Eighth Edition, Edited by T. Baumeister, et al., McGraw Hill Book Company, NY, 1978, reprinted with permission.

A propeller mounted in the flow will spin faster as the velocity increases. Flowmeters using this principle can measure the turning speed either through a mechanical linkage or magnetic sensor coupled with a counter or tachometer. Turbine flow meters operate on this principle and provide accurate measurements.

Slide 13-15
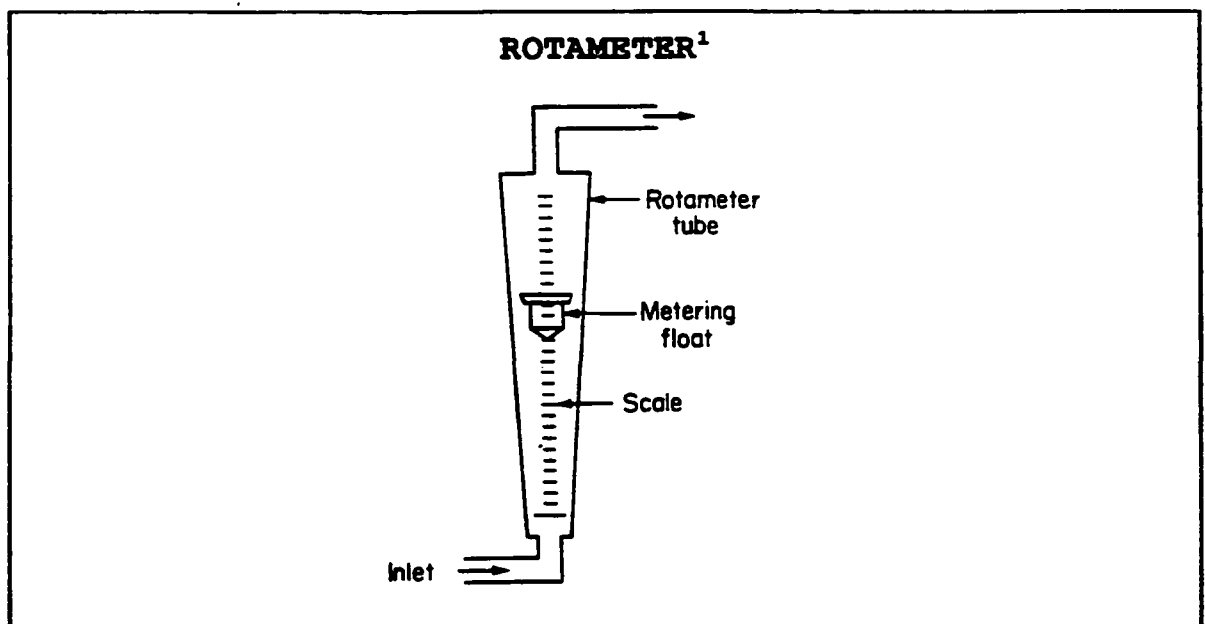
ROTAMETER[1]

From Robert T. Corry et al., "Instruments and Control", Mark's Standard Handbook for Mechanical Engineers, Eighth Edition, Edited by T. Baumeister, et al., McGraw Hill Book Company, NY, 1978, reprinted with permission.

Rotameters operate on the principle of balancing of gravitational forces with drag forces. The weight of a float placed in a tapered tube is balanced by the drag force of the fluid on the float. Fluid is directed upward in a tapered tube which causes the velocity to decrease as height increases. Since the weight of the float is fixed, the drag forces will cause the float to stabilize at a point where the velocity is appropriate. If the bulk fluid velocity is increased, the float will move upward and the height of the float will be proportional to the velocity.

Slide 13-16
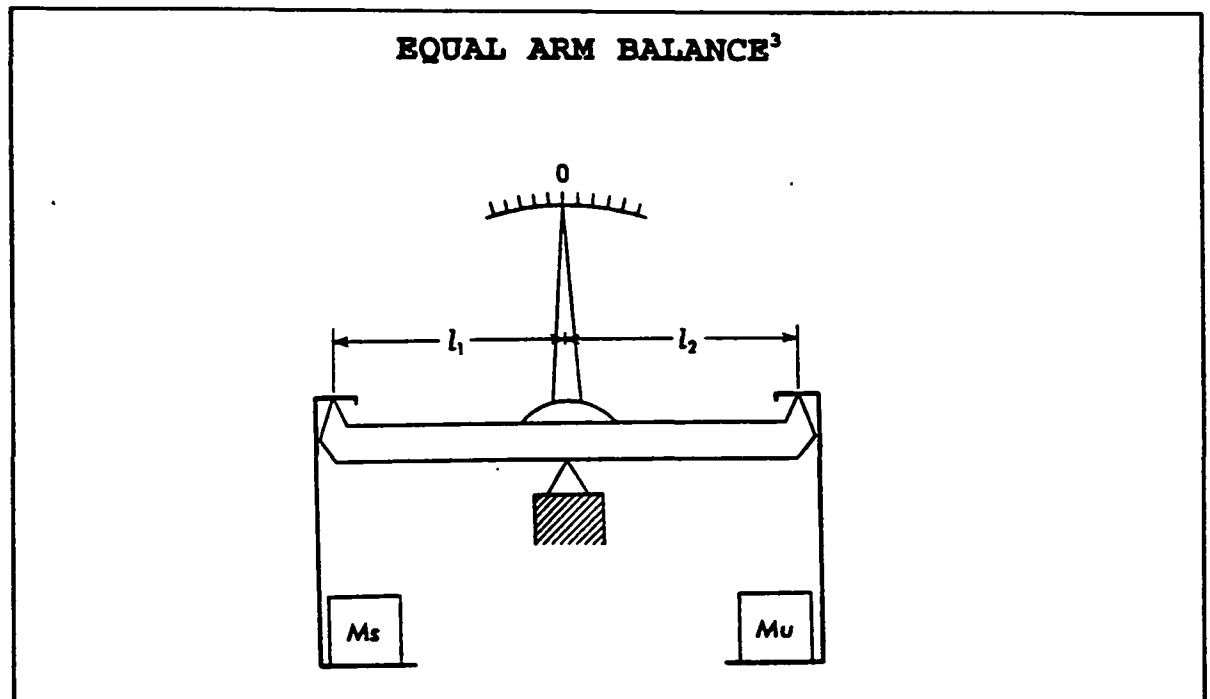
EQUAL ARM BALANCE[3]

From Edgar E. Ambrosius et al., <u>Mechanical Measurement and Instrumentation</u>, Ronald Press, New York, 1966, printed with permission.

Weight scale equipment falls into two major categories: balances and force-deflection devices. The simplest form of scales is the equal-arm balance which is commonly found in a laboratory. In this example, an unknown weight, Mu, is determined by adding up the various standard weights, Ms, which are required to make the balance indicator point to zero.
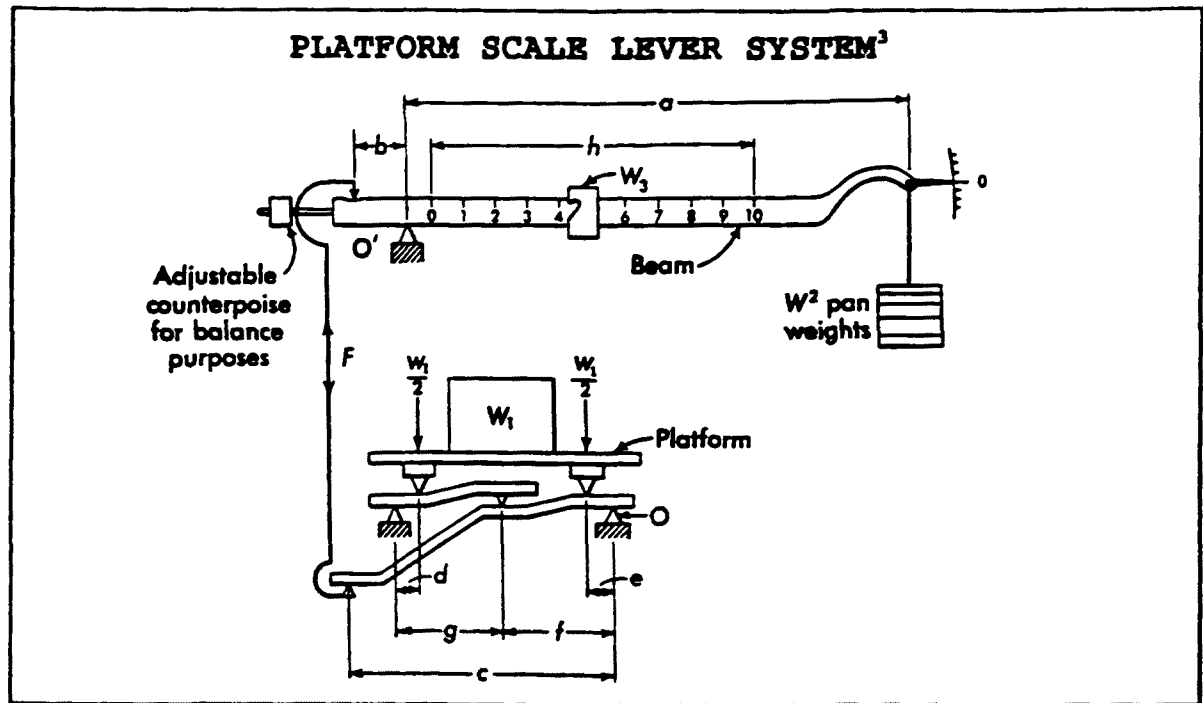
PLATFORM SCALE LEVER SYSTEM[3]

From Edgar E. Ambrosius et al., Mechanical Measurement and Instrumentation, Ronald Press, New York, 1966, printed with permission.

Large weight scales are based on a modification of the principles used in the equal arm balance scales. The difference is that linkages are used so that mechanical advantages allow for the use of proportionality, rather than direct weight balancing.
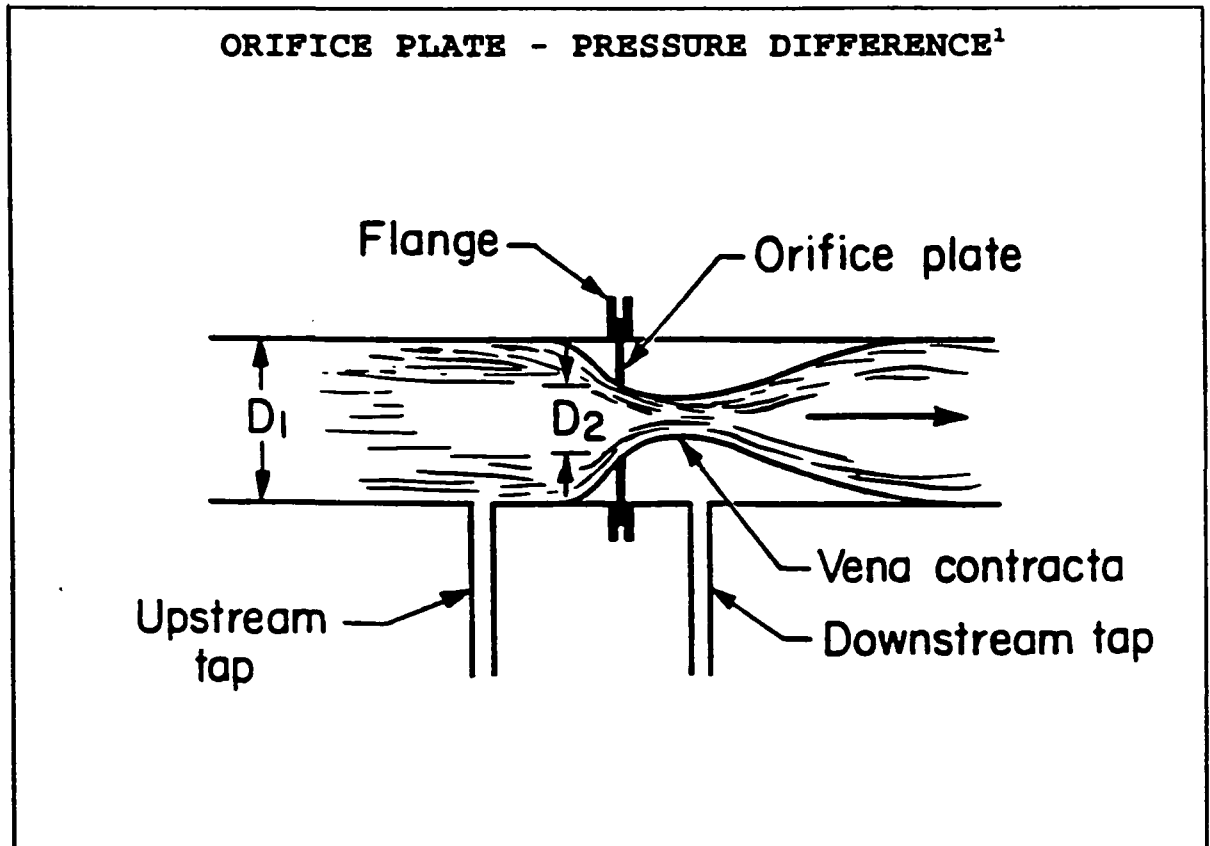
REFERENCES

1. Robert T. Corry et al., "Instruments and Control", Mark's Standard Handbook for Mechanical Engineers, Eighth Edition, Edited by T. Baumeister, et al., McGraw Hill Book Company, NY, 1978, pp. 16-9 to 16-16.

2. "Gas Temperature Measurement by Acoustic Pyrometer," Boilerwatch Model 31AP-H, Scientific Engineering Instruments, Inc., Sparks, NV.

3. Edgar E. Ambrosius et al., Mechanical Measurement and Instrumentation, Ronald Press, New York, 1966, pp. 252-255, 360-361.

4. J. P. Holman, Experimental Methods for Engineers, MCGraw Hill Book Company, New York, Fifth Edition, 1989, p. 213.

14. INSTRUMENTATION II: CONTINUOUS EMISSION MONITORING

Slide 14-1

```
CONTINUOUS EMISSION MONITORING SYSTEMS

    1.   Temperature
    2.   Fluid Flow Rate (Velocity)
    3.   Opacity
    4.   Concentrations of Gases
```

Learning Unit 13 presented various types of general instrumentation which can be used to provide combustion units operating and control information. Included were the continuous emission monitoring system (CEMS) instruments for fluid flow and temperature typically required at MWC units.

This learning unit presents the design and operational features of instruments which are used to measure stack opacity and the concentrations of selected gases.

Slide 14-2

```
TYPICAL CEMS USED AT MWC UNITS

    1.   Temperature of Gas Entering APCD
    2.   Steam Flow Rate (Load)
    3.   Opacity
    4.   Carbon Dioxide
    5.   Oxygen
    6.   Carbon Monoxide
    7.   Sulfur Dioxide
    8.   Nitrogen Oxides
    9.   Hydrogen Chloride
```

CEMS requirements depend upon the regulatory agency, unit size, and whether the unit is considered to be new or existing. In addition to those listed above, CEMS for total hydrocarbon, ammonia, stack gas flow rate and/or pH may be required.

The NSPS for new MWC units require CEMS for inlet flue gas temperature at the APCD, steam flow rate (load), opacity, nitrogen oxides, carbon monoxide, and sulfur dioxide. Although not specifically listed, CEMS for oxygen may be required so that concentrations can be corrected to the 7% oxygen standard. Alternatively, some regulations are based on concentrations corrected to the 12% carbon dioxide standard.

Monitoring of load is required by the NSPS only if the unit recovers energy. However, continuous emission rate monitors (CERMs) are currently being developed to measure flow and provide readings of emission rates rather than concentrations.

Federal regulations applicable to CEMS in MWCs have been published.[1,2] These include daily calibration drift tests, accuracy tests, accuracy audits, and gas cylinder audits. Relative Accuracy Test Audits (RATA) are required each year, using the applicable Performance Specification Tests (PST) procedures. Up to three quarterly Relative Accuracy Audits (RAA) are also required each year.

Slide 14-3

```
CATEGORIES OF CEMS

In-situ:
    Stack Mounted Analyzer
Extractive:
    Sample Flows to Remote Analyzer
```
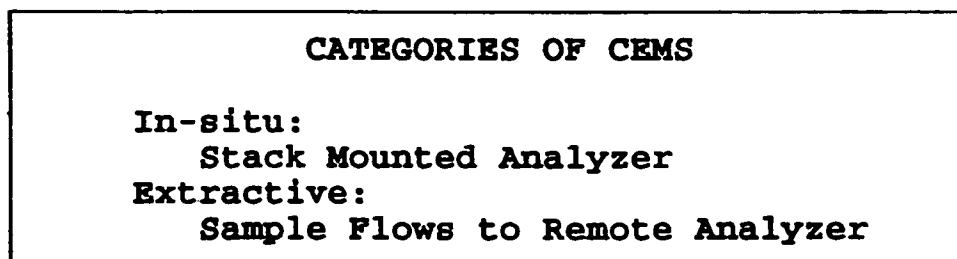
Monitoring systems are categorized as either in-situ CEMS or extractive CEMS according to the location of the gas analyzer.[3]

The extractive systems remove a continuous sample gas stream using probes, gas conditioning equipment, and tubing for transporting the sample to a remote analyzer.

The sensors and analyzers for in-situ analyzers are either mounted within or adjacent to the gas stream. The typical in-situ instrument will utilize an energy (light) source which is directed in a beam across the stack to a detector. The detector can produce an electrical signal whose strength is proportional to the energy received. The desired measurement can be based on the reduction of energy associated with gas absorption or particle scattering.

The physical measurement concepts of dispersive and non-dispersive absorption devices used to measure gas concentration will be presented later.

SINGLE-PASS OPACITY IN-SITU CEMS
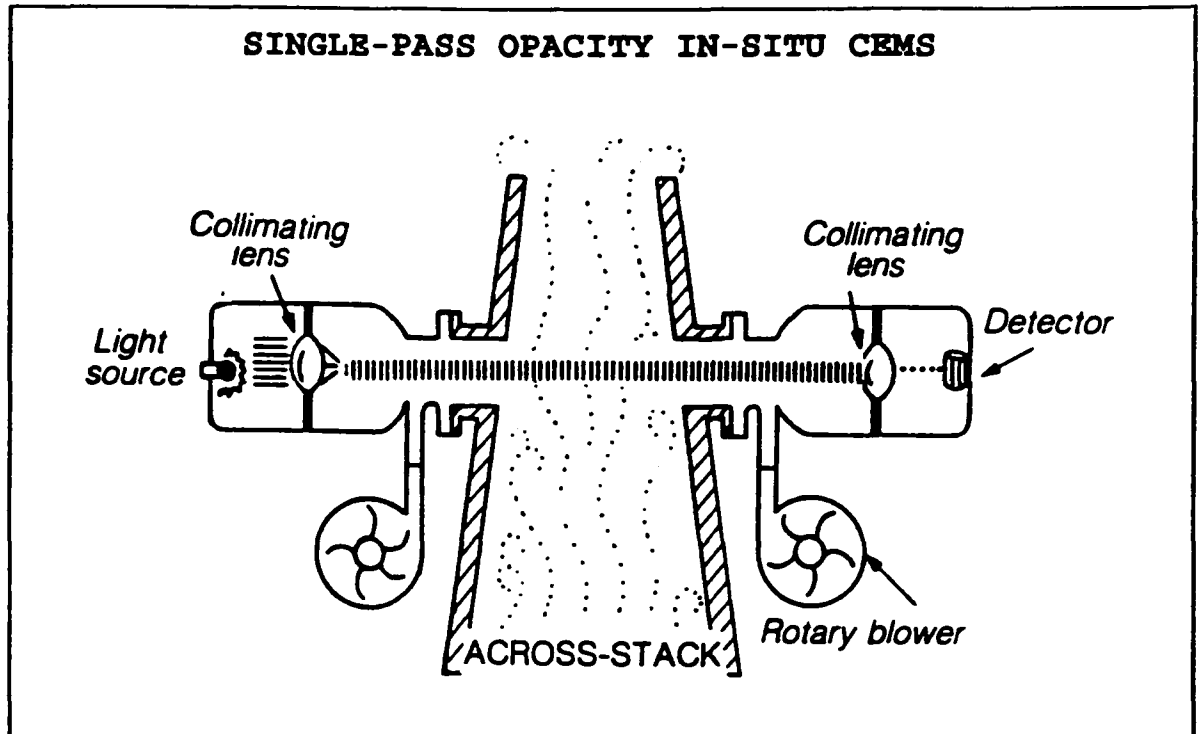
From J. A. Moore, "Key Measurements in Power Plants," Standard Handbook of Power Plant Engineering, Thomas C. Elliott, editor, McGraw Hill Book Co., NY, 1989, printed with permission.

Opacity is defined as the amount of attenuation of a visible light beam as it passes through stack gases. The visible light attenuation by smoke is primarily due to the scattering of light by small particulates.

Opacity CEMS are the simplest of the in-situ monitoring devices. Continuous opacity measurements are made at a fixed line through the flue gas as it passes up the stack.

The single pass transmissometer incorporates a light source, collimating and focusing lens, and a detector.[3] A linear detector is required to measure the intensity of light transmitted through the stack. The ratio of the detector signal to that at zero opacity is the stack transmittance. The opacity is equivalent to 1.0 minus the transmittance. This fraction is generally expressed as a percentage.

Before such devices were developed, visual opacity measurements were made by individual smoke readers who observed the flue gas plume leaving the top of the stack. Legally binding visual opacity observations can be made by smoke readers who are certified through standard visual emissions examinations. However, visual opacity observations have limited precision and require a subjective accommodation for different atmospheric conditions.
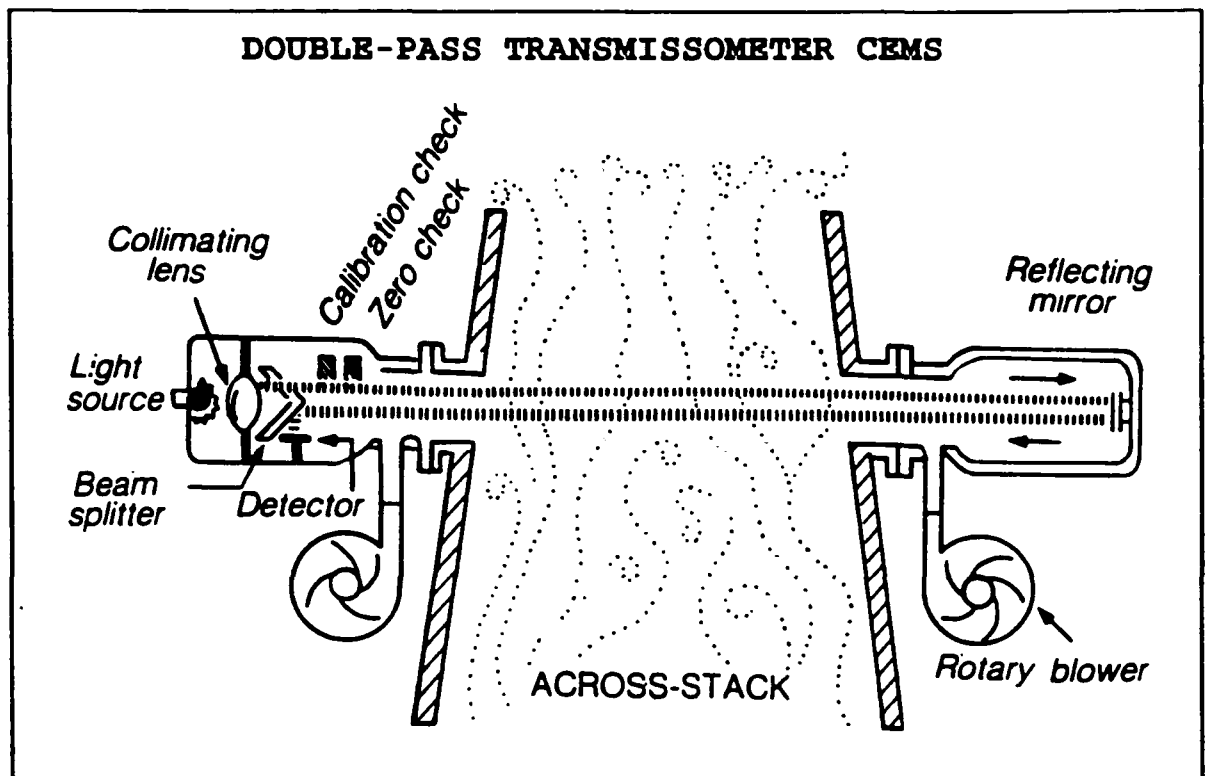
DOUBLE-PASS TRANSMISSOMETER CEMS

J. A. Moore, "Key Measurements in Power Plants," Standard Handbook of Power Plant Engineering, Thomas C. Elliott, editor, McGraw Hill Book Co., NY, 1989,

Double-pass transmissometer systems have various advantages. A chopper is used to pulse the light passing through the stack. The light is reflected back across the stack and onto the detector. A controlled reference beam is also directed onto the detector. The alternating signal from the detector at the chopper frequency provides a measurement which is proportional to transmittance and insensitive to ambient light. Calibration at zero and span values is obtained through the use of standard filters which can be inserted into the path of the beam.

Although fans are provided to limit the accumulation of deposits on the optical surfaces, routine maintenance includes cleaning of such surfaces and recalibration.

IN-SITU MONOCHROMATOR FOR GAS CONCENTRATION[4]
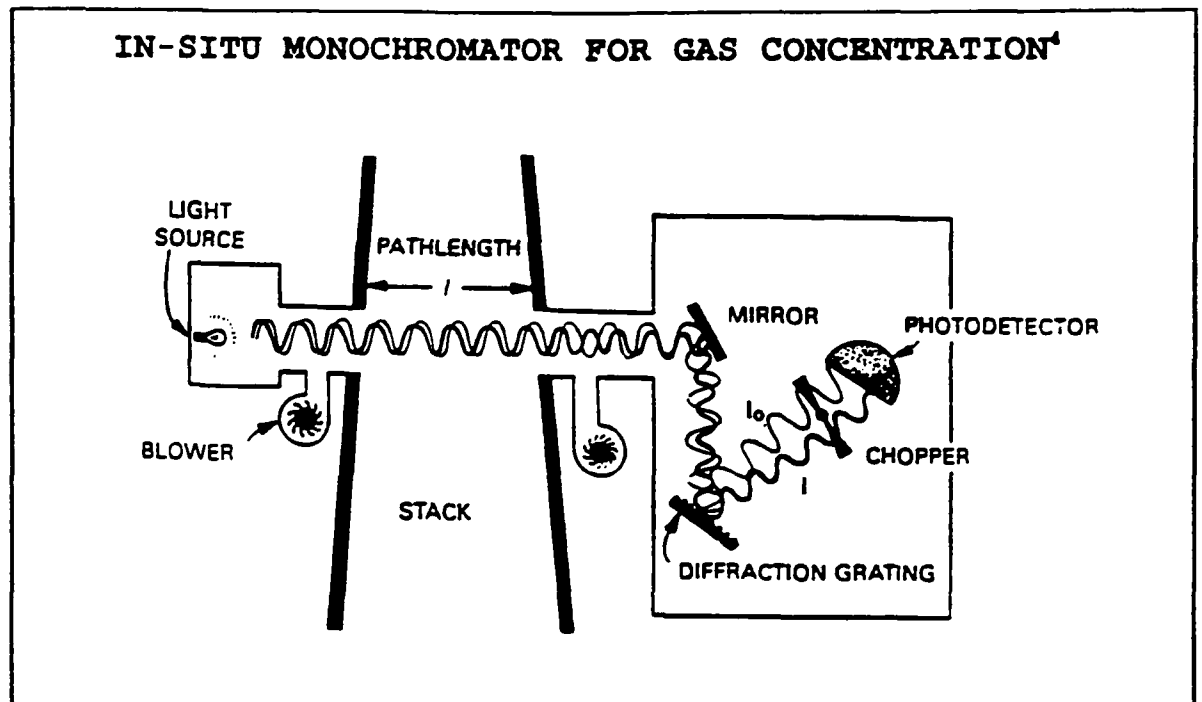
A cross-stack in-situ device for measuring for gas concentration is illustrated above. Gas concentration measurements differ from opacity in that opacity uses the entire visible light spectrum, whereas only selected wave lengths are used for gas concentrations. Such measurements may use a monochromator system as illustrated in Slide 12-7. Measurements are based on the concept of absorption spectroscopy in which each gas absorbs infrared energy at characteristic wave lengths or regions in the spectrum. The diffraction grating works like a prism to separate the beam of light into wavelengths of interest.

Other in-situ monitors make use of probes which are inserted into the stack. Such probes are designed to operate as a double-pass gas absorption cell. They are surrounded by a ceramic or stainless steel filter which allows gases to diffuse into the cell but prevents particulate contamination of internal optics. Typical probe lengths range from 5 cm to 1 m. Calibration is obtained by using solenoid valves which can allow either a span gas of known concentration or fresh air to purge the probe.

```
EXTRACTION TYPE OF GAS ANALYZER

Extraction of Gas Sample by a Probe
Removal of Particulates
Removal or Compensation for Water
Transport to Remote Detector/Analyzer
Conversion from Wet Basis to Dry Basis
```

Extractive CEMS use probes to remove a continuous gas sample. Multiple probes can be used to provide for the spatial averaging. The collected gas sample is directed through special conditioning equipment before being delivered to a remote analyzer. Otherwise, the particulates and condensate could cause blockages in the pipes and/or chemical changes which would impair the validity of the measurement. Conditioning generally includes filtration to remove particulate and a refrigeration drying, dilution, or heating system which eliminates acid and water condensation.

Many extractive systems provide measurements on a dry gas basis, whereas in-situ systems typically make measurements on a wet basis. Concentrations on a wet basis are smaller than the corresponding dry basis values. The concentrations measured on a wet basis (in-situ insturments) may be converted to a dry basis by dividing by (1.0 minus the moisture fraction in the flue gas).

Slide 14-8

```
WATER REMOVAL OR COMPENSATION SYSTEMS

1.  Desiccant
2.  Refrigeration
3.  Dilution
4.  Heating of Sample Line
```

The selection of the method for preventing water condensation depends upon the type of component to be analyzed. For example, the refrigeration drying system is not suitable for measuring HCl because condensed water absorbs HCl, resulting in an incorrect measurement by the analyzer. Therefore, HCl sampling systems typically use either a heat traced line (e.g., electrical heaters) to keep the gas temperature above the dew point or a dilution type extraction probe. Heated sample lines are also used to prevent the condensation of hydrocarbon gas when total hydrocarbons are measured.

The dilution probe system uses a supply of dry air to dilute the sampling gas by a constant and known ratio (e.g., 100). A large amount of dilution is provided to assure that the dew point of the diluted sample is low enough to prevent water

condensation. The diluted sample stream is analyzed by ambient level analyzers. Since no moisture is removed from the sample, the measurements are on a wet basis.

After leaving the conditioner, the sample flows through a pipe to a conveniently located analyzer. A problem with extractive systems is related to the time delay which occurs between the taking of the sample and its arrival at the analyzer. If proper procedures are not followed, chemical changes can occur between the time when the sample is removed from the gas stream and when it is analyzed. Also, the ducting system is vulnerable to plugging and leakage.

Slide 14-9

```
┌─────────────────────────────────────────────────┐
│         ABSORPTION SPECTROSCOPY                  │
│                                                  │
│    Dispersive Absorption                         │
│        Differential Absorption                   │
│                                                  │
│    Nondispersive Absorption                      │
│        Gas Filter Correlation Method             │
└─────────────────────────────────────────────────┘
```

Absorption spectroscopy is used in both in-situ and extractive CEMS applications to determine the presence and concentration of specific gases. These analytical techniques are based on the fact that gases absorb energy at characteristic wavelength regions of the energy spectrum. Some gases such as water vapor and carbon dioxide have broad absorption bands, whereas other gases absorb energy in a narrow wavelength region.

The characteristic absorption wavelength for a gas is most often in the infrared portion of the spectrum. However, some gases have characteristic absorption wavelengths in visible and ultraviolet regions. Corresponding instruments are commonly referred to as infrared analyzers and ultraviolet analyzers.

The influence of energy at all the other wavelengths can be averted by using either non-dispersive or dispersive analyzers. Dispersive devices such as gratings or prisms can be used to separate the energy into a beam having a single wavelength. The wavelength can be properly selected to measure the concentration of the gas of interest.

A traditional dispersive system would have an optical arrangement with a sample gas cell and a reference gas cell which alternately receive the beam of light before it is eventually focused onto the detector. The detector signal will be dependent upon the amount of energy absorption by the gases in the respective cells. The concentration of the gas in the sample can be obtained after calibration.

14-7

DIFFERENTIAL ABSORPTION EXTRACTIVE CEMS[4]
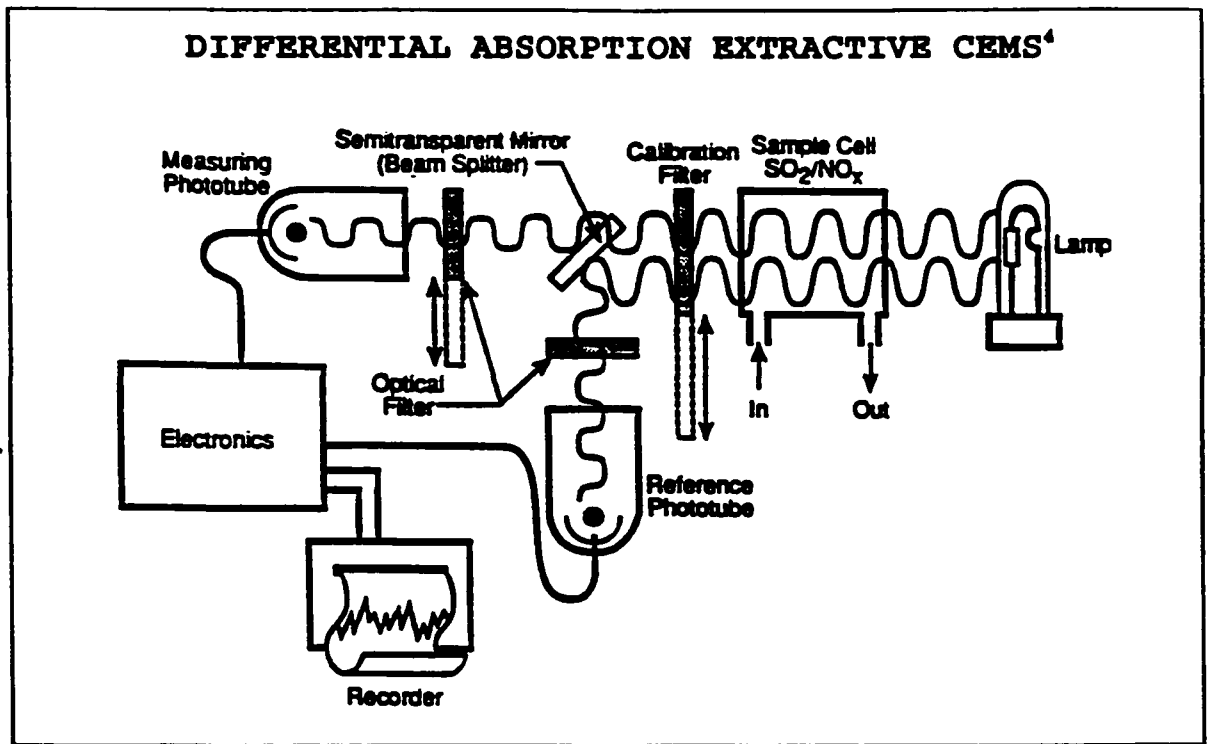
Differential absorption measurements are alternatives to the traditional dispersive energy absorption concept. A grating or special filter can be used to disperse the energy into two beams having different wavelengths but equal intensities. An application using a grating was illustrated in Slide 14-6. The above slide illustrates an application using a filter with two different detectors.

One beam is selected at the characteristic wavelength of the gas in question and the other wavelength is selected for a region where the gas is transparent. A measurement of the concentration can be obtained from a detector signal which is proportional to the ratio of transmitted energy at the two wavelengths.

A differential absorption in-situ monitor has been developed to allow a single instrument to sequentially measure up to three of the following gases SO_2, NOx, CO, CO_2, and/or H_2O. The design includes a filter wheel which sequentially selects the appropriate wavelengths for detection of each applicable gas. Special provisions in the instrument can compensate for background electrical noise, temperature and pressure influences, interference from other gases, and the non-linearity of the detector.

NONDISPERSIVE INFRARED EXTRACTIVE CEMS[4]
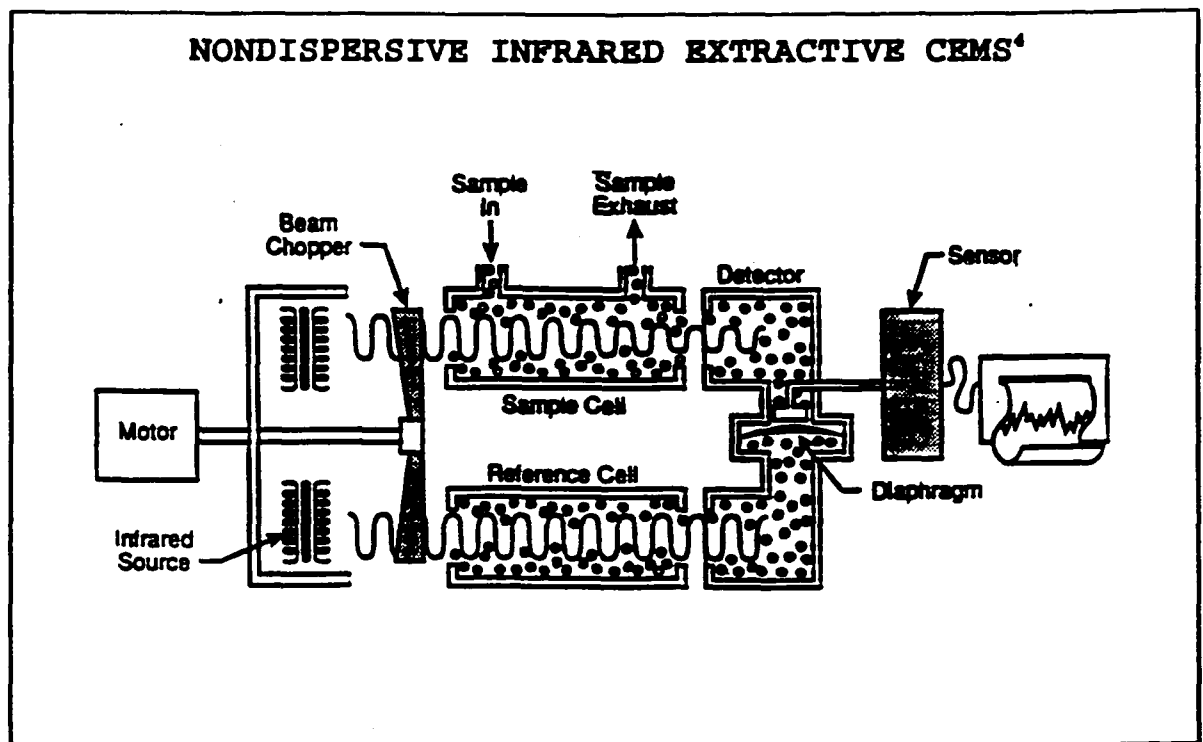
Nondispersive infrared analyzers are used extensively for measuring the concentrations of CO, CO_2, NO, and SO_2. Nondispersive ultraviolet analyzers can be used for the direct measurement of NO_2. Nondispersive infrared and ultraviolet analyzers operate on the same principles, although the filtering devices and detectors are different.

Nondispersive analyzers make use of a sample cell containing the flue gas, a reference cell which does not have any of the specific gas, and a detector. The detector is designed with two regions which are filled with a significant concentration of the specific gas. The two regions of the detector are separated by a diaphragm.

The energy absorbed by gas in the section of the detector adjacent to the sample cell is less than that of the section adjacent to the reference cell because of energy absorption by the gas in the sample cell. The different levels of absorbed energy cause the diaphragm to oscillate.

By alternately passing a beam of energy through the sample and reference cells, the position of the diaphragm will oscillate. Such changes can be measured by a microphone-type sensor. The signal can be calibrated to give measurements of the concentration of the specific gas.

NONDISPERSIVE GAS FILTER CORRELATION CEMS[5]
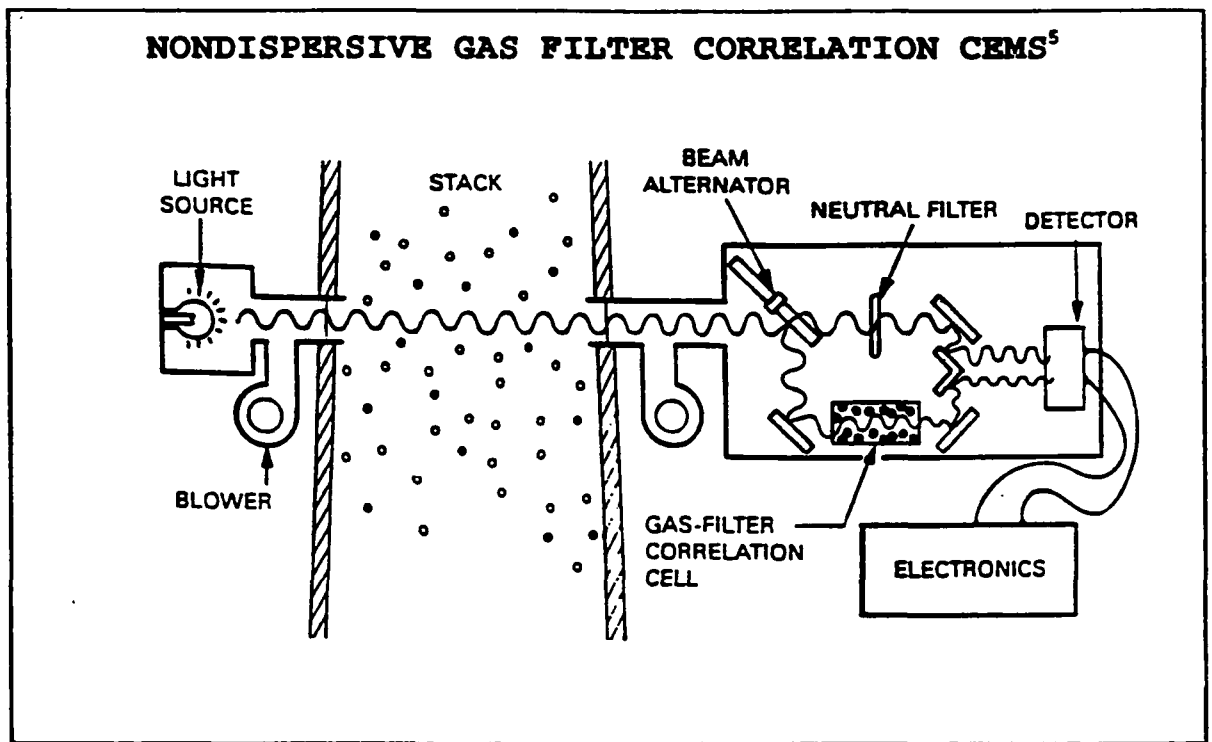
Another nondispersive concept is used in the gas filter correlation method. After passing through the stack, the beam is split. One beam passes through a neutral filter and the other passes through a gas filter cell containing a significant quantity of the specific gas. The neutral filter is selected so that the detector signals are equal when the specific gas is not found in the stack. When the specific gas is in the stack, the energy transmitted through the neutral filter will be decreased, but the energy passing through the gas filter cell will not change. A detector can measure this energy difference.

Calibration is often performed by inserting a gas-filter cell of known concentration into the optical path between the light source and the unit.

Slide 14-13

OTHER ANALYTICAL TECHNIQUES

Chemiluminescence
Electrocatalytic
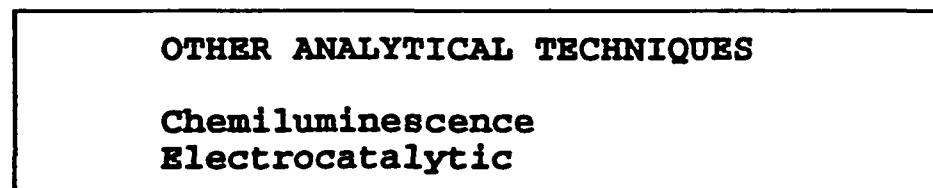
There are various other analytical techniques which are available for use in determining gas concentrations. Chemiluminescence is often used for NOx measurements, and oxygen is often measured using a electrocatalytic analyzer.

CHEMILUMINESCENCE ANALYZER[4]
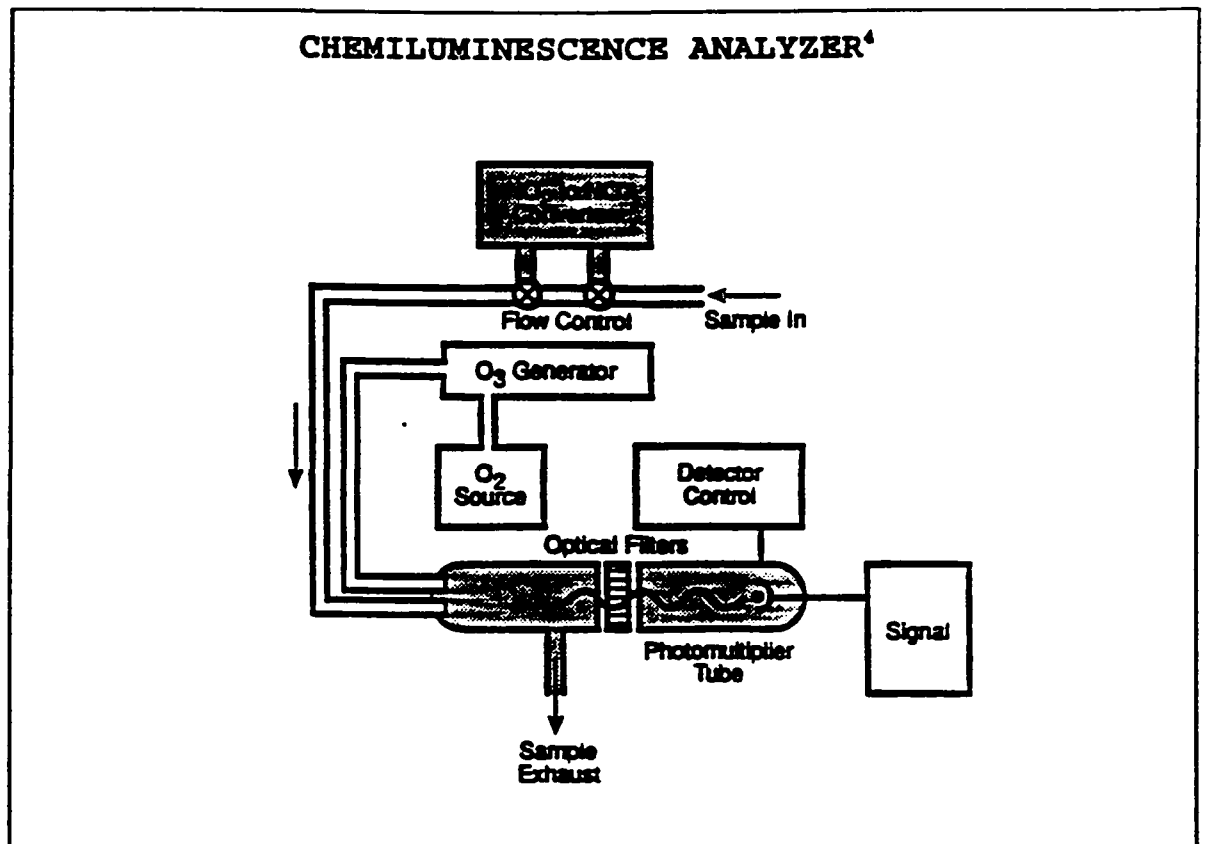
Light is emitted by the chemiluminescent reaction which occurs when nitric oxide molecules react with ozone. An ozone generator uses oxygen to make ozone, which is then mixed with nitric oxide in a reaction chamber. If adequate ozone is available, the light given off will be proportional to the concentration of nitric oxide. Chemiluminescence analyzers typically use a photomultiplier tube to measure the light given off by the reaction.

In order for the instrument to measure nitrogen dioxide, a catalytic reduction of nitrogen dioxide to nitric oxide is first required. One molecule of nitric oxide is produced for each molecule of nitrogen dioxide, so the light signal will be proportional to the total of nitrogen dioxide and nitric oxide in the original gas sample. The amount of nitrogen dioxide can be obtained by subtracting the results from runs with the catalytic converter operational from those with it not operational.

An NO_2 to NO converter efficiency test is generally established by injecting a known concentration of NO_2 into the supply line. These tests are typically run for 30 minutes to determine any degradation in the ozone driven NO_2 to NO conversion process.
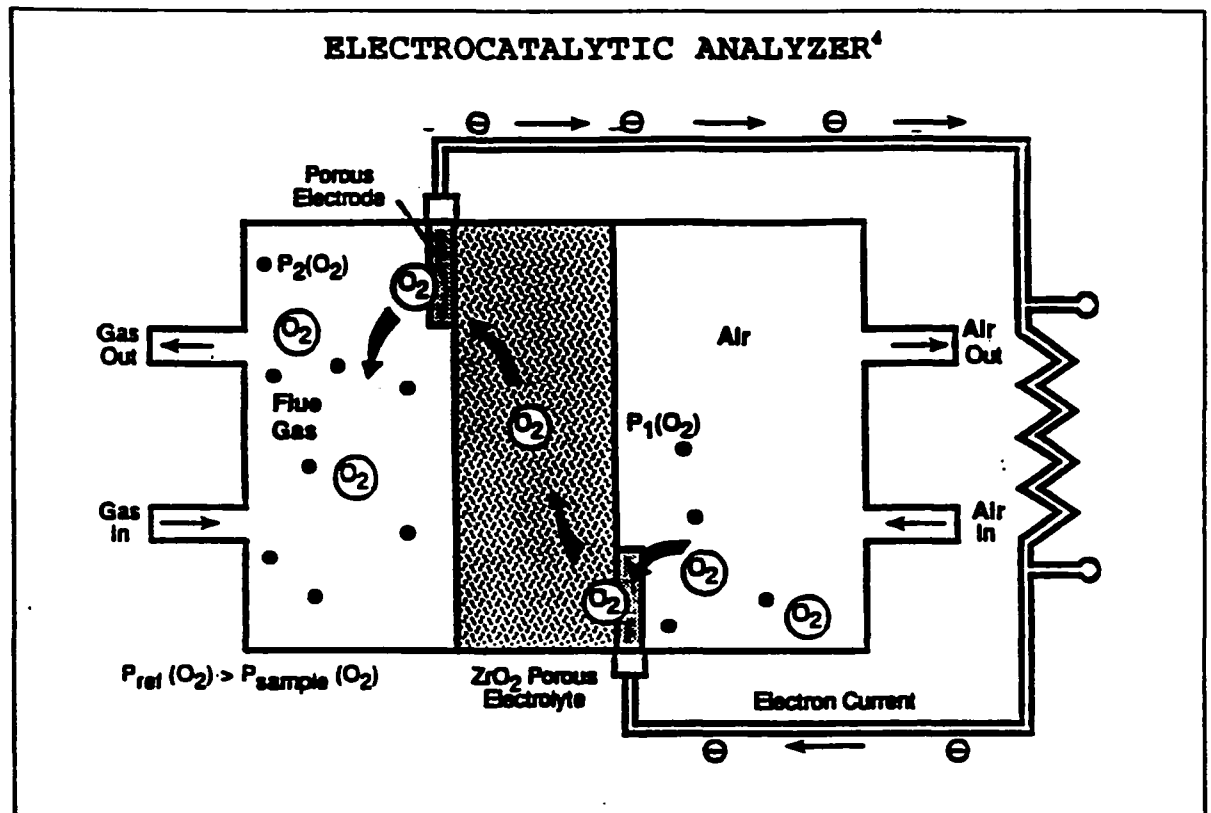
Electrocatalytic analyzers are widely used for in-situ measurements of the concentration of oxygen in a flue gas stream.

The electrocatalytic analyzer operates as a high temperature fuel cell, producing an electrical current which is related to the oxygen concentration.

The basis of the process occurs in a special porous ceramic material made of zirconium oxide. When it is heated to around 1,550 °F, the unit will catalytically produce oxygen ions.[5] Oxygen ions are oxygen atoms which have absorbed an electron.

Air is supplied to one side of the ceramic and flue gas to the other. Oxygen atoms in the air will diffuse through the ceramic material because of the difference in oxygen concentration between the flue gas sample and ambient air. In the above slide the flue gas sample is on the left and ambient air is on the right. Upon arriving at the electrode on the flue-gas side of the cell, the oxygen ions give up their electrons to an electrode.

The resulting current is used for measuring oxygen concentrations. The current is proportional to the concentration difference between air and flue gas and is inversely proportional to the flue gas concentration.

```
┌─────────────────────────────────────────────────┐
│        GAS ANALYZER MAINTENANCE PROCEDURES       │
│                                                  │
│            Routine Calibration                   │
│                 Zero Gas or Filter               │
│                 Span Gas or Filter               │
│            Delivery System Bias Checks           │
│                 Probe Blockage                   │
│                 Probe Leaks                      │
│            Electrical Circuit Problems           │
│                 Component Replacement            │
└─────────────────────────────────────────────────┘
```

The maintenance of CEMS includes routine calibration. Calibration of the individual instruments can be achieved through the use of standard calibrated optical filters or through the use of zero and span gases, depending upon the design of the instrument.[5] Span gases must be analyzed periodically to assure their validity.[6]

The calibration procedure for each instrument is dependent upon its design. Generally, an extraction CEMS must be zeroed and spanned using special bottled gases of known concentrations. Nitrogen is normally selected as a zero gas, and it must be free of moisture and oil. Span gases are selected to cover the concentration ranges for the instruments being calibrated. They should have a reasonable shelf life without undergoing changes in concentration. CEMS are normally zeroed and spanned at least once a day, with some units performing the function automatically.

The blockage of gas sampling probes and lines can be a serious problem, particularly if the flue gas contains significant fly ash or hydrated lime (e.g., from dry scrubber) concentrations. Filters which are used to remove particulates must be cleaned or replaced routinely. If the temperature of the moisture trap is not properly regulated, the condensate may freeze, forming a blockage of the sampling stream.

Other problems related to the condensation of moisture and acid gases can occur. These liquids can absorb gases and cause chemical reactions which lead to scale build-up and corrosion.

Leakage of gases into tubes transporting collected samples to analyzers can occur if the pipe joints are not properly sealed. Vibration and thermal expansion can cause leakage to occur. Because the sample line is generally below atmospheric pressure, leakage will be into the sampling line. Such leakage will result in sample dilution and gas concentration readings which are too low.

Operating instruments under excessive temperature and vibration conditions can be a particularly difficult problem for the optical and electronic components. Because such problems may be more severe for in-situ instruments, special design considerations are required.
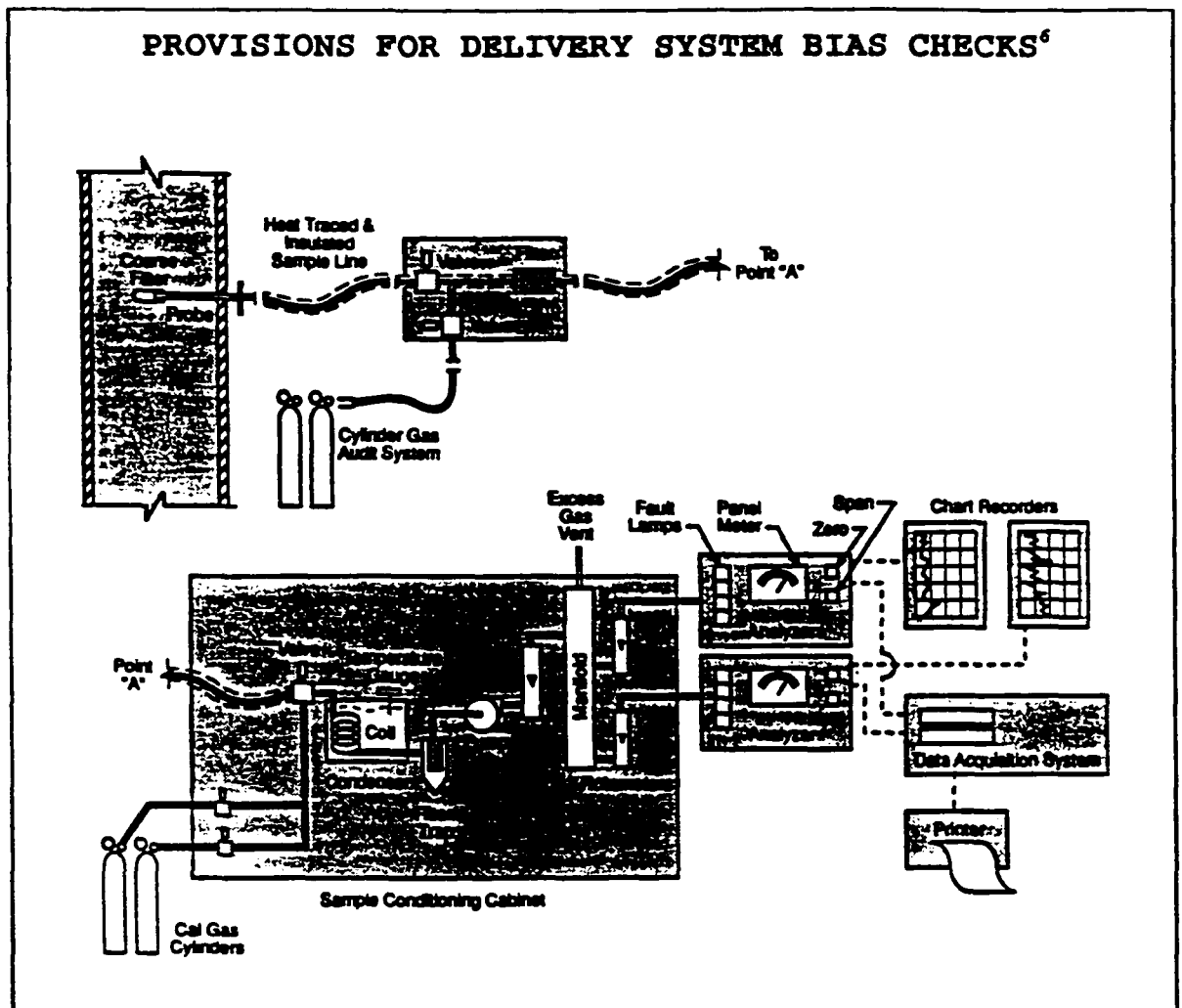
From John Richards, "Municipal Waste Incinerator Air Pollution Control Inspection Course," Submitted to U. S. Environmental Protection Agency by Entropy Environmentalists, Inc., June 1991, printed with permission.

A delivery system bias check is routinely performed to confirm that changes have not occurred as a result of the gases flowing through the conditioning and delivery system. A continuous flow of "span gas" is inserted into the delivery system as close as possible to the entrance probe. The instrument is then operated for a continuous time period to determine if the instrument readings change.

An instrumentation preventive maintenance program can make use of the bias check records. This should help prevent unplanned instrument outages, which under some regulations could be considered the same as an emissions violation.

A number of new instrumentation initiatives are currently under development. One includes the possibility of making site-specific correlation tests between CEMS opacity readings and various emissions which are difficult to measure. If such correlations are sufficiently valid, the opacity monitor could provide important indications of unit operations.

REFERENCES

1. Title 40--Protection of Environment, Code of Federal Regulations Part 60, Subpart Ea, "Standards of Performance for Municipal Waste Combustors," Office of the Federal Register, National Archives and Records Administration, Washington, DC, pp. 325-328, July 1, 1991.

2. Title 40--Protection of Environment, Code of Federal Regulations Part 60, Appendix B, "Performance Specifications," Office of the Federal Register, National Archives and Records Administration, Washington, DC, pp. 1099-1128, July 1, 1991.

3. J. A. Moore, "Key Measurements in Power Plants," Standard Handbook of Power Plant Engineering, Thomas C. Elliott, editor, McGraw Hill Book Co., NY, 1989, p. 6-61.

4. James Jahnke and G. J. Aldina, Handbook, Continuous Air Pollution Source Monitoring Systems, Technology Transfer, EPA 625/6-79-005, June 1979.

5. Robert Holloway, W. S. Lanier, and S. B. Robinson, "Alternative Approaches to Real-Time Continuous Measurement for Combustion Efficiency of Hazardous Waste Incinerators," Contract 68-03-3365, Work Assignment 03 Report to U. S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Submitted by Energy and Environmental Research Corporation, March 25, 1987.

6. John Richards, "Municipal Waste Incinerator Air Pollution Control Inspection Course," Submitted to U. S. Environmental Protection Agency, June 1991.

15. AIR POLLUTION I: INTRODUCTION

Slide 15-1

```
COMBUSTION SOURCE AIR POLLUTANTS

Fuel Dependent
Combustion Quality Dependent
APCD Temperature Dependent
```

There are a number of different types of air pollutants which are emitted from combustion sources. In general, their formation is dependent upon the composition of the fuel, combustion quality, and temperature of the flue gas as it enters the particulate collection device.

Slide 15-2

```
FUEL DEPENDENT AIR POLLUTANTS

Acid Gases
    Sulfur Oxides
    Hydrogen Chloride
    Nitrogen Oxides (Fuel NOx)
Metals (Heavy Metals)
    Lead
    Cadmium
    Mercury
Carbon Dioxide
```

Fuel dependent air pollutant emissions generally can be controlled by either changing the fuel mixture before combustion or by removing the contaminant from the flue gas after combustion. For instance, chemically bound nitrogen (fuel nitrogen) in MSW produces undesirable emissions of NOx. These emissions will be reduced if yard wastes (which are high in nitrogen content) are removed from the MSW before combustion. Stack gas cleaning also is an important emission control option.

MSW typically contains modest amounts of sulfur, chlorine, fluorine, and other halogen elements. During combustion, these elements will form acid gases. Acid gases create emission problems and tend to cause fire-side corrosion of the metal heat exchanger surfaces. Acid gas emissions from large MWC units are limited through requiring the best demonstrated control technology. Allowable emission limits are considerably below those levels allowable in conventional fuel fired power plants.

MSW contains trace concentrations of heavy metals such as cadmium, lead, and mercury. Upon being heated during combustion, mercury will tend to vaporize and react to form oxides or chlorides. Other metals will vaporize, react or remain unchanged in the solid residue. By cooling flue gases adequately, many of the metal vapors and compounds will condense on the fly ash and be removed by the APCD.

Carbon dioxide is not generally considered to be an air pollutant. It is a naturally occurring compound which participates in the carbon cycle of organic growth and decay. However, atmospheric carbon dioxide does act as a greenhouse gas. Carbon dioxide gas is transparent to solar energy but opaque to the long wavelength infrared energy emitted from the earth to the sky. Therefore, it may effectively trap radiant energy in the earth's atmosphere and create global warming.

Global warming issues relate to the potential effect of increased atmospheric temperatures on weather, and in particular on polar ice melting, reduced rainfall, and increased cloud cover. There is general agreement that carbon dioxide emissions have increased as a result of the combustion of fossil fuels. The reduction or redistribution of rainfall could cause major agricultural problems.

MSW is generally considered to be a renewable energy source since it is primarily composed of both organic and waste materials. MSW buried in landfills will eventually decay and produce methane and carbon dioxide. Therefore, energy recovery from MSW can help to both conserve fossil fuels and reduce the emission of the methane, which is an important greenhouse gas.

Slide 15-3

```
COMBUSTION DEPENDENT AIR POLLUTANTS

Products of Incomplete Combustion (PIC)
      Smoke
      Particulates
      Carbon Monoxide
      Volatile Organic Hydrocarbons
      MWC Organics
            Dioxins & Furans
Nitrogen Oxides
```

A number of air pollutants can be formed from incomplete combustion of organic materials. Carbon monoxide, volatile organic hydrocarbons, MWC organics (including dioxins & furans) and nitrogen oxides will be discussed in subsequent learning units.

Smoke is composed of small particulates which have the effect of obscuring the transmission of light (increasing opacity). The particles, which include solid and condensed liquid materials, actually cause the opacity by scattering light.

```
SMOKE & PARTICULATES

Black Smoke
    Carbon in Particulates

Particulates
    Removed by APCDs

White Smoke
    Condensed Hydrocarbon Gases
    Ammonium Chloride
    Water Droplets (Not Smoke)

Blue Smoke
    Ammonium Sulfate

Brown Smoke
    Nitrogen Oxides
```

Black smoke is flue gas which contains unburned carbon particles. Although the major constituents of the particulate are inorganic materials, the unburned carbon and carbonaceous materials are responsible for the black color. Improving the combustion conditions will generally reduce the smoke emissions.

Particulate emissions are controlled by APCDs, as will be discussed in Learning Unit 19. The very small particulates are the most difficult to collect and are of most concern because they are able to pass into the lungs of humans and become trapped there.

White smoke can be formed by the condensation of unburned hydrocarbon gases. It can also result from the reaction of ammonia with HCl in the flue gas, which forms ammonium chloride. Vapors often are condensed when cooled by the air, forming small droplets which scatter light very well. Such smoke is visually detached from the stack because a period of cooling is required for droplet formation.

Condensed water vapor, such as the emission from a scrubber stack, has the appearance of white smoke. Such droplets will tend to re-vaporize after a fairly short period of time in the atmosphere, unless the ambient relative humidity is very high.

Blue smoke can result from reactions of sulfur oxides with the ammonia or urea used for NOx control. The reaction produces gaseous ammonium sulfate which will condense in the atmosphere, so this smoke will appear as a detached plume.

Brown smoke can be caused by NOx emissions and/or particulates. Formation and control of NOx emissions will be discussed in Learning Units 17 and 21.

Slide 15-5

```
┌─────────────────────────────────────────────────────────┐
│         APCD  TEMPERATURE  DEPENDENT  AIR  POLLUTANTS    │
│                                                         │
│             MWC Organics (Dioxins/Furans)               │
│             Metal Vapors (Mercury)                      │
└─────────────────────────────────────────────────────────┘
```

The temperature of the flue gas as it enters the particulate collection device is very important.[2] Fly ash collected in APCDs has been found to act catalytically in the formation of dioxins and furans. These reactions are temperature dependent, so that cooling the gas before it enters the APCD will limit dioxin and furan formation.

Mercury vapor and other heavy metal vapors in the flue gas will condense or be adsorbed onto the surfaces of particulates as the gas cools. A fabric filter can act as a sieve to remove such condensate materials. The APCD temperatures are generally maintained above the dew point to avoid acid gas condensation problems.

Slide 15-6

```
┌─────────────────────────────────────────────────────────┐
│     GAS  CONCENTRATIONS:   MOLECULAR  FRACTIONS          │
│                            MOLE  FRACTIONS               │
└─────────────────────────────────────────────────────────┘
```

In Learning Unit 5, we considered complete combustion under stoichiometric and excess air conditions. We now wish to consider gas concentrations, which may be fractions of total molecules or mole fractions. The balanced chemical reaction equation can be used to obtain ideal gas concentrations. A mole fraction for a gas can be obtained by dividing the moles of the gas by the total moles in the mixture.

Slide 15-7

IDEALIZED (STOICHIOMETRIC, COMPLETE) COMBUSTION OF MSW

$$C_{1.85}H_{5.4}O_{2.08}N_{.02}Cl_{.006}S_{.006} + 1.22\ H_2O + 2.165\ O_2 + 8.14\ N_2 \longrightarrow$$

$$1.85\ CO_2 + 3.92\ H_2O + 8.15\ N_2 + 0.006\ HCl + 0.006\ SO_2$$
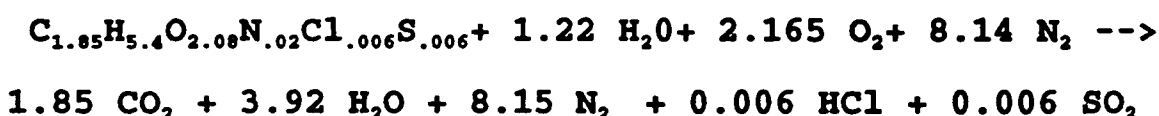
Product Gas	Wet Gas Moles	Dry Gas Moles	Dry Gas Mole %
CO_2	1.85	1.85	18.48
H_2O	3.92		
N_2	8.15	8.15	81.4
HCl	0.006	0.006	0.06
SO_2	0.006	0.006	0.06
Total	13.932	10.012	100.00

A complete combustion reaction equation for burning MSW under stoichiometric air conditions was presented in Slide 5-24.

The product gases for this idealized condition are composed of 1.85 moles of CO_2, 3.92 moles of water vapor, 8.15 moles of N_2, 0.006 moles of SO_2, and 0.006 moles of HCl. If the water vapor is neglected, the product gas analysis can be performed on a dry basis. Therefore, there will be 10.012 moles of dry gas.

Slide 15-8

```
EQUIVALENCE OF GAS CONCENTRATIONS

Mole Fraction X 100 --> Percentage
Mole Fraction X 1,000,000 --> ppm
Percentage X 10,000 --> ppm
```

Mole fractions are volume fractions. Such concentrations can be converted to either mole percentages or parts-per-million (ppm or ppmv) by the simple mathematics of moving the decimal point.

Literally, a percentage is a part-per-hundred, whereas a part-per-million (ppm) is defined with one million in the denominator instead of one hundred. A mole fraction can be converted to a ppm basis by moving the decimal six places to the right.

Conversions from a percentage to a ppm basis involve four orders of magnitude or moving the decimal four places to the right. Correspondingly, the 1 ppm is equivalent to 0.0001 percent, with the decimal going four places to the left.

Using the previous example of stoichiometric combustion of MSW, the dry gas mole fraction of CO_2 is 1.85/10.012 = 0.185, which can be expressed as 18.5 percent. The mole fraction of both HCl and SO_2 in the dry product gases are 0.006/10.012 = 0.0006, which can also be expressed as 0.06 percent or 600 parts-per-million (ppm).

Slide 15-9

```
GAS CONCENTRATIONS AT STANDARD DILUTION

Example:   CO Concentration Limit

           50 ppm at 7% O₂  on a
                    Dry Gas Basis
```

Gas concentration limits are expressed at standard dilutions in order to prevent the dilution from being a method for meeting the concentration requirements.

Emission standards used over the years have been referenced to different dilution bases. For instance, both 12% CO_2 and 50% excess air have been widely used. The early nitrogen oxide data for coal and oil combustion was often presented with 3% O_2 as the basis. The NSPS for MWC units uses 7% O_2 as its basis, with alternative provisions for making corrections to a 12 CO_2 basis.

Slide 15-10

```
EQUATION FOR CONVERTING TO 7% OXYGEN²

Assume CO_m  is the Measured Dry Gas CO
             Expressed as a ppm or %
        O_2m  is the Measured Dry Gas O_2
             Expressed as a Percentage

CO (@ 7% O_2 ) = CO_m x (21 - 7)/(21 - O_2m)

             = CO_m x (14)/(21 - O_2m)
```

As indicated in the slide, gas concentrations can be corrected to 7% oxygen by multiplying the measured concentration by (21 - 7) and dividing by (21 - O_{2m}). The variables with a subscript "m" are the measured dry gas concentrations. If the available data is obtained from in situ instruments, the values will be on a wet basis. Corrections to a dry basis are made by dividing by (1.0 - moisture fraction).

The derivation of the above gas concentration conversion equation is based on theoretical gas mixture considerations, including the assumption that air is 21% oxygen on a volumetric basis.[2]

Slide 15-11

PRODUCT GAS ANALYSIS, METHANE @ 20% EA			
Gas	Wet Gas Moles	Dry Gas Moles	Dry Gas Mole %
CO_2	1.0	1.0	9.59
H_2O	2.0		
O_2	0.4	0.4	3.84
N_2	9.024	9.024	86.56
CO	0.001	0.001	0.01
Total	12.425	10.425	100.00

To illustrate corrections of concentrations from the measured values to a standard basis, let us consider the combustion of methane gas at 20% excess air as presented in Slide 5-29. Note that for illustrative purposes, 0.001 moles of CO have been arbitrarily added to the product gases.

The flue gas analysis is illustrated above, with the oxygen content in the dry gases being 0.4/10.425, 0.0384 or 3.84 percent on a dry gas basis. This is fairly typical of operating numbers for commercial and industrial gas-fired equipment.

Let us now consider the incomplete combustion indicated in the above gas analysis, with 100 ppm CO measured on a dry flue gas basis. Note that 100 ppm corresponds to a mole fraction of 0.0001 or 0.01 percent. Therefore, the mole fraction of CO is so small that it will not significantly change either the moles of oxygen or the total moles in the mixture.

Slide 15-12

CONVERSION OF GAS CONCENTRATIONS TO 7% OXYGEN

$$Let: \quad CO_m = 100 \ ppm$$
$$O_{2m} = 3.84\% \ (dry \ gas)$$

$$CO \ (@ \ 7\% \ O_2) = CO_m \times (21 - 7)/(21 - O_{2m})$$

$$= 100 \times (14)/(21 - 3.84)$$

$$= 81.6 \ ppm$$

The correction of the CO concentration to the standard dilution rate of 7% O_2 is a straightforward calculation. In the above example, the measured 100 ppm of carbon monoxide became 81.6 ppm when corrected to 7% oxygen.

Slide 15-13

CONVERSION OF PARTICULATES TO 7% OXYGEN

$$Let: \quad PM_m = 0.035 \ gr/dscf \ (Particulate \ Matter)$$
$$O_{2m} = 3.84\% \ (Measured \ Dry \ Gas \ O_2)$$

$$PM \ (@ \ 7\% \ O_2) = PM_m \times (21 - 7)/(21 - O_{2m})$$

$$= 0.035 \times (14)/(21 - 3.84)$$

$$= 0.0286 \ gr/dscf \ @ \ 7\% \ O_2$$

Particulate concentrations which are presented on a mass per unit volume basis can be corrected by the same equation as before. Particulate loadings are a case in point, regardless of whether they are measured in [gr/dscf] or [mg/dscm].

Slide 15-14

```
EQUATION FOR CONVERTING TO 12% CARBON DIOXIDE[2]

    Assume  CO_m    is the Measured Dry Gas CO
                    Expressed as a ppm or %
            CO_{2m} is the Measured Dry Gas CO_2
                    Expressed as a Percentage

    CO (@ 12% CO_2 ) = CO_m x (12/CO_{2m})
```

Gas concentrations (e.g., CO in the above slide) can also be corrected to 12% CO_2 by multiplying the measured concentration by the ratio of 12% divided by the measured percentage of CO_2. As before, the variables with a subscript "m" are the measured dry gas concentrations. If the gas concentration data were to be obtained using in situ instruments, the values will be on a wet basis, so that corrections to a dry basis would require dividing original concentrations by (1.0 - moisture fraction).

The derivation of the above conversion equation is based on theoretical mixture considerations, including the assumption that the percentage of CO is much less than the percentage of CO_2, which is valid for most combustion product gas samples.

The logic of the equation is consistent with the fact that if the measured CO_2 were less than 12%, the actual volume of mixture would be larger than that corresponding to 12% CO_2, so that the actual gas concentration would be less than the standard concentration. Therefore, the gas concentration is adjusted by multiplying by 12 divided by the measured percent of CO_2.

Slide 15-15

```
EXAMPLE CONVERSION TO 12% CARBON DIOXIDE

    Let:    CO_m    = 100 ppm
            CO_{2m} = 9.59% (dry gas)

    CO (@ 12% CO_2 ) = CO_m x (12/CO_{2m})

                     = 100 x (12/9.59)

                     = 125 ppm
```

Consider the previous example of incomplete combustion with 100 ppm CO (or 0.01 percent) measured on a dry flue gas basis. The correction of the CO concentration to the standard dilution of 12% CO_2 yields 125 ppm of carbon monoxide when corrected to 12% carbon dioxide.

Slide 15-16

```
CONVERSION OF [gr/dscf] TO [mg/dscm]

Basic Identities:

1 pound [lb]  = 7,000 grains [gr]
1 pound [lb]  = 453.6 grams [g]
1 gram [g]    = 1,000 milligrams [mg]
1 foot [ft]   = 0.3048 meters [m]

For Dry Gases at Standard Conditions:

1 dry standard cubic foot = 1 [dscf]
1 dry standard cubic meter = 1 [dscm]
1 cubic ft [dscf] = 0.0283 cubic meters [dscm]

So That:

1 [gr/dscf] =
     1 [gr/dscf] x (1 lb/7000 gr) x (454 g/lb)
     x (1000 mg/g) x (1 dscf/0.0283 dscm)

Therefore:    1 [gr/dscf] = 2,290 [mg/dscm]
```

Many of the current regulations are in System International (SI) Units. For example, the NSPS standard for MWC metals is given in terms of particulate matter measured in [mg/dscm]. Other particulate standards are expressed in [gr/dscf] units, where there are 7,000 grains in a pound. The abbreviation, dscf, refers to dry standard cubic foot, and dscm refers to dry standard cubic meter.

The factor for converting expressions in units of [gr/dscf] to units of [mg/dscm] is presented above. Conversion factors are developed using various identities and simple multiplication and division. The theoretical basis for conversion factors relates to the fact that the quantity obtained by dividing one side of an identity by the other can be treated as unity. For example, an expression can be multiplied by (1 lb/7000 gr) without changing its value.

Slide 15-17

```
EXAMPLE APPLICATION OF THE CONVERSION FACTOR

Factor:        1 [gr/dscf] = 2,290 [mg/dscm]

Given:         34 [mg/dscm]

Therefore:     34 [mg/dscm] =

34 [mg/dscm] x (1 [gr/dscf]/2,290 [mg/dscm]) =

               34 [mg/dscm] =  0.015 [gr/dscf]
```

The application of the conversion factor, 1 [gr/dscf] = 2,290 [mg/dscm], is demonstrated in the above slide. The given particulate concentration of 34 [mg/dscm] is shown to be equivalent to a concentration of 0.015 [gr/dscf].

Note also, if it were desired to convert a given quantity expressed in [gr/dscf] units into [mg/dscm] units, the quantity would need to be multiplied by (2,290 [mg/dscm]/1 [gr/dscf]).

Slide 15-18

```
EQUATION FOR COMBUSTION EFFICIENCY
(BASED ON CARBON COMBUSTION TO CO₂)

C.E.(%)  =   (100% x CO₂ₐ) / (CO₂ₐ + COₐ)

or

C.E.(%)  =   100% x (1 - (COₐ / (CO₂ₐ + COₐ))
```

Many state regulations require a minimum combustion efficiency to avoid a fine and mandatory shut-down. There are two equivalent forms of the combustion efficiency equation, both of which are illustrated in the above slide. The equations are often referred to as a carbon combustion efficiency, but they actually measure the carbon monoxide combustion efficiency.

```
+-----------------------------------------------------------+
|      EXAMPLE COMBUSTION EFFICIENCY CALCULATION            |
|                                                           |
|    Let   CO_{2m}  be   9.59 Percent                       |
|          CO_m     be   0.01 Percent (100 ppm)             |
|                                                           |
|    C.E.(%)  =   (100% x CO_{2m})/(CO_{2m} + CO_m)         |
|                                                           |
|             =   (100% x 9.59)/(9.59 + 0.01)              |
|                                                           |
|             =   99.9%                                     |
+-----------------------------------------------------------+
```

The above slide provides an example calculation of combustion efficiency. Note that carbon monoxide is generally measured as ppm and will require conversion to a percentage basis.

```
+-----------------------------------------------------------+
|            DETERMINATION OF EXCESS AIR[2]                 |
|               FROM DRY GAS ANALYSIS                       |
|                                                           |
|   Assume  CO_{2m} is the Percent Dry Gas CO_2            |
|           CO_m    is the Percent Dry Gas CO              |
|           O_{2m}  is the Percent Dry Gas O_2             |
|                                                           |
|   Therefore N_{2m} = 100 - (CO_{2m} + CO_m + O_{2m})     |
|                                                           |
|   And EA = (O_{2m} - 0.5 CO_m)/(.264 N_{2m} - O_{2m} + 0.5 CO_m) |
+-----------------------------------------------------------+
```

The average amount of excess air can be determined from a set of dry gas measurements for oxygen, carbon dioxide, and carbon monoxide. The procedure includes the assumption that the gas concentrations are expressed as a percentage and that sulfur oxides, nitrogen oxides, and hydrogen chlorine are small enough to be neglected. Therefore, the nitrogen in the dry product gas can be determined by subtracting each of the other percentages from 100 percent.

Next, the excess air expressed as a percentage can be found using the indicated equation, which is derived using theoretical considerations.[2] Note that CO_m is included in the above equations. However, when CO is expressed on a percentage basis, it generally has a trivial influence on the excess air calculation.
In the example of Slide 15-11, the CO value of 100 ppm corresponds to 0.01%, which is much smaller than the other values used in the equation.

EXAMPLE DETERMINING EXCESS AIR

$$\text{Let } CO_{2m} = 9.59\%$$
$$CO_m = 0.01\%$$
$$O_{2m} = 3.84\%$$

$$\text{Therefore } N_{2m} = 100 - (CO_{2m} + CO_m + O_{2m})$$

$$N_{2m} = 100 - (9.59 + 0.01 + 3.84) = 86.56$$

$$\text{And EA} = (O_{2m} - 0.5\, CO_m)/(.264\, N_{2m} - O_{2m} + 0.5\, CO_m)$$

$$EA = (3.84 - 0.005)/(.264 \times 86.56 - 3.84 + 0.005)$$

$$EA = 0.20 \longrightarrow 20\%$$

The basic excess air calculation process is illustrated using the previous example of methane gas combustion. The above calculation for excess air gives the value of 20 percent. We know that this calculation is correct, since our original numbers were based on 20% EA.

REFERENCES

1. P. J. Schindler and L. P. Nelson, "Municipal Waste Combustion Assessment: Technical Basis for Good Combustion Practice," U. S. Environmental Protection Agency, EPA-600/8-89-063, August 1989.

2. J. T. Beard, F. A. Iachetta, and L. U. Lilleleht, APTI Course 427, Combustion Evaluation, Student Manual, U. S. Environmental Protection Agency, EPA-450/2-80-063, February 1980, pp. 5-4 to 5-21.

16. AIR POLLUTION II: PRODUCTS OF INCOMPLETE COMBUSTION

Slide 16-1

```
PRODUCTS OF INCOMPLETE COMBUSTION (PICs)

Smoke & Particulate Matter
Carbon Monoxide
MWC Organics (Dioxins & Furans)
Volatile Organic Hydrocarbons
```

There are potentially a large number of chemical compounds which can be formed from incomplete combustion. Visual smoke emissions, as discussed in Learning Unit 15, are an indication of incomplete combustion.

The combustion conditions which lead to products of incomplete combustion were discussed in Learning Unit 9. These conditions include non-uniform and low temperature conditions, poor mixing of oxygen and volatile gases in the fuel-bed and the over-bed regions, inadequate air, and/or too much air which cools the gases.

Carbon monoxide is the most easily measured toxic product of incomplete combustion. Trace amounts of many organic compounds have been found in the flue gas of MWCs. These include both volatile organic hydrocarbons (VOHC) and semi-volatile hydrocarbons. Compounds of interest include chlorobenzenes, chlorophenols, polycyclic aromatic hydrocarbons (PAH), and polychlorinated biphenyls (PCBs).

Slide 16-2

```
SURROGATES FOR MWC ORGANIC EMISSIONS

Routine Operations:   Carbon Monoxide
Annual Stack Test:    Total Dioxins/Furans
```

The magnitude of carbon monoxide concentrations in the flue gas is an important indicator of combustion quality. In general, if carbon monoxide levels are high it has been demonstrated that the MWC organic emissions will be unacceptably high. The current regulatory trend is to limit carbon monoxide emissions as the surrogate for the MWC organic emissions during routine operations.

Considerable research has been performed to develop knowledge about the formation and control of trace organic emissions from incinerators.[1,2,3,4,5] Much of it has focused upon dioxins and furans, which are potentially carcinogenic materials.

Dioxins and furans are representative of the other organic compounds in that control techniques for dioxins/furans will also control the other organics. The total of the tetra- through octa- isomers of dioxin and furan emissions are used in federal regulations as the surrogate for MWC organics in annual stack tests.

Slide 16-3

```
DIOXINS/FURANS (CDD/CDF)

Dioxins (CDD)
    Polychlorinated Dibenzo-p-dioxins
Furans (CDF)
    Polychlorinated Dibenzofurans
```

Dioxin is the name given to polychlorinated dibenzo-p-dioxins (CDD), and furan is the name of polychlorinated dibenzofuran (CDF) compounds. Dioxins and furans are non-volatile, chlorinated organic compounds from the PAH group.

Slide 16-4

DIAGRAMS OF DIOXIN AND FURAN STRUCTURES[1]
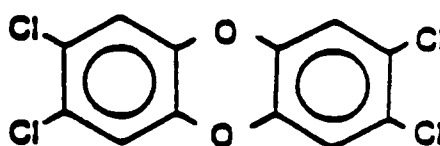
Example Dioxin
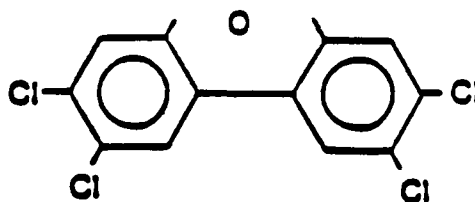
Example Furan

Dioxins and furans are a complex group of chemical compounds of carbon, hydrogen and chlorine. Chemists refer to both groups as "ring compounds." Dioxins and furans come in a variety of possible molecular configurations and have different toxicity features.

For instance, the number of chlorine atoms in the dioxin/furan group of molecules can vary from one to eight (with four each shown in the illustration). Total CDD/CDF are defined by the NSPS and EG as the total tetra- through octa-chlorinated dibenzo-p-dioxins and dibenzofurans. Such molecules will have from four to eight chlorine atoms.

In addition, the chlorine atoms can be attached at different positions, leading to different "isomers". The dioxin illustrated is the "2,3,7,8 isomer," which is the most toxic of all dioxins.

Slide 16-5

```
CONDITIONS WHICH CONTROL DIOXINS/FURANS

COMBUSTION ZONE
      Adequate Temperature & Mixing

FLY ASH COLLECTION DEVICE
      Low Temperature
```

There are two different regions where operating conditions determine the dioxin and furan emissions.[2] Reduced emissions will come from the combustion zone if the complete combustion conditions of adequate temperature and mixing are achieved. Additional formation of dioxins and furans can occur under relatively high temperatures in particulate collection devices (ESPs, fabric filters).

Slide 16-6

```
FORMATION OF MWC ORGANICS

COMBUSTION ZONE
      Relatively Low Combustion Temperatures
      Poor Mixing - Pockets of Rich Mixtures
      High Particulate Loadings
            Operating Above Unit Capacity
```

A considerable fraction of the dioxin/furan emissions are related to the incomplete combustion in the combustion zone.[3] Low temperatures and inadequate mixing can lead to high dioxin and furan emissions. Poor mixing can result in pockets of fuel rich mixtures which do not get the oxygen required for complete combustion until after they leave the combustion chamber.

Some chlorinated compounds undergo partial combustion reactions. For example, the incomplete combustion of complex chlorophenol and PCB molecules can lead to the formation of dioxins and furans. Another process is the burning of organic material in the presence of chlorine compounds. For instance, vegetable matter, wood, and lignite coal can form dioxins and furans when burned in the presence of chlorinated compounds, such as hydrogen chloride.[3]

High particulate loading is associated with high velocity particle entrainment in the fuel bed and combustion chamber. When a unit is operated above its rated capacity, higher gas velocities and poor mixing generally occur. Under such conditions, the solids have less residence time in the combustion zone, leading to their cooling before the combustion process is completed. Under such conditions, one would expect increased carbon content in the fly ash, as well as increased dioxin/furan emissions.

Slide 16-7

```
FORMATION OF MWC ORGANICS

APCD: ESP or Fabric Filter
      Catalytic Formation on Fly Ash
      High Operating Temperatures (450° F)
      Low Carbon Loadings in Stack Gas
          More Dioxin/Furan Emissions
          Less Retained in Collected Fly Ash
```

Another way in which dioxins and furans are formed is through catalytic reactions downstream of the combustor. These reactions occur on the surface of fly ash. Fly ash is composed of many inorganic and metal materials (e.g., copper) which are known to act as catalysts.

Some dioxins and furans can be formed on the surface of fly ash when it is held for a relatively long time at a high enough operating temperature in the ESP and/or fabric filter. Considerable increases have been measured[5] when the operating temperatures are increased from around 350° to 600°F.

Therefore, regulations limit the APCD inlet temperature to a small amount higher (30°F) than was present during the most recent successful annual stack test[6,7]. One operating constraint in selecting the APCD operating temperature is that it should be above the acid gas dew point to avoid condensation and corrosion problems.

There is a partitioning of dioxin and furan emissions between that which is emitted up the stack and that which is retained in the collected ash. As the carbon loading goes down, it appears that more of the dioxin/furan is emitted in the stack gas, whereas when carbon loadings go up, more is retained on the collected fly ash.

Slide 16-8

```
ANNUAL TEST FOR DIOXINS/FURANS

       Stack Test:   EPA Method 23
       Total Dioxins/Furans
                   Gaseous & Solid
```

Although dioxins and furans are non-volatile, they may be emitted in either a gaseous form or as absorbed onto solid surfaces, such as fly ash. The amount of each isomer can be obtained by a standard stack test, using EPA Method 23. Under the NSPS method, the total MWC organics are determined by adding the mass of all the tetra- through octa- isomers of dioxins and furans.

Slide 16-9

```
REGULATORY BASIS FOR EMISSIONS LIMITS

NSPS:   Total Mass of All Dioxins and Furans

Some States:   Toxic Equivalent Limitation
        Determine Mass of Each Isomer
        Toxicity Level Assigned to Each Isomer
        Multiply Masses by Levels to Obtain Total
```

Some states use a toxic equivalent limitation instead of the total mass of dioxins/furans. In the toxic equivalency method, a toxicity value is assigned to each isomer. The overall toxic equivalent is determined by summing the products of the mass fraction of each isomer times its toxicity value.

REFERENCES

1. "Municipal Waste Combustion Study, Report to Congress," U.S. Environmental Protection Agency, EPA-530-SW-87-021-a, June 1987, pp. 42-61.

2. J. D. Kilgroe, W. S. Lanier, and T. R. Von Alten, "Montgomery County South Incinerator Test Project: Formation, Emission and Control of Organic Pollutants," presented to Second International Conference on Municipal Waste Combustion, Tampa, Florida, April 16-19, 1991.

3. W. R. Seeker, W. S. Lanier, and M. P. Heap, "Municipal Waste Combustion Study, Combustion Control of Organic Emissions," U.S. Environmental Protection Agency, EPA-530-SW-87-021-c, June 1987, pp. 4-1 to 4-8.

4. "National Incinerator Testing and Evaluation Program, Mass Burning Technology, Quebec City," Volume II, Main Report, Prepared by Lavalin Inc., for Environment Canada, Conservation and Protection, December 1987, pp. 79-287.

5. H. Vogg, J. Metzger, and L. Stieglitz, "Recent Findings on the Formation and Decomposition of PCDD/PCDF in Solid Municipal Waste Incineration," Proceedings of Emissions of Trace Organics From Municipal Waste Incinerators, Specialized Seminar, Part 1, Sec. 2, Copenhagen, January 1987.

6. U. S. Environmental Protection Agency, "Standards of Performance for New Stationary Sources; Municipal Waste Combustors," Federal Register, Vol. 56, No. 28. February 11, 1991, pp. 5488-5514.

7. U. S. Environmental Protection Agency, "Emission Guidelines; Municipal Waste Combustors," Federal Register, Vol. 56, No. 28. February 11, 1991, pp. 5514-5527.

17. AIR POLLUTION III: NITROGEN OXIDES

Slide 17-1

```
┌─────────────────────────────────────────────────┐
│          SOURCES OF NITROGEN OXIDES             │
│                                                  │
│       Mobile Combustion Sources                 │
│            Automobiles, Trucks                  │
│       Stationary Combustion Sources             │
│            Power Plants, Heaters                │
│       Natural Combustion Sources                │
│            Forest Fires, Volcanos               │
│       Non-Combustion Sources                    │
│            Nitric Acid Manufacturing            │
└─────────────────────────────────────────────────┘
```

Nitrogen oxides are emitted from almost all combustion sources, including stationary sources such as power plants, mobile sources such as automobiles, and natural sources such as forest fires. Non-combustion sources include those associated with the manufacture and use of nitric acid.

Slide 17-2

```
┌─────────────────────────────────────────────────┐
│          NITROGEN OXIDES                        │
│                                                  │
│       Nitric Oxide (NO)                         │
│       Nitrogen Dioxide (NO₂)                    │
│       Nitrous Oxide (N₂O)                       │
│       Nitrogen Trioxide (N₂O₃)                  │
│       Nitrogen Pentoxide (N₂O₅)                 │
└─────────────────────────────────────────────────┘
```

There are a number of different oxides of nitrogen listed above. Nitrogen oxides are essential to the nitrogen cycle in nature. Nitrogen dioxide (NO_2) can be converted to nitric acid in the atmosphere, which under normal circumstances reacts to form nitrates which return to the earth as either dry deposition or precipitation (rain and snow). Nitrates are an important natural fertilizer for organic growth.

For regulatory purposes, nitrogen oxides (NOx) are composed of nitric oxide (NO) and nitrogen dioxide (NO_2), the two major combustion related oxides of nitrogen. NO is the dominant molecular form produced during combustion. It undergoes slow oxidation to NO_2, with most of the conversion occurring in atmospheric air. As described in Learning Unit 14, NOx emission measuring instruments have provisions for measuring NO and NO_2.

Nitrous oxide is commonly known as laughing gas. It is a greenhouse gas which reacts in the upper atmosphere (stratosphere) to form nitric oxide which subsequently depletes ozone.[1]   Nitrous oxide is generally not included as part of NOx, because conventional NOx instruments do not measure it.

Nitrogen trioxide and nitrogen pentoxide are found in very small, trace quantities.

Slide 17-3

```
ENVIRONMENTAL CONCERNS ABOUT NOx

Acid Rain
     Damage to Structures
     Damage to Water Quality & Fish Life
     Sudden Release of Acids

Photochemical Smog
     Impairs Human Health, Respiration
     Stunts Growth of Vegetation
     Oxidizes Materials
```

A significant fraction of the NOx emitted from stationary combustion sources can result in either the formation of acid rain and/or photochemical smog.

Environmental concerns about acid rain can relate to the damage done to structures, plants and fish-life both near and far from the acid's emission sources. The problems are worsened by the sudden release of acid materials, such as occurs during the melting of accumulated snow. The first rain after a drought generally is much more acidic than normal due to the scrubbing action of rain water on the atmosphere.

Photochemical smog is the brownish colored air, first identified in the 1940s in the Los Angeles air basin. Sunlight causes the dissociation of nitrogen dioxide, which leads to a series of chemical reactions with hydrocarbons and other gases. Photochemical smog is often trapped by an atmospheric inversion,[2] which prevents its dilution with fresh air. Smog is particularly observable by looking through the horizontal layers of such stratified air.

The high oxidant levels associated with smog can impair human health, particularly for those individuals with respiratory diseases. Other measurable effects of smog are the stunting of growth of vegetation, the discoloration of fabrics, the cracking of rubber, the deterioration of concrete structures, and the corrosion of metals.

Slide 17-4

```
GENERALIZED PHOTOCHEMICAL REACTION EQUATIONS²

NO₂ + Solar Energy ---> NO + O
O +  O₂ ---> O₃
O₃ + NO ---> NO₂ + O₂
O + CₓHᵧ ---> Stable Products + Radicals
O₃ + CₓHᵧ ---> Stable Products + Radicals
Radicals + CₓHᵧ ---> Stable Products + Radicals
Radicals + NO ---> Radicals + NO₂
Radicals + NO₂ ---> Stable Products
Radicals + Radicals ---> Stable Products
```
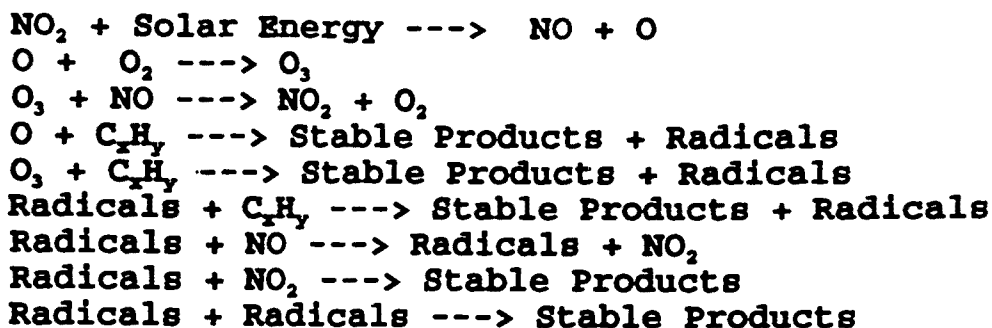
The formation of photochemical smog in atmospheric air is associated with the special ability of NO_2 molecules to absorb ultraviolet solar energy which causes the molecule to dissociate to NO and atomic oxygen (O). These atoms of oxygen are very unstable, reacting readily with almost any molecule with which they collide. This reactivity is characterized by high oxidant levels which cause environmental concerns.

Photochemical smog formation is a transient process which varies with sunlight, atmospheric mixing conditions, and the emissions of NOx, hydrocarbons and other products of combustion.

Slide 17-5

```
FORMATION OF NOx - CONVENTIONAL POWER PLANTS

    FUEL NOx
        Combustion of Chemically-Bound
            Nitrogen in the Fuel with Oxygen

    THERMAL NOx
        High Temperature Reaction of
            Oxygen and Nitrogen from Air
```

Depending upon the combustion conditions, NOx can be produced by either the oxidation of the nitrogen in the fuel or the high temperature "thermal fixation" of molecular nitrogen from air.[3]

Fuel NOx designates the NO formed by oxidation of the chemically-bounded nitrogen in the fuel. During the devolatilization process, most of the fuel nitrogen will be released as N_2, HCN, NO and NH_3, with a modest fraction remaining with the char.[4] The stoichiometric and mixing conditions will determine the fractions of the HCN and NH_3 which is oxidized to NO. Conversions of fuel nitrogen to NO range from around 5% at starved-air conditions to 50% under well-mixed conditions.

Thermal NOx designates the NO formed through the mechanism of high temperature oxidation of nitrogen from the air. A fuel with a low fraction of chemically-bound nitrogen, such as natural gas, forms mainly thermal NOx. Most MWC designs have much lower peak combustion temperatures than conventional fossil fuel units. Therefore, very little thermal NOx is formed by MWC units.

As will be discussed in Learning Unit 21, in addition to flue gas treatment, the applicable combustion modification techniques for NOx control depend upon the mechanism of formation. Controlling stoichiometric conditions, which limits the formation of fuel NOx, will be effective in MWCs. By contrast, thermal NOx techniques which reduce peak gas temperatures are not expected to be effective.

Slide 17-6

IMPACT OF TEMPERATURE AND FUEL NITROGEN ON NOx EMISSIONS[4]
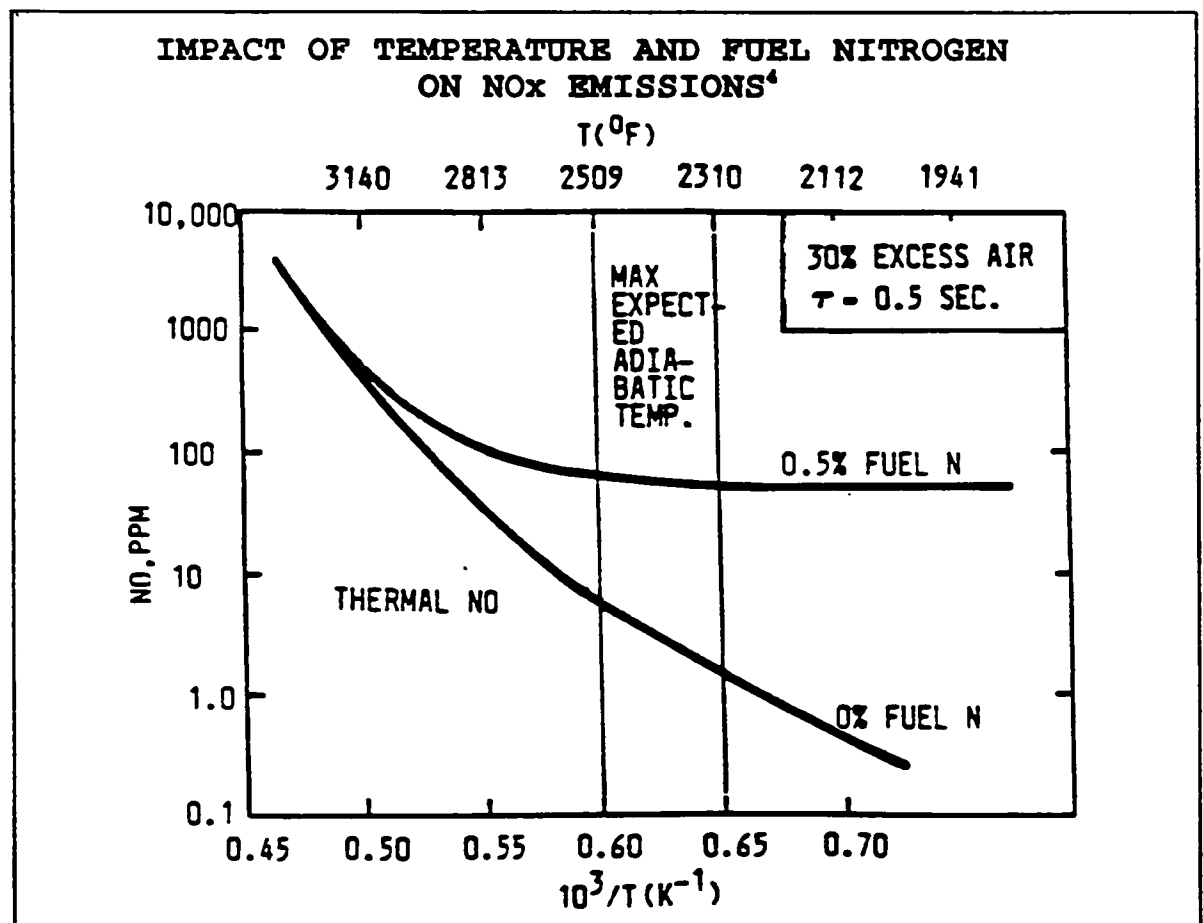
Theoretical studies have demonstrated that most of the NO formed from burning MSW is fuel NOx.

In the case illustrated above, a mixture of MSW volatiles is burned with 30% excess air in a combustion chamber with a half second residence time. When the MSW does not contain nitrogen, the illustration shows that NO formation is strongly dependent upon temperature, but is very small (<10 ppm) in the 2,300 - 2,500°F peak operating temperature range of MWC units.

17-4

By contrast, when the fuel contains 0.5% fuel-bound nitrogen, the NO theoretical concentrations are in the range of 100 ppm, a value which has the same order of magnitude as the typical NO measurements at MWC units. Note also, in this MWC operating range the NO formation is almost independent of temperature.

Slide 17-7

```
┌─────────────────────────────────────────────────────────────────────┐
│        IDEALIZED REACTION EQUATION FOR MSW TO PRODUCE                 │
│              MAXIMUM FUEL NOx WITH 50% EXCESS AIR                     │
│                                                                       │
│                                                                       │
│ C₁.₈₅H₅.₄O₂.₀₈N.₀₂Cl.₀₀₆S.₀₀₆ + 1.22 H₂O + 1.5a O₂ + 5.64a N₂ -->   │
│                                                                       │
│    b CO₂ + c H₂O + d N₂ + e HCl + f SO₂ + g NO +.5 a O₂              │
└─────────────────────────────────────────────────────────────────────┘
```

$$C_{1.85}H_{5.4}O_{2.08}N_{.02}Cl_{.006}S_{.006} + 1.22\ H_2O + 1.5a\ O_2 + 5.64a\ N_2 \longrightarrow$$
$$b\ CO_2 + c\ H_2O + d\ N_2 + e\ HCl + f\ SO_2 + g\ NO + .5\ a\ O_2$$
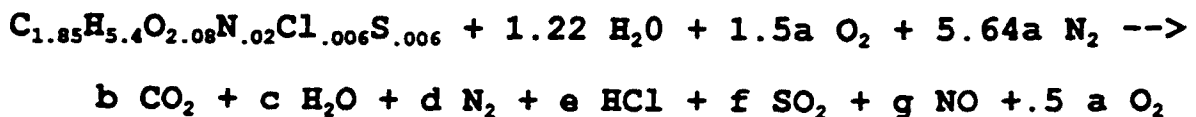
This analysis assumes that all the fuel nitrogen goes to NO and that the excess air level is 50%. Also, we assume that all the Cl goes to HCl.

The influence of the 50% excess air assumption is illustrated above with 1.5(a) moles of oxygen and 5.64(a) or 1.5 x 3.76(a) moles of nitrogen in the combustion air. Likewise, the excess 0.5(a) moles of oxygen appear on the product side of the equation.

Slide 17-8

```
┌─────────────────────────────────────────────────────────────────────┐
│   CONSERVATION EQUATIONS                                             │
│                                                                       │
│   Carbon:      1.85 = b                                              │
│   Hydrogen:    5.4 + 2(1.22) = 2c + e                                │
│   Oxygen:      2.08 + 1.22 + 3a = 2b + c + 2f + g + a                │
│   Sulfur:      0.006 = f                                             │
│   Chlorine:    0.006 = e                                             │
│   Fuel N:      0.02  = g                                             │
│   Air N:       5.64(2a) = 2d                                         │
└─────────────────────────────────────────────────────────────────────┘
```

The respective equations for the conservation of the atoms for each element are presented above. Note that all the fuel nitrogen goes to make g moles of NO, and that the nitrogen in the air simply passes through unchanged.

Slide 17-9

```
┌─────────────────────────────────────────────────┐
│   SOLUTION OF CONSERVATION EQUATIONS:            │
│                                                  │
│   a=2.175;   b=1.85;   c=3.92;   d=12.26         │
│   e=0.006;   f=0.006;  g=0.02                    │
└─────────────────────────────────────────────────┘
```

The corresponding solution of the equations is illustrated above.

Slide 17-10

IDEALIZED COMBUSTION OF MSW TO PRODUCE MAXIMUM FUEL NOx WITH 50% EXCESS AIR

$$C_{1.85}H_{5.4}O_{2.08}N_{.02}Cl_{.006}S_{.006} + 1.22\ H_2O + 3.262\ O_2$$

$$+\ 12.26\ N_2 \longrightarrow 1.85\ CO_2 + 3.92\ H_2O + 12.26\ N_2$$

$$+\ 0.006\ HCl + 0.006\ SO_2 + 0.02\ NO + 1.09\ O_2$$
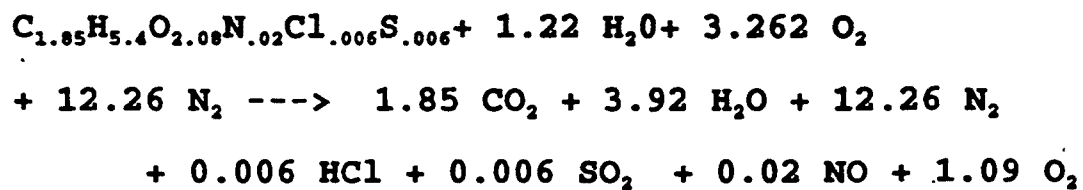
Product Gas	Wet Gas Moles	Dry Gas Moles	Dry Gas Mole %
CO_2	1.85	1.85	12.04
H_2O	3.92		
N_2	12.26	12.26	80.49
HCl	0.006	0.006	0.04
SO_2	0.006	0.006	0.04
NO	0.02	0.02	0.13
O_2	1.09	1.09	7.16
Total	19.152	15.232	100.00

The dry gas analysis for the idealized combustion example is illustrated above. Note that the NO is 0.13 percent of the dry gas, which corresponds to 1,300 ppm. Because NOx emissions are often around 200 ppm, this example confirms that there is more than enough fuel nitrogen in MSW to account for the NOx formation.

Note that in actual combustion systems, the maximum theoretical amount of fuel NOx is not obtained. There are some indications that around 20% of the fuel nitrogen can be expected to form NOx in MWC units. Therefore, about 260 ppm would be expected to be formed. This approximation is generally consistent with the stack gas concentration measurements of many operating MWC units.

As a point of reference, the NSPS for large MWC units limits NOx emissions to 180 ppm. Therefore, new units must have design provisions which either limit the formation of fuel NOx or cause its dissociation.

Slide 17-11

```
┌─────────────────────────────────────────────────────────┐
│        COMBUSTION MODIFICATIONS FOR FUEL NOx            │
│                                                         │
│        Two-Stage Combustion                            │
│        Excess Air - Stoichiometric Control             │
│        Controlled Mixing - Low NOx Burners             │
└─────────────────────────────────────────────────────────┘
```

Fuel NOx may be controlled through the modification of local combustion stoichiometries. If combustion occurs under sub-stoichiometric (starved air) conditions, there will not be enough oxygen for complete combustion of the hydrogen and carbon. Reactions favor hydrogen and carbon oxidation over that of nitrogen, so the oxygen could be depleted before significant NOx is formed. The nitrogen atoms released under starved air combustion conditions will generally tend to form molecular nitrogen.

A subsequent addition of excess air will be required to provide for the oxidation of carbon monoxide and other products of incomplete combustion before the gases leave the combustion zone.

As discussed in Learning Unit 9, the fuel bed of a grate-burning system acts as a gasifier. If more uniform bed conditions were possible, it may be that the fuel bed could also act as a low NOx burner. However, the fuel variability leads to oscillations in local stoichiometry and control of stoichiometry is very difficult.

Starved-air incinerators have consistent performance features which produce sub-stoichiometric conditions in the primary chamber. This makes the primary chamber function as a low-NOx burner.

Slide 17-12

```
┌─────────────────────────────────────────────────────────┐
│      COMBUSTION MODIFICATIONS FOR THERMAL NOx          │
│                                                         │
│  THERMAL NOx                                           │
│      Not a Significant Source of MWC NOx               │
│                                                         │
│  Thermal NOx Control Techniques                        │
│      Limit Peak Combustion Temperatures                │
│          Heat Sinks (Flue Gas, Steam)                  │
│          Control Mixing to Reduced Hot Spots           │
│      Control Stoichiometry                             │
└─────────────────────────────────────────────────────────┘
```

Although thermal NOx is not an important mechanism for NOx formation in MWCs, it is important in many conventional combustion systems. Thermal NOx can be controlled by limiting the peak combustion temperatures through such techniques as flue gas recirculation, steam injection, low NOx burners, and excess air control.

Inert flue gas and/or steam can be mixed with the combustion gases and act as heat sink materials which reduce combustion gas temperatures. Flue gas recirculation is often used to control thermal NOx emissions from natural gas fired power plants. Steam injection is a traditional means of NOx control in gas turbines.

Flue gas recirculation is used in some modular starved air incinerators as a method of controlling primary chamber gas temperatures. Because of the starved-air condition, its use will have limited impact on their NOx emissions.

The low NOx burners attempt to eliminate "hot spots" in the flame where very intense combustion occurs. Low NOx burners can also be used to control local stoichiometry.

Controlled stoichiometry is used to limit the amount of oxygen available for oxidizing nitrogen, as in the case of fuel NOx. Controlling excess air and/or the stoichiometry under peak combustion temperature conditions may also control gas temperatures. Depending on whether conditions are fuel rich or lean, the combustion temperatures will increase or decrease upon an increase in the air supply.

Slide 17-13

```
FLUE GAS CONTROL OF NOx

Catalytic and Non-Catalytic
     Reducing Agent Injection
```

Reducing agents can be injected into the combustion gases to create a reducing atmosphere. Under such conditions, the reaction kinetics will cause the NO to be dissociated as the reagent is oxidized. Molecules of water and nitrogen are formed from the decomposition process.

Reducing atmospheres can be obtained by injecting ammonia and urea into the combustion gases. Reagent injection must be properly controlled to assure that the right amount of agent is injected, the temperature where the injection occurs is appropriate, and the reagent does not slip through the reaction and become a significant pollutant emission. Some reagents require the use of a catalyst surface, whereas others do not. The details of such flue gas treatment techniques will be presented in Learning Unit 21.

REFERENCES

1. H. Whalely et al., "Control of Acid Rain Precursors," Emissions from Combustion Processes: Origin, Measurement, Control, Raymond Clement and Ron Kagel, editors, Lewis Publishers, Chelsea, Michigan, 1990, pp. 315-316.

2. Philip A. Leighton, Photochemistry of Air Pollution, Academic Press, New York, 1961, pp. 1-5, 254-278.

3. "Nitrogen Oxide Control For Stationary Combustion Sources," EPA/625-5-86/020, U. S. Environmental Protection Agency, July 1986, pp. 1-3.

4. W. R. Seeker, W. S. Lanier, and M. P. Heap, "Municipal Waste Combustion Study, Combustion Control of Organic Emissions," U.S. Environmental Protection Agency, EPA-530-SW-87-021-c, June 1987, pp. 4-8 to 4-11.

18. AIR POLLUTION IV: METALS AND ASH

Slide 18-1

```
┌─────────────────────────────────────────────────┐
│         METAL COMPOSITION IN MSW                 │
│                                                  │
│  Example Composition of MSW:  6.4% Metals        │
│                              16.4% Inorganic (Ash)│
│                                                  │
│  Major Toxic Metals:   Lead, Cadmium, Mercury    │
│  Other Trace Metals:   Antimony, Arsenic, Barium │
│                        Beryllium, Chromium, Nickel│
│                        Silver, Thallium          │
└─────────────────────────────────────────────────┘
```

The example MSW presented in Learning Unit 4 had a metals content of 6.4% and an inorganic (ash) content of 16.4%. The difference between these two numbers relates primarily to silica and oxygen. Much of the ash is in the form of an oxide, so the oxygen contributes to its weight. As illustrated below, the metallic constituents contribute about 60% of the total weight of ash, with oxygen providing the balance.

Slide 18-2

```
┌─────────────────────────────────────────────────┐
│  EXAMPLE OF METALLIC CONSTITUENTS IN ASH[1]      │
│                                                  │
│         Silicon          30. %                   │
│         Iron             10.                     │
│         Calcium           8.                     │
│         Sodium            6.                     │
│         Aluminum          3.                     │
│         Titanium          0.7                    │
│         Manganese         0.6                    │
│         Potassium         0.4                    │
│         Zinc              0.3                    │
│         Lead              0.2                    │
│         Copper            0.1                    │
│         Molybdenum        0.1                    │
│         Barium            0.05                   │
│         Chromium          0.02                   │
│         Selenium          0.004                  │
│         Arsenic           0.003                  │
│         Cadmium           0.003                  │
│         Mercury           0.0006                 │
│         Silver            0.0006                 │
└─────────────────────────────────────────────────┘
```

The metal contents in ash vary considerably depending on the sources and the degree of materials separation utilized. Silicon is listed here as a metal but it is generally in the form of sand and glass.

Ferrous metals in ash include iron and the various steel alloys. The sodium is generally in the form of a salt. Aluminum is a significant component. Other non-ferrous metals are found to have small but important trace contents.

Slide 18-3

```
┌─────────────────────────────────────────────────────┐
│                                                      │
│      COMMON TERMS WHICH CHARACTERIZE METALS          │
│                                                      │
│      TOXIC METALS                                    │
│            Threat to Human Health                    │
│                                                      │
│      HEAVY METALS                                    │
│            High Molecular Weight                     │
│                                                      │
│      TRACE METALS                                    │
│            Found in Low Concentrations               │
│                                                      │
└─────────────────────────────────────────────────────┘
```

Terms such as "toxic metals," "heavy metals," and "trace metals" are often used to characterize metals which are of concern as air and water pollutants. Toxic metals are so characterized because of their threat to human health. Heavy metals are those with relatively high molecular weights. A metal is characterized as a trace metal if it is found in very small concentrations.

The above terms for toxic metals are often used interchangeably because the toxic metals are those of high molecular weight which are often found in small concentrations. For instance, lead is a toxic, trace, and heavy metal with a national ambient air quality standard (1.5 micrograms/cubic meter) established to protect public health and welfare.

Slide 18-4

```
┌─────────────────────────────────────────────────────┐
│                                                      │
│      NSPS:   MWC METALS                              │
│                                                      │
│      Metals and Metal Compounds Emitted              │
│      in Exhaust Gases from MWC Units                 │
│                                                      │
│      Particulate Matter (Solid and Liquid)           │
│      Vapors (Gas)                                    │
│                                                      │
└─────────────────────────────────────────────────────┘
```

The NSPS has defined MWC metal emissions as those metals and metal compounds which are emitted in the exhaust gases of MWC units. MWC metals include the emissions of metals found in both particulate and vapor forms.

```
+------------------------------------------------------------+
|                   METAL PATHWAYS IN MWCs                   |
|                                                            |
|   High Melting Point (Non-Volatile) Metals                |
|        Form Oxides, Chlorides, Sulfides                   |
|        Remain in the Solid Residue (Ash)                  |
|                                                            |
|   Low Melting Point (Volatile) Metals                     |
|        Form Liquids which Solidify when Cooled            |
|        Form Vapors which Condense when Cooled, Are        |
|           Adsorbed onto Fly Ash, or Remain As Vapor       |
+------------------------------------------------------------+
```

Metals which enter the combustion zone as MSW can follow different paths, depending on their chemical characteristics, the combustion temperatures, melting points, and vapor pressures.

Many of the metals in MSW have high melting temperatures and are non-volatile. Upon heating in the combustion zone, metals can react to form oxides, sulfides and chlorides. If local starved-air conditions exist, some metal compounds can be reduced back to a pure metal, but they generally leave the combustion chamber in an oxide form.

These metal compounds are generally collected in solid form. They are the major constituents of the residual (bottom) ash and grate siftings. They are also the major constituents of the fly ash which is collected in the heat recovery regions and by flue gas cleaning equipment.

Metals such as lead and aluminum may be melted and partially vaporized during the combustion process. Liquid metals may be deposited and solidified on the relatively cold surfaces of the grate, wall, or ash. As flue gas cooling occurs, vapors of volatile metals may be adsorbed on the fly ash or may condense in the form of small liquid metal droplets. A fraction of the metals in MSW are emitted by the unit in gaseous (vapor) form in the exhaust gas.

```
+--------------------------------------------------+
|         TOXIC METALS AS AIR POLLUTANTS          |
|                                                  |
|             Particulates                        |
|             Gases (Vapors)                      |
+--------------------------------------------------+
```

The primary environmental concern about metals relates to their toxicity as air pollutants. Metals can be emitted in either particulate form or as vapors in the stack gases.[2] With the exception of mercury, most of the toxic metals are retained in solid form as part of the MWC fly ash and bottom ash residues.

Slide 18-7

```
TOXIC METALS WITH LARGEST CONCENTRATIONS

      Lead, Mercury and Cadmium

      Lead -  Particulate
      Mercury - Particulate and Vapor
      Cadmium - Particulate
```

The toxic metals with the largest concentrations in the flue gas before the APCDs are lead, mercury and cadmium. Lead and cadmium are generally deposited (condensed, adsorbed) on the surface of fly ash. Their concentration is higher in the smaller particulates of fly ash, because the transfer process is limited by surface area, and the smaller sized particles have considerably more surface area per unit weight.

The volatile toxic metal of greatest concern is mercury. It is vaporized during combustion and has relatively high vapor pressures at flue gas temperatures. Because condensation is inversely related to vapor pressure, a considerable fraction of mercury does not condense as the flue gases are cooled before leaving the stack. Mercury is emitted both in vapor and particulate forms.

Slide 18-8

```
CONTROL STRATEGY FOR METAL AIR POLLUTANTS

Provide for Condensation and Adsorption
     by Controlling APCD Temperature

Collect Metals as Particulates
```

The metal emissions control strategy is to provide for adequate condensation and adsorption of metal vapors onto the particulates as the gases cool so that metals can be collected by the particulate control equipment. Some vapors will condense and form small diameter liquid droplets which can be collected if the APCD is adequate.

Slide 18-9

```
SURROGATES

For MWC Metals (Except Mercury):
        Particulate Matter, PM
        Opacity
```

As discussed in Learning Unit 12, surrogates are specified to indicate the adequacy of controls for MWC metals. Particulate matter (PM) is the surrogate for MWC metals, other than mercury, during an annual stack test. Opacity is the surrogate during continuous operations.

Slide 18-10

```
HEAVY METALS - OPERATIONAL CONCERNS

Procedures to Prevent Exposure
Special Equipment (Suits, Aspirators)
Personal Monitors
```

MWC plants operate under Occupational Safety and Health Act (OSHA) requirements which include special procedures designed to limit a worker's exposure to heavy metals. The safety procedures at many plants include provisions for the monitoring of heavy metals (lead, cadmium and mercury), blood testing, and the use of respirators or special suits in contaminated and confined areas.

Slide 18-11

```
TOXIC METALS AS GROUND WATER POLLUTANTS

Organic Decomposition to Form Acids
Acid Extraction of Heavy Metals from Ash
Leakage of Leachate into Ground Water
```

Another major environmental concern about toxic metals relates to ash disposal and the long-term possibility of polluting the ground water. Depending upon the applicable regulations, combustion residues can be disposed either alone in a single composite-lined monofill or with mixed waste in a modern landfill having a double composite-liner.[1]

Acids, which are formed by organic decomposition in landfills, can leach the heavy metals from the ash and form a liquid called leachate. Ground water pollution occurs when the leachate leaks into the ground water.

Ground water contamination from landfills and monofills can be controlled by proper construction, verification and treatment. Modern landfills and monofills must have the liners, caps and leachate monitoring, collecting, and treating systems specified by the RCRA regulations.

A monofill, which is restricted to receive ash, will have very little organic material which can form acids. Therefore, the leachate from a monofill is predominantly inorganic, with salts and metal compounds.[1] Although, the metal concentrations in monofills are greater than in sanitary landfills, the metals are generally retained better in ash than in MSW disposed in a sanitary landfill.

Slide 18-12

```
IS MWC ASH HAZARDOUS OR NON-HAZARDOUS?

Answer Varies from State to State
        Regulatory Definitions
        Toxicity Test Requirements
        Ash Sampling Procedures
```

Currently, an unresolved national question is whether MWC ash residue should be classified as a hazardous or non-hazardous material.

The USEPA presently has no formal statement on MWC ash. However, many states have developed their own answer to this question. The definitions and requirements for testing and disposal varying from state to state.[3]

Amendments to RCRA, which were passed in 1984, have provisions which define MSW ash as being non-hazardous, subject to some limitations[3]. However, Section 3001 of RCRA specifically classifies a waste material as being hazardous if it fails tests for ignitability, reactivity, corrosivity, or toxicity.

MSW ash can generally pass the ignitability, reactivity and corrosivity tests. The typical carbon burn-out of ash prevents it from being ignited, and the reactivity is controlled by keeping radioactive materials out of MSW. The corrosivity test considers the pH of the material, and the pH of MSW ash is generally within the acceptable limits of 7.0 to 12.5. However, the testing for toxicity has presented problems.

```
┌─────────────────────────────────────────────────┐
│         LABORATORY PROCEDURES FOR TOXICS          │
│                                                   │
│   EP - Extraction Procedure Toxicity Test         │
│        (an early procedure)                       │
│                                                   │
│   TCLP - Toxicity Characteristic Leaching         │
│          Procedure  (EPA Method 1311)             │
│                                                   │
│   EPA Method 1312 - Synthetic Precipitation       │
│           Leach Test for Soils                    │
│                                                   │
│   EPA Method 3050 - Acid Digestion of             │
│           Sediments, Sludges & Soils              │
└─────────────────────────────────────────────────┘
```

Testing of the leaching characteristics of ash is used to determine if an improperly managed waste poses an unacceptable risk to groundwater and therefore should be managed as a hazardous waste.[4] This testing of ash samples is typically required before ash can be disposed in a sanitary landfill or monofill.

The initial USEPA method for determining ash toxicity is the Extraction Procedure Toxicity Test (EP). Regulatory thresholds, based on the EP test, have been established for 8 metals, 4 pesticides and 2 herbicides.[4]

The Toxicity Characteristic Leaching Procedure (TCLP)[5] is a newer regulatory test, which has been proposed as a replacement for the EP test.[4] This test method is designed to simulate the leaching of toxic constituents in a co-disposal sanitary landfill and to measure the toxicity of such leachate. The TCLP involves passing waste material through a sieve, adding various extraction fluids, and agitating the mixture. The mixture is filtered and the leachate is analyzed for 40 constituents. If any of the constituent's concentrations exceed their specified limit, the waste is classified as hazardous.[3]

Ash sampling requires complicated procedures because of the variations in the MSW constituents. Bottom ash represents around 90% of the ash formed. Bottom ash is composed mainly of glass, metal and other inorganic compounds from paper, plastic, rubber, food wastes, and other products (e.g., clays in papers, stabilizers in plastics, pigments in printing inks, salts in vegetables).[6]

Because of the large number of fly ash particles in the flue gas, they provide a considerable amount of surface area for absorption of heavy metals. Fly ash concentrations of heavy metals are generally greater than those of bottom ash. When fly ash has been tested alone by the TCLP procedure, it sometimes exceeds the regulatory thresholds for lead and cadmium.[3]

By contrast, bottom ash and combined mixtures of bottom ash and fly ash often pass TCLP tests. Combining the fly ash with bottom ash is a common practice in regions where the practice is not prohibited by regulations.

The regulatory requirements for ash disposal are not currently uniform, and vary from state to state. Some states[3] have adopted requirements which specify the testing of ash through the use of EPA Method 1312[7] or the EPA Method 3050.[8] These tests have some contrasting features, so that one or the other may better simulate landfill or monofill conditions.

Slide 18-14

```
        MWC ASH TREATMENT & UTILIZATION

  Treatment Before Disposal
            Chemical Extraction
            Chemical Additives
            Compaction
            Vitrification

  Create Useful End-Products
            Road-Bed Aggregate
            Landfill Cover
            Ash/Concrete Blocks
```

There are a number of ash treatment and utilization strategies currently in use and under development.

Ferrous metal separation from the bottom ash residues can be accomplished by the use of magnetic separation and screening techniques. This not only reduces the amount of ash, but can also provide additional revenue at mass burn facilities.

Various treatment strategies are designed to reduce the amount of leaching of toxic metals from the ash.[9] One possibility, which is very expensive, is to use chemical extraction in which the ash is treated with an acid to extract the metals prior to either disposal or utilization.

The ash can be treated with additives which bind the metals in a stable form that is effectively impermeable to acids. Physical compaction of ash, combined with the injection of mixtures of water and either lime or portland cement, can reduce the effective amount of exposed surface area so that less leaching occurs.

Reported end-product applications include the use of ash as a low-grade road bed aggregate and as a landfill cover. However, ash treatment may be required for such applications to prevent the previously described leaching problems.

A higher quality end-product can be formed as an ash/concrete block or building material. The carbon content of the ash may have to meet certain specifications, however, to assure the formation of a stable aggregate or building block.

A considerable research effort is under way to develop an optimum method of encapsulating ash in such a way as to permanently fix the metals within glass beads and, therefore, be highly resistant to ground water leaching. This process is called "ash vitrification" and provides for the melting of ash into a slag in special high temperature furnaces.[10] The product formed is expected to be acceptable for use as a light-weight aggregate material suitable for construction projects.

REFERENCES

1. Jeffrey L. Hahn, "Managing Ash--Closing in on Policy Decisions," <u>Solid Waste & Power</u>, August 1989, pp. 12-18.

2. Robert G. Barton, et al., "Fate of Metals in Waste Combustion Systems," <u>Combustion Science and Technology</u>, Vol. 74, Number 1-6, 1990, pp. 327-343.

3. Marc J. Roggoff, "The Ash Debate: States Provide Solutions," <u>Solid Waste & Power</u>, October 1991, pp. 12-18.

4. R. Mark Bricka et al., "A Comparative Evaluation of Two Extraction Procedures: The TCLP and The EP," U. S. Environmental Protection Agency, EPA/600-S2-91/049, March 1992.

5. "Toxicity Characteristic Leaching Procedure," Method 1311, U. S. Environmental Protection Agency, SW-846, 1985.

6. David B. Sussman, "Municipal Waste Combustion Ash: Testing Methods, Constituents and Potential Uses," <u>Proceedings, International Conference on Municipal Waste Combustion</u>, Volume 2, April 11-14, 1989, Hollywood, Florida, pp. 118-13 to 118-25.

7. "Synthetic Precipitation Leach Test for Soils," Method 1312, U. S. Environmental Protection Agency, SW-846, 1985.

8. "Acid Digestion of Sediments, Sludges, & Soils," Method 3050, U. S. Environmental Protection Agency, SW-846, 1985.

9. "Treatment and Use: The Future of Ash Management?" <u>Solid Waste & Power</u>, October 1991, pp. 20-28.

10. G. L. Harlow, et al., "Ash Vitrification--A Technology Ready for Transfer," <u>Proceedings of the 1990 ASME National Waste Processing Conference</u>, Long Beach, CA, June 3-6, 1990, pp. 143-150.

19. FLUE GAS CONTROL I: PARTICULATE MATTER (PM)

Slide 19-1

PARTITIONING OF SOLID RESIDUES[1,2]		
COMBUSTION SYSTEM	EXAMPLE VALUES, %	
	BOTTOM ASH	FLY ASH
Pulverized Coal	30	70
RDF - Spreader	25	75
Mass Burn - Grate	90	10
Modular Starved-Air	98	2

The above slide illustrates the influence of fuel type and combustion equipment design on the distribution of the solid combustion residues between the bottom ash and fly ash entrained in the flue gases. The particulate entrainment is greatest with suspension-firing systems. Spreader stokers burning RDF have combined suspension and bed combustion features. Spreader stoker units also have high entrainment of particulates (fly ash) in the gases leaving the radiant zone.[1]

Some mass burning systems which use grates have been reported to collect in the range of 75% of the solid residue as bottom ash.[1] Other grate-fired facilities with grates have indicated as much as 85 to 95% of the solids collected as bottom ash.[2] Variations are dependent upon the metal and other inorganic composition of MSW.

By contrast, the modular starved-air units attempt to minimize the entrainment in the primary chamber, so that only a very small fraction of their solid residues are collected as fly ash.

The inorganic material in MSW makes up a substantial fraction of the ash residues from MWC units, with unburned carbon often being less than two percent of the solid residues. Dry sorbent injection (DSI) and spray dry absorber (SDA) systems provide additional solid residues which are collected as fly ash.

Slide 19-2

INDICATORS OF PARTICULATE COLLECTION
1. Visible Emissions
2. Opacity CEMS
3. APCD Inlet Gas Temperature
4. Stack Test Results

There are various indicators of particulate emissions escaping an air pollution control device (APCD). A visual observation of the plume opacity is the most obvious. High opacity is an indication that something is wrong with either the design or operation of either the combustor or the air pollution control device.

The opacity CEMS provides an instantaneous reading which can be reviewed conveniently by the operator. It can provide readings with greater precision and without the subjective features of visual observations. In addition, a continuous record of stack opacity is typically maintained. These records can be examined to provide an indication of the history of unit operations.

One requirement of GCP is to operate with the flue gas at the inlet of the particulate removing APCD being below a temperature limit. Continuous monitoring of this operating temperature is generally required. The inlet temperature should be compared with that of the most recent annual stack test for dioxin/furan emissions. Temperatures more than 30 °F above those test conditions would indicate a violation of federal NSPS and EG requirements for applicable MWC units.

Flue gas temperature conditions at the APCD inlet must be maintained to limit the catalytic formation of dioxin/furan compounds on the surfaces of collected ash and to assure adequate condensation of the MWC organics and toxic metals.

An annual stack test of particulate matter is required by federal standards and guidelines to assure that both the MWC organic emissions and MWC metal emissions are adequately controlled.

Slide 19-3

```
PARTICLE ENTRAINMENT FACTORS

1.  Particle Size, Shape & Density
2.  Fuel Charging Method
3.  Underfire Air Velocity
4.  Fuel Burning Rate
5.  Primary Zone Velocity
```

Entrainment of particulate matter is influenced by particle size, shape, and density. For instance a small piece of paper is fairly easily entrained, whereas a large piece of wood tends to remain on the fuel bed.

Some MWC combustion designs provide charging or grate agitation methods which result in considerable entrainment of burning fuel and ash particles. These include the RDF systems which use air-swept distributors for suspension burning and rotary waterwall units which have a constant tumbling bed agitation.

Entrainment can be reduced by limiting the velocity through the fuel bed and limiting fuel bed agitation. Modular starved air units have low particulate loadings because less air is supplied to the primary chamber and there is limited fuel bed agitation. Additional combustion air is delivered at the entrance to the secondary chamber. The reduced fuel bed agitation which reduces gaseous particulate loadings unfortunately also reduces carbon burnout in the bottom ash. This is partially compensated for by allowing a relatively long residence time in the burn-out section of the primary chamber.

Other mass burn units direct substantial amounts of underfire air through the burning fuel bed. This causes considerable entrainment of particulates. However, the relatively high velocities and temperatures in the primary combustion region can also provide for good mixing and carbon burn-out.

The sizes of the entrained particles are reduced as the combustibles are either evolved or burned on the surface. Their residue can be either removed as boiler ash or as fly ash. Some boiler ash will be deposited on the heat exchanger surfaces and removed during soot blowing. Boiler ash includes the particulates which are large enough to be collected by inertial separation as the flue gases change directions through the convective section of the boiler. Those particulates which are entrained in the flue gas and pass out of the boiler make up the fly ash loading at the APCD.

Slide 19-4

```
TYPES OF PARTICULATE APCDs

1.  Fabric Filters
2.  Electrostatic Precipitators
3.  Venturi Scrubbers
4.  Mechanical Collectors
```

This learning unit focuses on fabric filters (FFs) and electrostatic precipitators (ESPs). They are the primary air pollution control devices (APCDs) which are currently used to meet the particulate matter collection requirements. Venturi wet scrubbers, which have been used for particulate control applications at earlier MWC units, are also introduced.

As will be discussed in Learning Unit 20, both dry and wet scrubbing systems have been used in combined particulate and acid gas control systems.

Dry scrubbing systems produce a dry waste product, and the flue gas which exits is not saturated with water. Spray dryers absorbers (SDA) and dry sorbent injection (DSI) systems are primarily designed for absorbing acid gases, leading to the

production of calcium based salts. These dry products and particulates are subsequently collected by fabric filters or ESPs. Dry scrubber systems influence the particulate collection performance by changing the flue gas temperature, total particulate load, and fly ash properties.

Venturi and other wet scrubbing systems produce a wet waste (sludge) and a flue gas saturated with water. Such systems are seldom used in MWC units in the United States, because of their high operating and maintenance costs associated with providing energy for the pressure drop, treating the sludge, and controlling corrosion and erosion.

Mechanical collectors, such as cyclonic and other inertial separation devices, are effectively limited to large size particulate removal applications, such as for boiler ash collection. Mechanical collectors are not presented in this training course because they have limited influence in meeting the particulate emission control requirements at MWC applications.

Slide 19-5

```
FABRIC FILTER COLLECTION MECHANISMS

    1.  Inertial Impaction
    2.  Direct Interception
    3.  Diffusion
    4.  Electrostatic Attraction
```

Fabric filters collect particles are through a combination of inertial impaction, direct interception, diffusion, and electrostatic attraction.[3] Inertial impaction is caused by the inability of large particles to change directions and turn past objects such as single fabric fibers. Upon impact, particulates are deposited on the fibers.

Direct interception is the sieving action which occurs when the size of the particle is greater than that of the passageways through the filter. This is the primary collection method of the filter cake, which is formed by the accumulation of particulates on the fabric fibers. Most of the moderate sized particulates are collected by direct interception by the filter cake.

Diffusion is the method whereby sub-micron (sub-micrometer) sized particulates are collected. Diffusion relates to the random motion of such particulates which allows collisions to occur in all directions, even though the gas stream is primarily moving in one direction. Sub-micron particles are primarily collected within the filter cake.

Electrostatic forces can affect collection because of the differences in electrical charge between the particulates and the filter.

Slide 19-6

```
FABRIC FILTER DESIGN FACTOR

AIR-TO-CLOTH RATIO
        Total Air Flow/Filter Surface Area
        Average Velocity Through Filter
```

Until recently ESP systems were the dominant particulate collectors at MWCs. Fabric filter systems, which for many years have been used in industrial applications, are now widely used in MWCs to collect the dry reaction products and particulate matter and as a secondary reactor for dry scrubbing. ESPs are also continuing to be used for particulate matter collection.

The collection mechanism of fabric filters is very similar to that of household vacuum cleaners. A fan sucks air through the bag which cleans air by filtration.

A standard design factor is the air-to-cloth ratio, which is the total air flow rate divided by the nominal filter surface area. This factor is equivalent to the average velocity of gas passing through the filter, with typical design values ranging from 1.5 to 4.5 ft/min (or $acfm/ft_2$). In general, greater filter surface areas result in lower velocities and require lower pressure drops to force the flue gas through the filter.

Slide 19-7

```
CLASSES OF FABRIC FILTER SYSTEMS

1.   Pulse-Jet
2.   Reverse-Air
3.   Shaker
```

Fabric filters may be classified, according to the method used for cleaning the bags, as either pulse-jet, reverse-air or shaker type units. The filter can be in the form of woven or felt fabrics and made from natural fibers like wool, or synthetic fibers like fiber glass. Each material generally has maximum recommended operating temperatures and known chemical resistance properties.

Operating pressure drops in fabric filters range from 1.5 to 5.0 inches w.c. Generally, fabric filter systems are equipped with automatic controls, which will initiate a cleaning cycle when the pressure drop across the fabric filter exceeds a particular value. Fabric filter cleaning can also be accomplished on a regular timed basis.

Slide 19-8

PULSE-JET FABRIC FILTER[4]
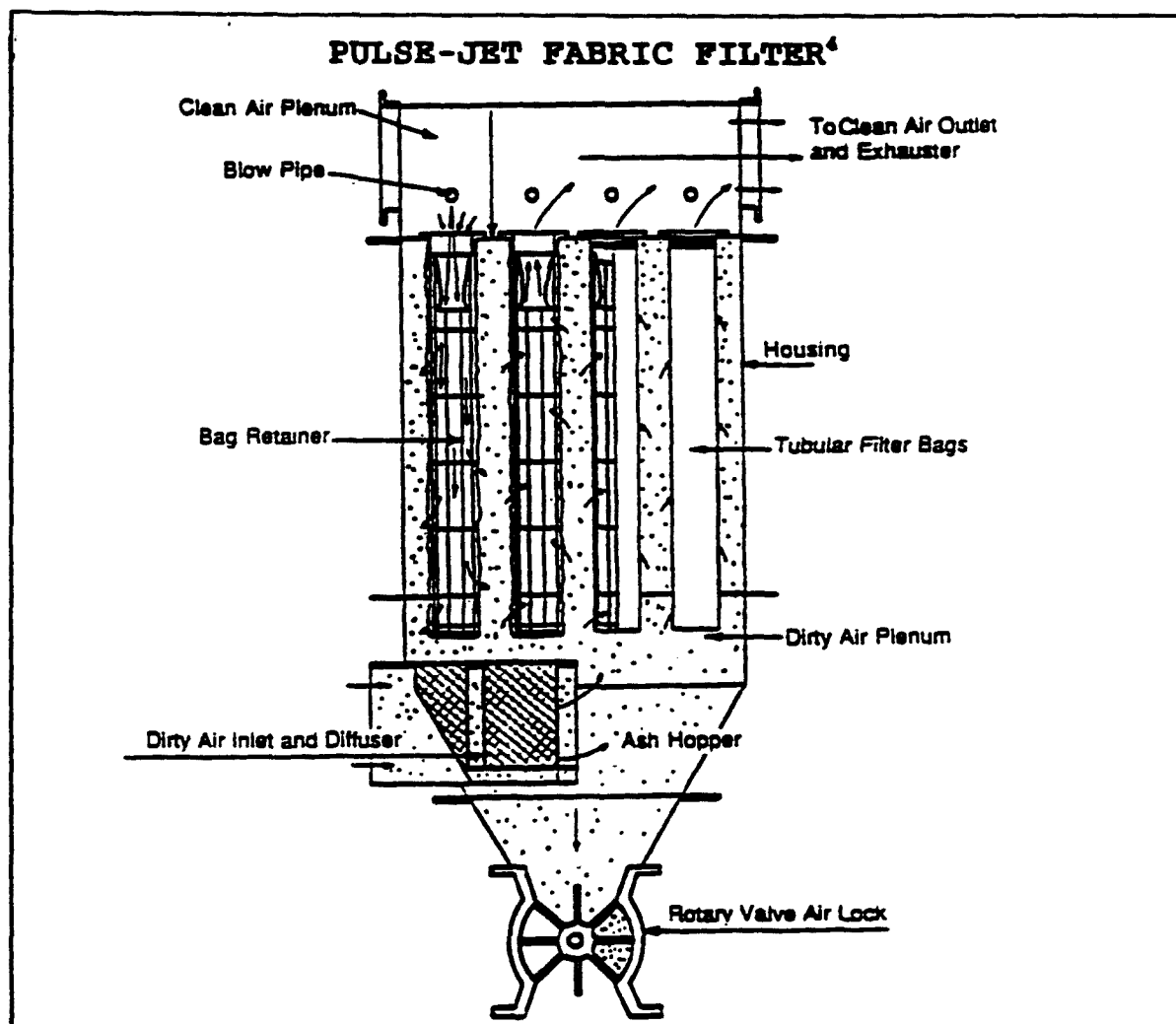
Courtesy of George A. Rolfes Company

Pulse-jet fabric filters are often used in MWC applications, probably because they tend to require the least capital cost of the three designs. Particulates are collected on the exterior surfaces of vertical bags. A cage inside each bag prevents it from collapsing. The top of each bag is attached to the tube sheet of the clean air plenum, and the bottom is closed.

Cleaning is initiated by directing a burst of high pressure air through a nozzle and down the inside of the bag. The pressure wave causes the bag to flex and dislodge the particulate cake material.

Most of the agglomerated particulate matter falls into a collection hopper, with a modest amount being re-entrained and returning to the fabric. If the fabric is cleaned too well, the collection efficiency will be poor until the filter cake is restored. The bags should not be cleaned too often, as cleaning can damage the bags. Operators are generally able to modify the pulse sequence for a pulse-jet fabric filter.

Cleaning in some pulse-jet applications occurs without having to remove the unit from service. The pressure front generally takes less than 0.2 seconds to move down the bag, so system operation can be quickly restored. Of course, there is some inefficiency of collection during this period.

Other pulse-jet filters are modularized to accommodate being taken off-line for cleaning. Gas flow can be directed to adjacent compartments so that air cleaning requirements are met while a particular compartment is off-line.

Slide 19-9

REVERSE-AIR FABRIC FILTER[5]
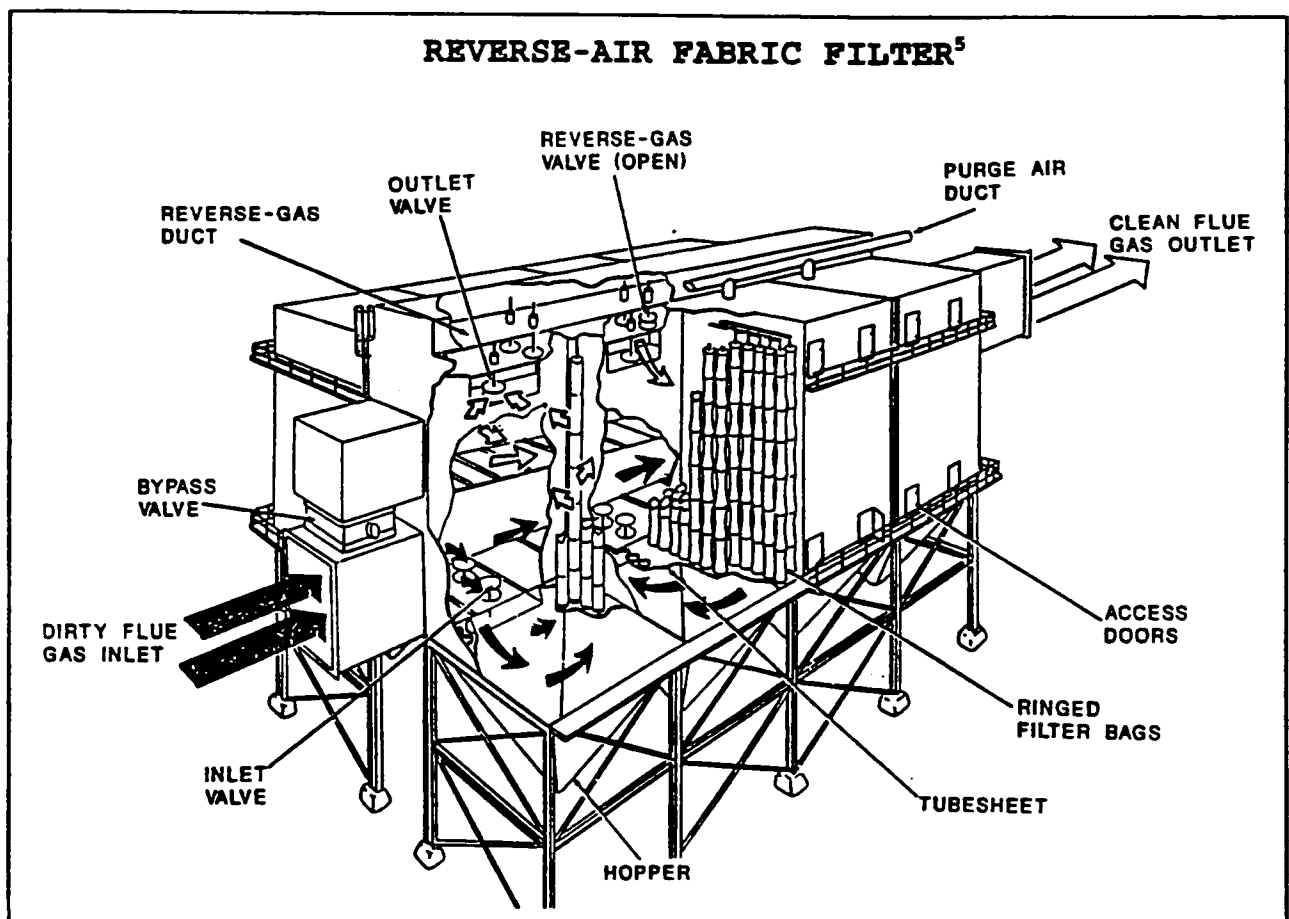
Courtesy of ABB Flakt, Inc., printed with permission.

The reverse-air fabric filter system is designed to collect particulates on the inside of the bags. Cleaning of this type system requires that a section be removed from service. A relatively low pressure supply of clean air is directed back through the filter, causing it to collapse and dislodge the collected particulate matter.

Slide 19-10

SHAKER-TYPE FABRIC FILTER[5]
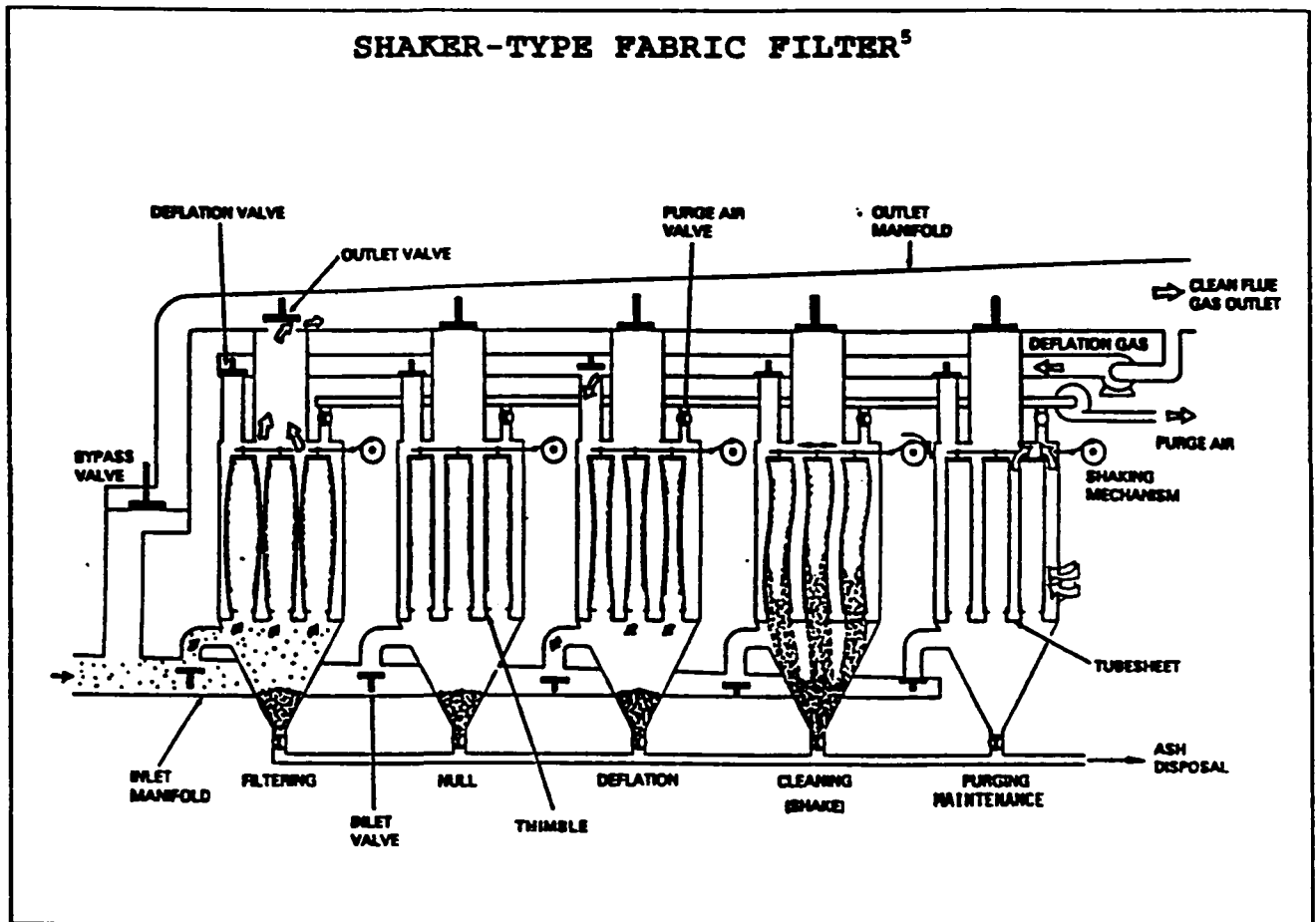
Courtesy of ABB Flakt, Inc., printed with permission.

The shaker-type fabric filter system uses a mechanical shaking device for cleaning the bags. As with the reverse-air system, the particulates are collected on the inside of the bags. The shaker-type units have the advantage of using mechanical linkages rather than a high pressure air supply or a special set of dampers and air ducts.

Slide 19-11

INDICATORS OF FABRIC FILTER PERFORMANCE

Opacity
Pressure Drop
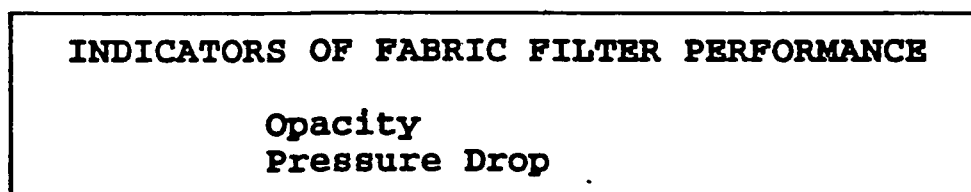
The major indicators of the performance of fabric filter systems are the records of stack opacity and the pressure drop. Fabric filters have vendor specified operating limits for maximum and minimum pressure drop. If the pressure drop gets too high, it may affect the combustion by not allowing the specified draft conditions. If the pressure drop is too low, the collection efficiency would be expected to be lower.

A ruptured bag is a typical problem which could be indicated by both above normal opacity and reduced pressure drop.

Slide 19-12

ELECTROSTATIC PRECIPITATOR
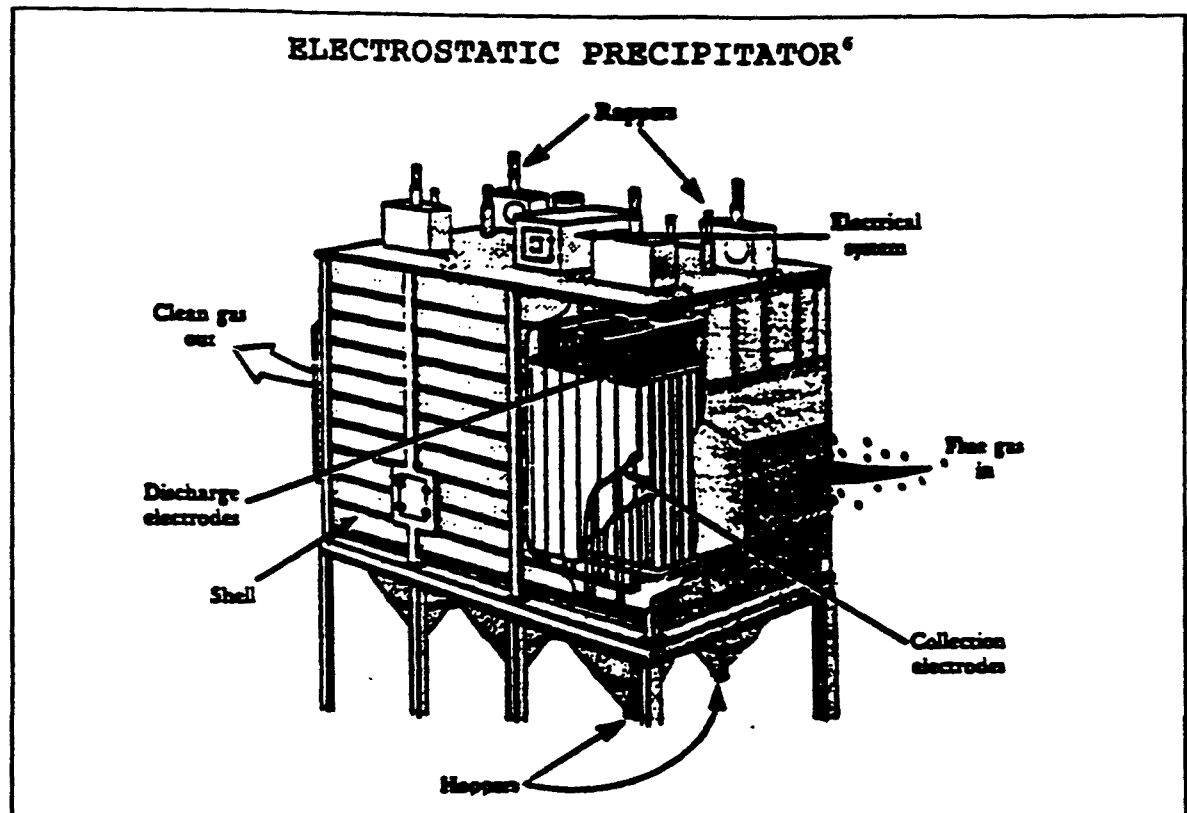
Particulate matter (PM) can be removed very effectively from MWC flue gas streams by ESPs, such as are illustrated above.

Slide 19-13

ESP DESIGN COMPONENTS

High Voltage Equipment
    Step-Up Transformer
    High Voltage Rectifier
Shell Enclosure for Support & Insulation
Vertical Wires - Discharge Electrodes Wires
Vertical Plates - Collection Electrodes
    Multiple Horizontal Gas Flow Paths
Rappers
Hoppers

Step-up transformers and high voltage rectifiers are generally found on the roof of ESPs. This electrical equipment is used to convert alternating current (a.c.) electricity into high voltage direct current (d.c.). Depending upon the design, the voltage can range from 20,000 to 100,000 d.c. volts.[7]

The shell enclosure is designed to provide a stable support structure for the various components and to prevent electrical shorts. Insulation is provided to prevent condensation associated with the cooling of metal surfaces to the dew point.

ESPs contain a number of vertical plates which act as collection electrodes. The plates form parallel gas flow paths which are horizontally oriented. Discharge electrodes are suspended between the plates. The electrodes can be either vertical wires or supported frames which are less prone to movement.

The length-to-height ratio of an ESP is an important design factor. If the ratio is too high, the flue gas may be channelized rather than flow through the ESP with a uniform velocity. Appropriately long geometries and low velocities are used to provide the required residence times for collection.

Slide 19-14

```
+---------------------------------------------------+
|        ELECTROSTATIC COLLECTION PROCESS           |
|                                                   |
|   High Voltage Ionization of Molecules            |
|   Corona & Electric Fields Created                |
|   Charges Transferred to Particulates             |
|   Migration of Particulates to Plates             |
|   Removal of Particulates                         |
+---------------------------------------------------+
```

The electrostatic collection process is based upon the attractive forces between particles with different electrical charges. Particles are given an electrical charge and then migrate out of the gas stream under the force of an electric field.

The charging is achieved by discharge electrodes which are charged with a negative-polarity direct current voltage. The voltage must be high enough to ionize the adjacent gas molecules and create a visible corona.

Electric fields are also created between the discharge electrodes and the collection plates, which are electrically grounded. The electric field causes the negatively charged gas molecules to migrate away from the corona and move toward the grounded plates.

CORONA & COLLECTOR PLATE CONFIGURATION*
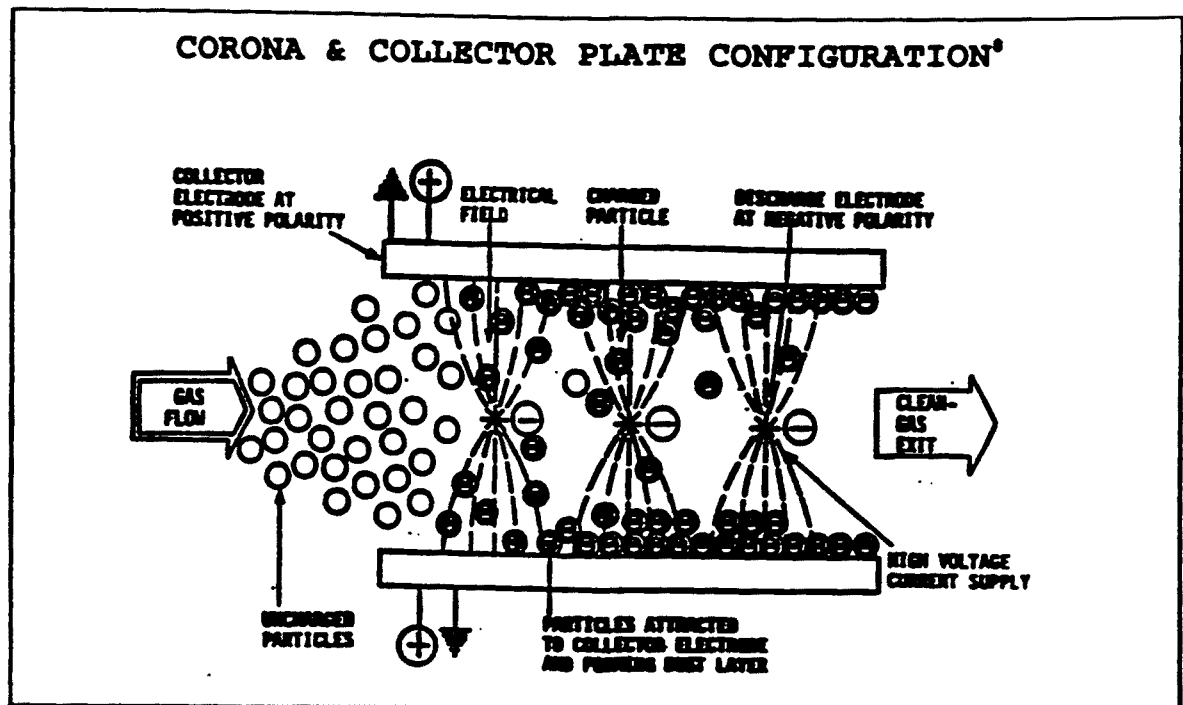
Particles in the contaminated gas stream will collide with the charged molecules flowing across the stream. As collisions occur, the particles absorb electrons and obtain a negative charge. The particles are then pulled by the electrical field toward the plate.

An electrical current is caused by the flow of electrons from the discharge electrode to the collection plates. If the particulate loading is very high, a significant current will result as will localized sparking and field instability. This can be controlled by limiting the discharge voltage.

The particulate concentration density is decreased as collection occurs and the flue gas flows through the ESP. Therefore, a corresponding increase in discharge voltage can be provided to the downstream electrodes to improve the overall collection efficiency. Separate transformer-rectifier sets can be used to supply the higher voltages at the downstream locations.

ESP designs provide for multiple opportunities for the particulate charging and collection. Many ESPs used on MWCs have three electric fields (or stages) in series. Particulates which pass one stage uncharged may be charged and collected in a subsequent stage.

Also, some of the particulates initially collected are re-entrained because of plate cleaning, electrical field instability, vibrations or turbulent gas flow. Generally, these can be collected in the next downstream section of the ESP.

```
ESP PARTICULATE REMOVAL

Charged Particle Adheres to Plate
Dry Removal - Mechanical Rappers
Wet Removal - Water Sprays
Delivery to the Hopper
```

Under normal conditions, the particles have fairly high electrical resistance and will only be partially discharged when they arrive at the collector plate. Since opposite charges attract, the particles will continue to adhere to the plate and to other collected PM as the charge is slowly leaked to ground. The charge of the collected particulate is generally maintained by the arrival of additional particles.

Layers of dry collected particulates are removed through the mechanical action of rappers or vibrators. Rappers are often actuated by pneumatic or solenoid devices. Some of these devices operate upon the release of a magnetic field or through a series of rotating cams or hammers. The dislodged PM is designed to fall into collection hoppers from which it is subsequently removed.

Some ESP systems use a wet removal process in which an intermittent or continuous streams of water is sprayed onto the collected dust and flows down the plates into a sump.

Slide 19-17

```
FACTORS AFFECTING ESP PERFORMANCE

1.   Particle Size Distribution
2.   Specific Collection Area
          Area/Gas Flow Rate
3.   Gas Stream Properties
          Velocity
4.   Ash Resistivity
          Temperature
          Moisture
          Composition (Carbon)
```

ESPs are very effective for large particulates. However, the collection efficiency of smaller particles is reduced. The particle sizes between 0.2 and 0.4 micrometers are especially difficult to collect. These are also very important in terms of meeting current emission requirements.

The specific collection area (SCA) is a general design parameter which establishes the amount of collector area required for a given gas flow rate. It is defined as the collector plate area divided by the flow rate. The specific collection area generally establishes an upper limit on the overall ESP collector efficiency.

The local gas velocity in the ESP is another variable which influences performance. As the gas velocity increases, the amount of time for particle migration to the collection plates is reduced and re-entrainment is increased. An increase in flue gas velocity is expected to occur with an increase in excess air and in unit load. In addition, the ESP collection efficiency decreases as the flue gas temperature increases because of the corresponding increase in velocity. Controlling the load (combustion rate) is the general method of assuring that gas velocities are maintained below maximum limits.

Ash resistivity is a parameter which influences the flow of current through the collected ash. Ash resistivity is reduced with an increase in either the flue gas temperature or the moisture, sulfur, or carbon content of the ash. If the electrical resistivity of the ash is too low, the charge will be drained away quickly and the particulates can be re-entrained in the flue gas. Since the resistivity of MWC ash is relatively low, re-entrainment is a typical problem for MWC units.

Some ESP applications may provide an injection of a low concentration of a gas as a "fly ash conditioning" agent. If the ash resistivity is too high, a modest injection of gaseous sulfur trioxide (e.g., 10 ppm) or ammonia will cause the ash resistivity to be reduced, resulting in better removal of collected particulates from collector plates.

By contrast, if the ash's resistivity is too high, sparking and back corona problems can occur which will impair collection efficiency by reducing the charging of particles. In addition the PM on the plate may be difficult to remove.

Slide 19-18

```
ESP MAINTENANCE & OPERATIONAL FEATURES

1.  Discharge Electrode Voltage
        Automatic Controls
        Transformer-Rectifier Data
2.  Electrical Component Failure
3.  Rapper Operation
4.  Air Leakage
        Excessive Temperature Drop
        Corrosion of Metals
        Fugitive Dust
5.  Start-up and Shut Down
        Heating; Purge Air
```

ESP designs which have been adequately designed and maintained have been demonstrated to adequately control the PM from MWC units.

Automatic circuits are used to control the voltage delivered to the discharge electrode and the resulting electric field conditions within the ESP. In general as soon as sparking occurs, the automatic voltage controller shuts down the power to the discharge electrode for a few milliseconds. Then the electrode's voltage is restored to approximately its pre-spark value.

Transformer-rectifier sets have gages which are used to monitor the ESP's electrical data.[9,10] The data include the primary and secondary voltages and currents associated with each field or set of fields. The primary data are associated with the supply side of the transformer, and secondary data are associated with the high voltage d.c. electricity supplied to the discharge electrodes. The secondary voltages and currents will vary with time as the automatic controls attempt to operate at near-sparking conditions for optimum charging and collection efficiency.

Abnormal transformer-rectifier data will signal the existence of problems caused by failures in either electrical or mechanical components. Electrical leakages or short circuits can be caused by broken insulators or by the accumulation of water and solids on the charged surfaces. Proper alignment of the discharge electrodes relative to collector plates is crucial for efficient ESP operation. Poor alignment could result from initial construction errors, insulator fatigue or failure, and thermal stresses associated with either improper thermal insulation, hopper fly ash fires, or air infiltration.

Entrainment can be caused by rapping too often or with too much force. Operators can adjust the rapping frequency and severity through the control system.

ESPs which operate at below atmospheric pressure can suffer from the leakage of ambient air through cracks into the unit. An excessive drop in temperature from the inlet to the exit of the ESP would be an indication of air leakage. The local cooling of surfaces below the acid dew points can be caused by air leakage. The resulting metal corrosion can weaken the metal structures and enlarge cracks leading to greater leakage.

Fugitive dust emissions are associated with leakage of ESPs which operate at above atmospheric pressure.

During unit start-up and shutdown, the ESP will typically swing through the dew points. An auxiliary system for heating could be used to maintain ESP temperatures above the dew points. Purging the ESP of any combustion gases upon shutdown may help control acid corrosion. However, excessive purging with ambient air could cool the ESP metal surfaces enough to cause condensation of moisture from the ambient air.

VENTURI SCRUBBER[11]

DIRTY FLUE GAS

CYCLONIC MIST ELIMINATOR

SPRAY NOZZLES

LIQUID INLET

VENTURI THROAT
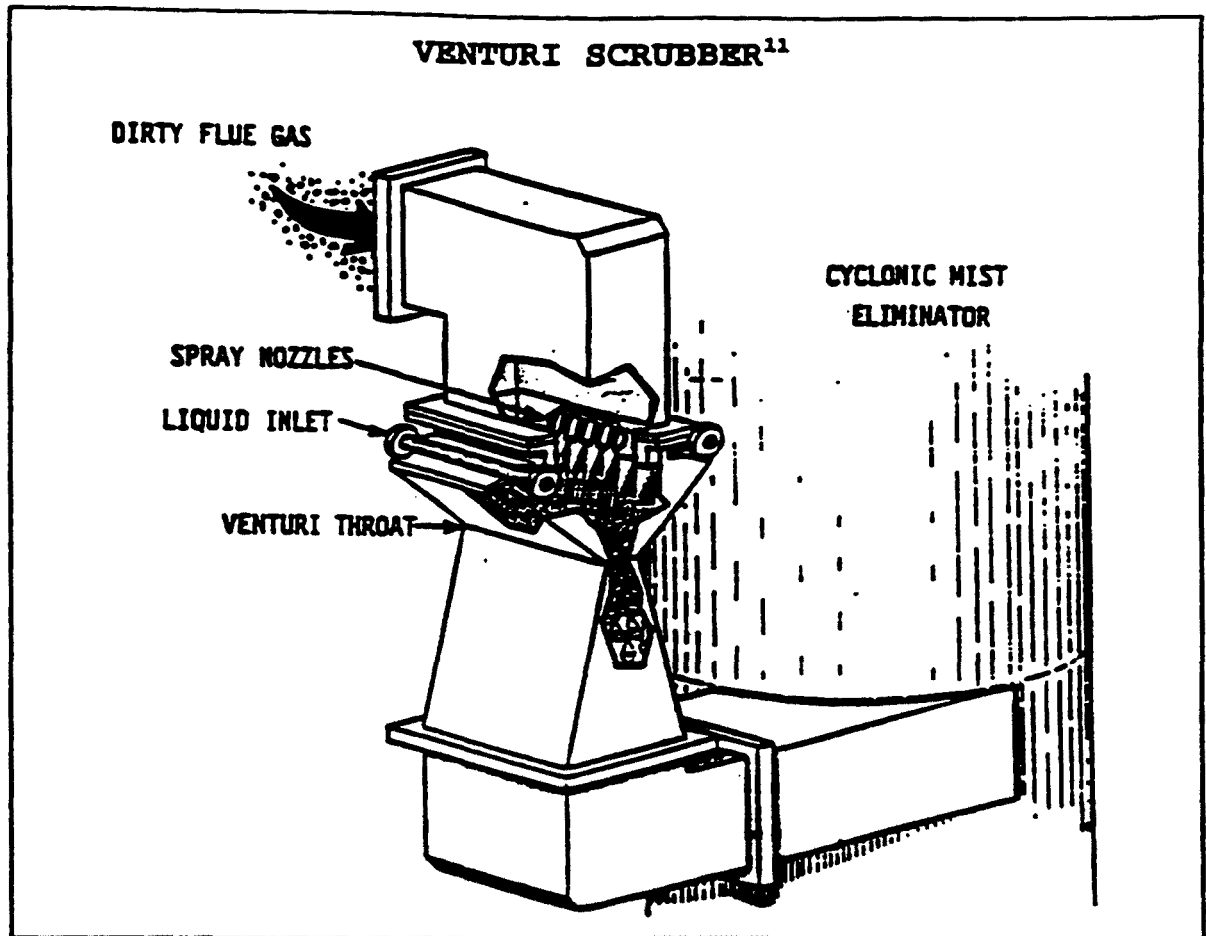
Venturi scrubbers are capable of high particle collection efficiencies, however a high pressure drop is required. Hydrochloric acid and sulfur dioxide can also be removed by a venturi scrubber with a suitable reagent.

A venturi nozzle has a restrictive throat area which creates a region of high velocity flue gas. Water droplets can be injected into the throat area, as illustrated in the slide. Another approach is to deliver a film of water at the entrance of the converging section of the nozzle, with water droplets being formed by the action of fluid friction in the throat region.

Variable throat designs are often used in order to have the desired scrubbing action over a range of flue gas flow rates. Such designs maintain the same throat velocities regardless of the flow rate.

Particulates in the high velocity flue gas collide with and are absorbed by the water droplets. The droplets are typically removed from the flue gas by inertial, gravity and/or centrifugal forces in either a flooded elbow section at the end of the diverging section or in a cyclonic mist eliminator or packed bed separator located downstream.

Slide 19-20

```
┌──────────────────────────────────────────────────────┐
│   KEY VENTURI SCRUBBER CONTROL VARIABLES             │
│                                                      │
│        Pressure Drop                                 │
│        Liquid/Gas Flow Rate Ratio                    │
│        Scrubber pH                                   │
└──────────────────────────────────────────────────────┘
```

The two primary control variables are pressure drop and the liquid-to-gas ratio.

Although high particulate collection efficiencies may be obtained by venturi scrubbers, a very high pressure drop is required. Industrial applications often call for a pressure drop of from 20 to 60 inches of water column. A considerable amount of operating cost is associated with the energy required to force the entire flue gas stream through such high pressure drops.

Most venturi scrubber applications are operated by an induced draft fan (fan located downstream). It effectively pulls a vacuum which sucks the flue gases through the scrubber and separator. The fan can either be operated by a variable-speed motor or by a fixed speed motor with a damper for flow control.

Generally, greater particulate removal efficiency occurs with more scrubbing liquid provided to the throat of the venturi.

If the venturi is used only for PM control, pH is used only as a sensor for potential corrosion problems. However, if the venturi is for acid gas removal, pH is an important control parameter. In acid removal systems, the liquid is a caustic solution which neutralizes the acids. Such systems recirculate the solution, with a blowdown stream bled-off to remove particulates and gases. Fresh make-up solution is added to compensate for the lost liquid, with the amount of caustic being regulated so as to maintain the pH at 7.0 or slightly less.

Slide 19-21

```
┌──────────────────────────────────────────────────────┐
│   DISADVANTAGES OF VENTURI SCRUBBERS                 │
│                                                      │
│   High Energy Requirements, Pressure Drop            │
│   Liquid Waste Residue                               │
│   Corrosion and Erosion                              │
└──────────────────────────────────────────────────────┘
```

The disadvantages of venturi scrubbers include the high energy requirement associated with operating at high particulate collection efficiencies, the fact that liquid residues must be processed for clean-up, and the associated corrosion and erosion of metal surfaces.

REFERENCES

1. David A. Tillman et al., <u>Incineration of Municipal and Hazardous Solid Wastes</u>, Academic Press, Inc., New York, 1989, pp. 67, 85, 98, 143.

2. David B. Sussman, "Municipal Waste Combustion Ash: Testing Methods, Constituents, and Potential Uses," <u>Proceedings of the International Conference on Municipal Waste Combustion</u>, Volume 2, Sponsored by U. S. Environmental Protection Agency and Environment Canada, Hollywood, FL, 1989, pp. 11B-13 to 11B-25.

3. David S. Beachler and M. M. Peterson, <u>APTI Course SI:412A, Baghouse Plan Review--Self Instructional Guidebook</u>, U. S. Environmental Protection Agency, EPA-450/2-82-005, April 1982.

4. <u>Control Techniques for Particulate Emissions from Stationary Sources</u>, Volume 1, U. S. Environmental Protection Agency, EPA-450/3-81-005a, September 1982.

5. Illustrations of Reverse-Gas-Cleaned Baghouse and Shake/Deflate-Cleaned Baghouse, ABB Environmental Systems, ABB Flakt, Inc., April 1992.

6. <u>APTI Course SI:412B, Electrostatic Precipitator Plan Review--Self Instructional Guidebook</u>, U. S. Environmental Protection Agency, EPA-450/2-82-019, July 1983.

7. <u>Municipal Waste Combustion Study, Flue Gas Cleaning Technology</u>, U. S. Environmental Protection Agency, EPA/530-SW-87-021d, June 1987, pp 2-1 to 2-19.

8. PEI Associates, <u>Operation and Maintenance Manual for Electrostatic Precipitators</u>, EPA-625/1-85-017, September 1984.

9. John Richards, "Municipal Waste Incinerator Air Pollution Control Inspection Course," Submitted to U. S. Environmental Protection Agency, June 1991, p. 6-13.

10. <u>Municipal Waste Incinerator Field Inspection Notebook</u>, U.S. Environmental Protection Agency, EPA-340/1-88-007, July 1988, p. 150.

11. J. Joseph and David Beachler, <u>APTI Course SI:412C, Wet Scrubber Plan Review--Self Instructional Guidebook</u>, U. S. Environmental Protection Agency, EPA-450/2-82-020, March 1984.

20. FLUE GAS CONTROL II: ACID GAS REMOVAL

Slide 20-1

```
ACID GAS REMOVAL TECHNIQUES

Dry Scrubbers
     Spray Dry Absorber
     Dry Sorbent Injection
Wet Scrubber - Packed Tower
```

Dry scrubber systems get their name from the scrubbing action of materials that absorb chemicals and from the removal of the reaction products and particulate matter as dry materials. Sorbent materials can be delivered into the flue gas stream as either a liquid or dry material. The sorbents are partially converted into chemical products by reacting with absorbed gases.

The reaction products and residual reagent are typically collected along with the fly ash by ESPs or fabric filters. Dry scrubber systems are usually considered to be comprised of acid gas neutralizing components plus the PM removal components. The particulate collection performance is influenced by the flue gas temperature, total particulate loading, and ash properties.

Slide 20-2

```
BEST DEMONSTRATED TECHNOLOGY

New MWC Units
     Good Combustion Practices
     Spray Dry Absorber &
     Fabric Filter

Large Existing Plants
     Good Combustion Practices
     Dry Sorbent Injection & ESP

Very Large Existing Plants
     Good Combustion Practices
     Spray Dry Scrubber & ESP (or FF)
```

Various combinations of scrubbing equipment and reagents can be used for acid gas control. However, the NSPS and EG require that emissions be at least equivalent to that attainable by the use of the best demonstrated control technology (BDT) for MWC organics, MWC metals, and MWC acid gases.

The USEPA has established that at new units larger than 250 tpd the BDT for controlling MWC acid gas emissions includes spray dry absorbers with fabric filters (SDA/FF) along with good combustion practices. The primary acid gas collection occurs in the spray absorber. However, additional collection occurs as the gases pass through the fabric filter and react with the dry chemicals in the filter cake.

Dry sorbent injection systems with ESPs (DSI/ESP) are the BDT for existing units larger than 250 tons/day at "large existing plants" (from 250 to 1,100 tons/day capacity).

Spray dry absorbers with ESPs (SDA/ESP) are identified as best demonstrated technology for controlling acid gas emissions from existing units larger than 250 tons/day at "very large existing plants" (greater than 1,100 tons/day capacity). Therefore, units with an ESP should be able to meet its acid gases requirements adequately with the addition of a spray dry absorber unit.

Slide 20-3

SPRAY DRYER ABSORPTION PROCESS[1,2]

1. LIME FEEDER
2. LIME SLAKER
3. FEED TANK
4. HEAD TANK
5. SPRAY ABSORBER
6. DUST COLLECTOR
7. STACK

FLUE GAS

PARTICLE RECYCLE

DRY WASTE
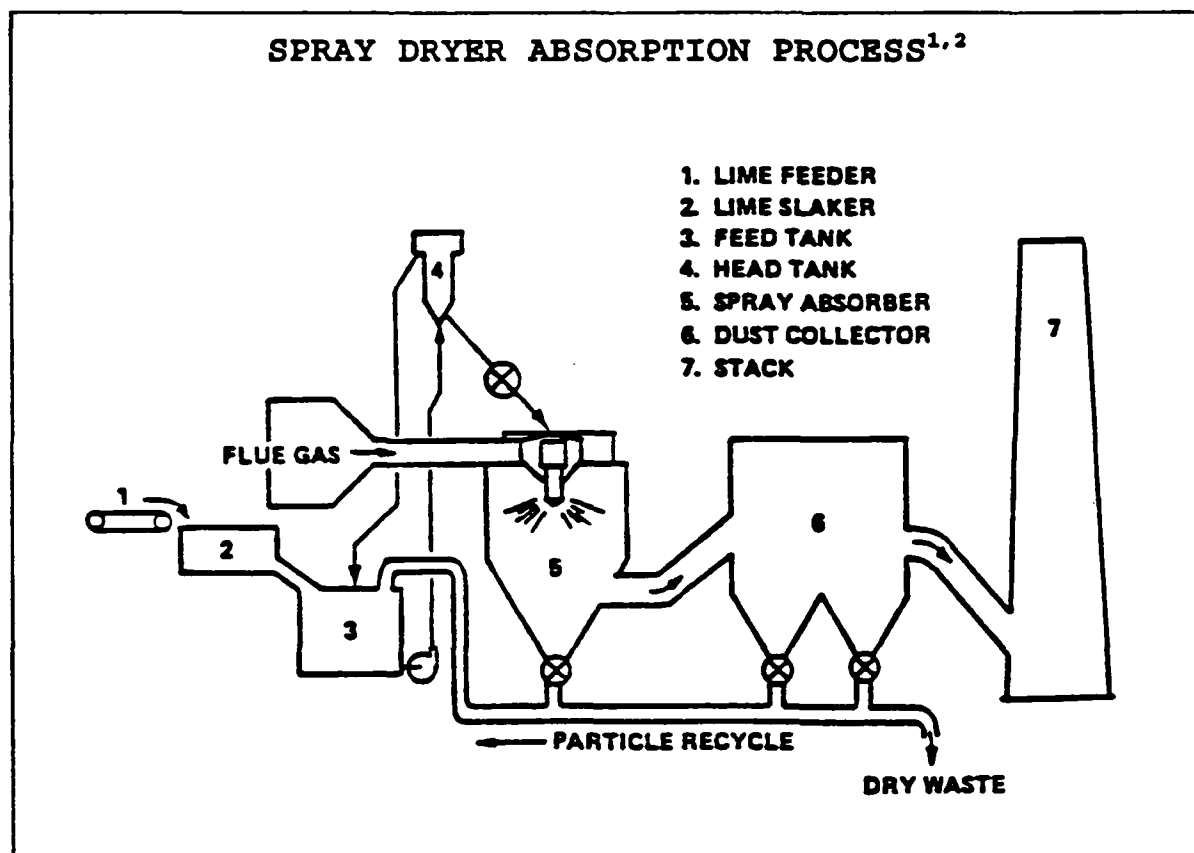
Spray dry absorbers are designed to remove acid gases. The typical slurry material is formed by blending pebble lime (CaO) with water to form wet calcium hydroxide (hydrated lime), an alkaline, sorbent material. The blending tank system, which is called a slaker, produces a liquid slurry which can range from 5 to 20 percent by weight of solids.[3] Screens are used to assure that the pebbles of lime remain in the tank and do not clog the slurry delivery piping.

The slurry is raised to the range of 165 to 190°F by the chemical energy released in the slaking process where the calcium hydroxide is produced. To prevent slurry solidification as a cement-type material, mixing the solution and maintaining its temperature to at least around 140°F are required.

Slide 20-4

```
SPRAY DRYER ATOMIZER & REACTION CHAMBER

Slurry Atomized to Fine Droplets
     High Speed Rotary Atomizer
     High Pressure Air Atomizer

Reaction Chamber Provides Residence Time for
     Acid Absorption on the Slurry Droplets

Slurry Droplets are Dried by Hot Flue Gas

Flue Gases are Cooled by Evaporation
```

The slurry is typically pumped to either a high speed rotary atomizer (e.g., 10,000 to 17,000 rpm) or to an air atomizer nozzle (e.g., 70 to 90 psig). Typically, a cone-shaped spray of small liquid droplets (e.g., 70 to 200 microns in diameter) is produced.[3] The flue gas flows through the spray, creating opportunities for collisions of gas molecules with droplets of sorbent material.

A reactor vessel which encloses the atomizer provides a period of residence time (e.g., up to 10 seconds[4]) for moisture evaporation from the slurry and for acid gas absorption on the surface of liquid droplets or solid particles. The typical reactor vessel length to diameter ratios are smaller for rotary atomizers than for air atomizers because of the spray shape.

Slide 20-5

SPRAY DRYER & FABRIC FILTER[5]
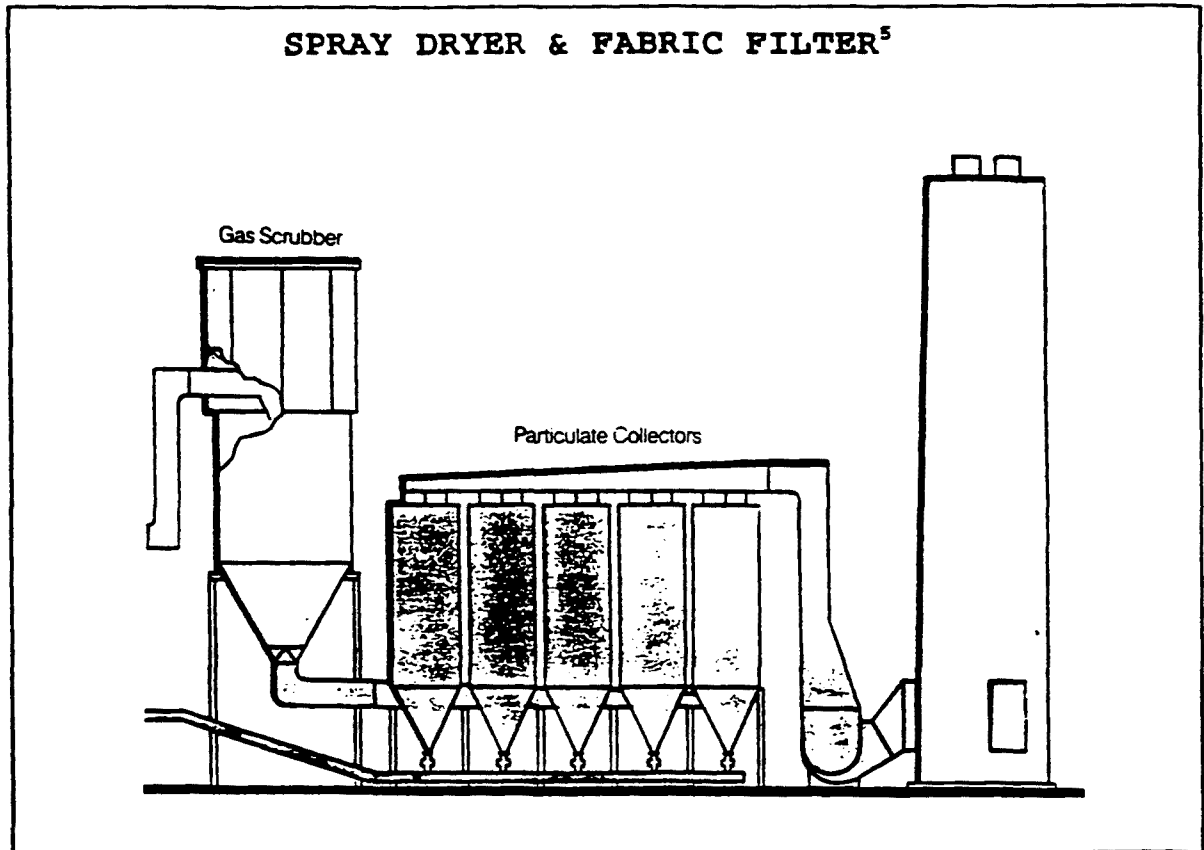
Courtesy of ABB Combustion Engineering, Incorporated

The acid gas absorption by calcium hydroxide (hydrated lime) is followed by the chemical reactions which produce calcium chloride and calcium sulfate. These reactions can occur in slurry droplets, on dried particles, and on the filter cake of the fabric filter.

Slide 20-6

SPRAY DRYER OPERATIONAL CONSIDERATIONS

1. Slurry Flow Rate
    Exit Acid Gas Concentration
2. Adequate Drying of Slurry Droplets
    Atomizer Maintenance
3. Overall Drying Conditions
    Exit Dry Bulb Temperature
    Exit Wet Bulb Temperature
    Exit Dry Bulb-Wet Bulb Difference
    Inlet-Exit Dry Bulb Difference
4. Slurry Water Content
    Exit Dry Bulb Temperature
5. Air Leakage Prevention
6. Maintenance of Hopper Temperatures

The slurry flow rate is designed to meet a desired reaction stoichiometric ratio. This stoichiometric ratio is defined as the ratio of calcium supplied in the lime slurry feed to the theoretical amount required to completely react with the SO_2 and HCl in the flue gas. Because of imperfect mixing of acid gases and sorbent, stoichiometric ratios have been reported to range from 1.2 to 1.3[3] up to as much as 2.2 and 3.0.[1]

Systems operating with the higher stoichiometric ranges are able to achieve SO_2 and HCl removal in excess of that required by the NSPS (see slide 12-4). As higher stoichiometric ratios are used, the amount of un-reacted sorbent goes up disproportionately. Various SDA/FF systems have been reported to remove over 90% of the hydrogen chloride gas and 85% of the sulfur dioxide.[6] An example MWC unit equipped with a SDA/FF system had 99% hydrogen chloride and above 93% sulfur dioxide removal, when operated at stoichiometric ratios from 2.4 to 3.0.[1] Some SDA/FF systems are able to remove above 99% of the heavy metals (nickel, cadmium, chromium and lead) and pilot scale tests have shown dioxin/furan emission reductions in excess of 99%.[7]

Example gas temperatures into and out of the spray dryer are 400°F and 250°F, respectively. In general, higher temperatures would help keep the absorber product dry, but the acid gas removal is more effective at the lower temperatures.[7]

The sorbent content can be adjusted to control acid gas removal, while dilution water in the slurry can be used to control gas temperatures leaving the SDA. Automatic control systems, which sense both downstream SO_2 concentration and temperature, can be used to control the slurry flow to the atomizer. Another control strategy is to set the feed rate appropriately for the maximum flue gas flow rate and acid gas concentration anticipated.

Slide 20-7

```
SPRAY DRYER OPERATIONAL PROBLEMS

1.   Slurry Droplets Sticking on Wall
2.   Liquid Carryover
3.   Caking of Solids on Fabric Filter
4.   Ash Hopper & Removal System Plugging
```

A number of problems have been experienced with spray dryer systems. Large slurry droplets from the atomizer can adhere to the vessel wall and create blockages and poor operations. Other problems include liquid carryover from the absorber vessel, caking of solids on the fabric filter, and ash hopper and removal system plugging. These problems are often of particular concern during the start-up of the system.

It is important for the slurry droplets to be dried adequately before impacting the surface of the reactor vessel. If drying is inadequate, a wet powder can build up on downstream surfaces. If the drying is too fast, acid absorption will be reduced.

A requirement for good drying is to have the atomizer produce uniform droplets of appropriate sizes. Atomizers can be removed from service for cleaning. However, this may require a system outage, unless multiple atomizers are available to permit system operation during the servicing of a single atomizer.

Even if the droplet sizes are appropriate, the overall drying process must be controlled. The difference between the dry bulb and the wet bulb temperature at the reactor vessel exit can be used as an indication of the relative humidity and overall drying conditions. Some control systems monitor the wet and dry bulb temperatures and modify the flow rate of slurry accordingly.

The water content in the slurry will also influence the amount of drying. Slaker operations can be modified to control the water content in response to exit flue gas temperature, although the time response for this control is slow.

Hopper heaters and adequate insulation are important techniques for reducing ash handling problems. In addition, seals must be maintained to prevent air leakage into the system, as ambient air can cause cooling and introduce excessive moisture. Seal leaks can cause serious problems for fabric filters and ash hoppers because calcium chloride absorbs water readily and becomes a putty or paste material.

Slide 20-8

DRY SORBENT INJECTION SYSTEM[7]
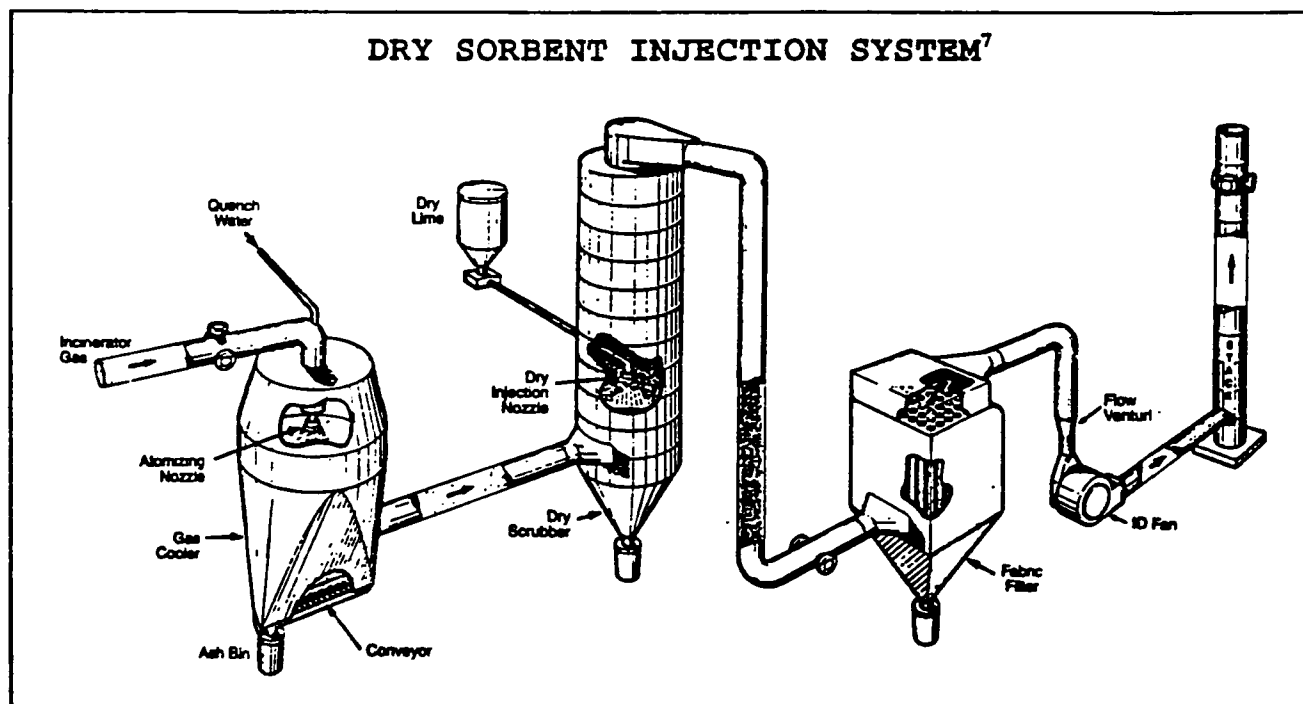
Courtesy of ABB Flakt, Inc., printed with permission

Dry sorbent injection (DSI) systems deliver a stream of dry hydrated lime (calcium hydroxide) powder into the flue gas. The powdered sorbent can be delivered directly into the flue gas by a blower.

Hydrated lime, which has been ground to the consistency of talcum powder, is commercially available and is often used as the sorbent. Magnesium oxide and sodium bicarbonate are alternative sorbent materials which can be used for acid gases. Activated carbon injection is a potential aid for enhancing the adsorption of mercury and dioxin/furan emissions.

The stoichiometric ratios for DSI systems are generally above those of SDA systems. Designers will consider the economic trade-off associated with the maintenance and operational costs of operating the slaker and atomizer versus the extra cost of dry sorbent materials.

An automatic control system is generally provided to regulate the delivery of the sorbent from the storage and into the air stream. The storage bin may be equipped with a shaker and screw auger feeder and rotary airlock to control the delivery rate and prevent clumping of the sorbent.

The optimum temperature for the dry adsorption of acid gases is between 250° and 350°F, with some recommendations urging operation at the lower temperature.[3]

Many DSI/FF systems for refractory wall MWC units require provisions for heat exchangers or evaporative cooling of the flue gas before the sorbent is added. The cooling chamber would be located upstream of the lime injection point, as illustrated above.

Most water-wall MWC units are able to obtain adequate gas temperature control from the upstream heat exchangers, so water sprays are not typically used in these applications.

Most system designs provide for a mixer or reactor vessel to be located between the injection point and the fabric filter.

Slide 20-9

```
DRY  SORBENT  OPERATIONAL  PROBLEMS

Ash Removal from Collection Hopper
      Air Impactors
      Vibrators
      Hopper Heaters & Insulation
      Maintenance of Air Seals
```

The main operational problem with dry sorbent systems is the removal of the final product from the ash collection hopper. Although the material is light, it has cohesive properties that lead to material accumulation on the hopper walls. Removal by pneumatic suction leads to air channeling and incomplete removal.

Some combination of air impactors, hopper vibrators, hopper heaters, adequate insulation, and proper maintenance of seals to prevent air leakage is required to assist the removal process.

Slide 20-10
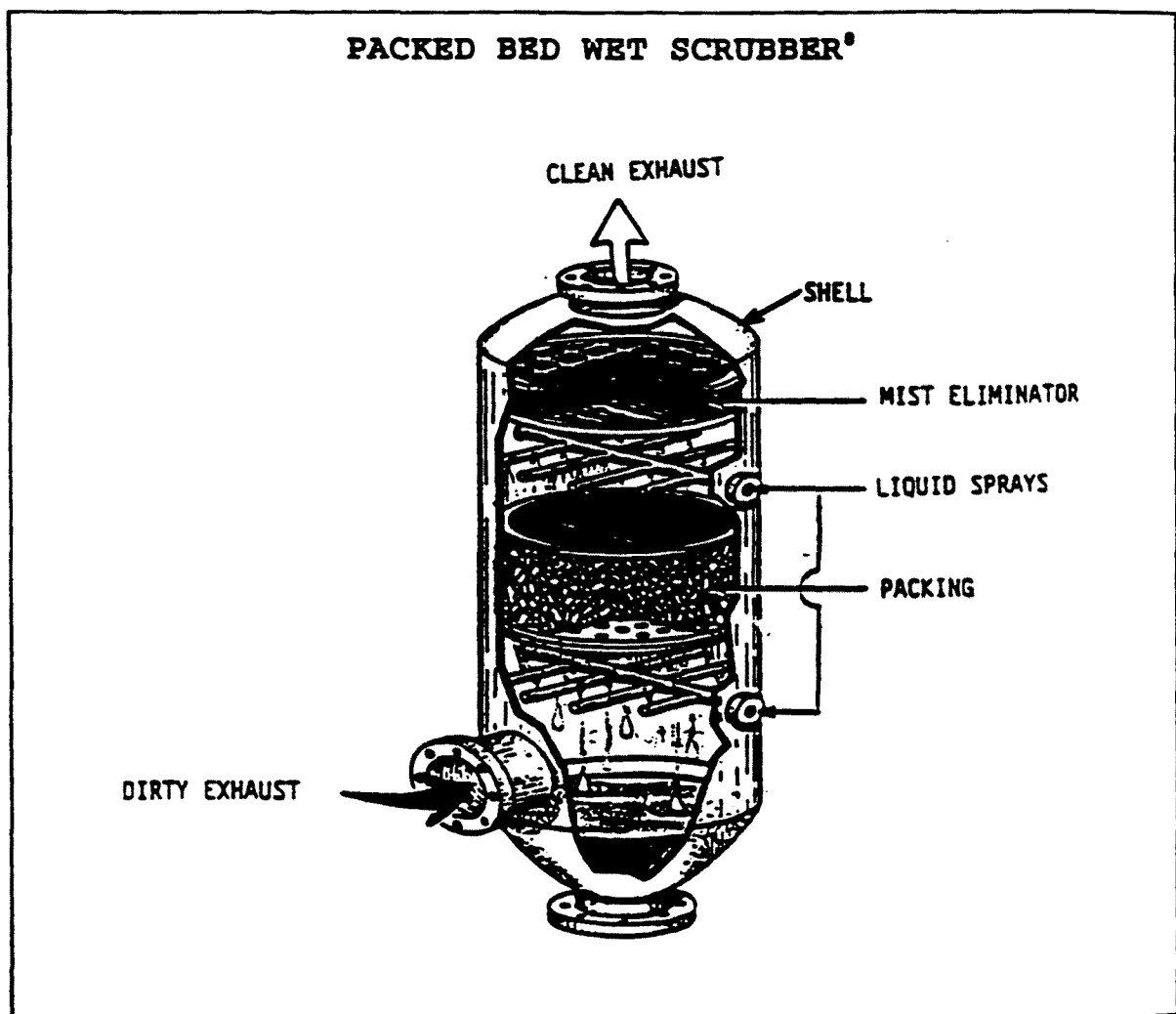
Wet scrubber equipment combinations have been considered for removing both acid gases and particulates. A typical combination would be a venturi scrubber, which primarily achieves particulate removal, and a packed bed scrubber supplied with a sodium hydroxide solution for acid gas removal. Venturi scrubbers may operate entirely with water for PM removal or with a caustic solution for both acid gas and PM control. Packed towers are provided with various packing materials which can provide greater liquid surface areas for enhanced acid gas removal.

```
┌─────────────────────────────────────────────────────┐
│              WET SCRUBBER APPLICATIONS               │
│                                                       │
│     Advantages                                        │
│          Handles Gases & Particulates                 │
│                                                       │
│     Disadvantages                                     │
│          May Not be Able to Meet Standards            │
│          High Pressure Drop (Energy Cost)             │
│          Liquid Residue Produced                      │
│          Corrosion and Erosion of Metals              │
└─────────────────────────────────────────────────────┘
```

Wet scrubbing systems (e.g., venturi and packed bed) are not currently used in the United States for MWC applications. It is unclear if such systems can meet the federal PM emission limits in the NSPS and EG. In addition, concerns exist about wet scrubbers' abilities to remove and control dioxin/furan and metal emissions.

In general, dry systems are found to operate with higher collection efficiencies and more reliably and economically.

Wet scrubbing systems have high maintenance and operating costs associated with treating the liquid waste, controlling erosion, and providing energy for the pressure drop. A contaminated wet sludge is a waste stream from a wet scrubber. It has generally higher disposal cost than the dry residues of fabric filter and ESP equipment.

Considerable erosion and corrosion of metal surfaces can occur with wet scrubbing systems. Erosion is particularly a problem with the high energy venturi scrubbers, where gases are often accelerated up to 400 ft/sec. The entrained particulates can cause serious erosion, essentially sand-blasting metal surfaces. Corrosion is associated with the imperfect neutralization of the absorbed gases, leading to acidic and caustic reactions, particularly on metal surfaces which have undergone erosion.

REFERENCES

1. Theodore G. Brna, "Cleaning of Flue Gases from Waste Combustors," Combustion Science and Technology, Vol. 74, 1990, pp. 83-98.

2. T. G. Brna and C. B. Sedman, "Waste Incineration and Emission Control Technologies," International Congress on Hazardous Materials Management, Chattanooga, TN, 1987.

3. Richards Engineering, "Municipal Waste Incinerator Field Inspection Notebook," U. S. Environmental Protection Agency, EPA-340/1-88-007, July 1988, pp. 45-55.

4. William Ellison, "Flue-Gas Desulfurization," Standard Handbook of Power Plant Engineering, Thomas C. Elliott, editor, McGraw Hill Book Co., NY, 1989, pp. 4.95-4.115.

5. "Prepared Fuel Steam Generation System," ABB Resource Recovery Systems, Windsor, Connecticut, Undated Pamphlet.

6. C. David Gaige and Richard T. Halil, Jr., "Clearing the Air About Municipal Waste Combustors," Solid Waste & Power, January/February 1992, pp. 12-17.

7. Robert G. McInnes, "Spray Dryers and Fabric Filters: State of the Art," Solid Waste & Power, April 1990, pp. 24-30.

8. J. Joseph and David Beachler, APTI Course SI:412C, Wet Scrubber Plan Review--Self Instructional Guidebook, U. S. Environmental Protection Agency, EPA-450/2-82-020, March 1984.

21. FLUE GAS CONTROL TECHNOLOGY III: NOx CONTROL

Slide 21-1

```
┌─────────────────────────────────────────────────────────────┐
│         POSSIBLE NOx CONTROL TECHNIQUES FOR MWCs             │
│                                                             │
│    COMBUSTION MODIFICATION                                  │
│         Combustion with Limited Excess Air                  │
│         Two-Stage Combustion Design                         │
│         Three-Stage Combustion Design                       │
│                                                             │
│    FLUE GAS TREATMENT                                       │
│         Selective Non Catalytic Reduction (SNCR)            │
│         Selective Catalytic Reduction (SCR)                 │
└─────────────────────────────────────────────────────────────┘
```

Most of the NOx from MWC units is produced as fuel NOx, although MSW has a fairly low nitrogen content. The techniques listed above for controlling fuel NOx emissions are presented in this learning unit.

Slide 21-2

```
┌─────────────────────────────────────────────────────────────┐
│    COMBUSTION MODIFICATION FOR FUEL NOx CONTROL            │
│                                                             │
│       1.  Combustion with Limited Excess Air               │
└─────────────────────────────────────────────────────────────┘
```

A full range of actual combustion conditions is simultaneously formed along the grate and within the combustion region above the grate. This is caused by the variations in the local delivery of under-fire and over-fire air and the fuel's variable drying, distillation, and combustion characteristics. Consequently, although the combustion can be characterized as occurring with excess air, a wide range of stoichiometric combustion conditions actually are found.

If limited excess air conditions are maintained in the early stages of combustion, some degree of NOx control would be expected. As lower levels of oxygen are delivered, lower fractions of the bound fuel-nitrogen will be converted to NOx. Although this results in some NOx control, there is concern about the pockets of fuel-rich mixtures which potentially pass through the combustion zone and produce products of incomplete combustion, including CO and MWC organic emissions.

Therefore, in order to obtain acceptable combustion in MWCs an adequate overall level of excess air must be delivered and the corresponding level of NOx control is limited.

```
COMBUSTION MODIFICATION FOR FUEL NOx CONTROL

  2.  Two-Stage Combustion in Starved-Air Units
          Sub-Stoichiometric Primary Combustion
          Excess Air Secondary Combustion
```

Two-stage combustion is an integral feature of the design of modular starved-air and controlled-air incinerators. The primary chambers of starved-air units can be thought of as low NOx burners. These systems can typically meet the NSPS NOx limits without the need for flue gas treatment.

Modular starved-air units achieve sub-stoichiometric conditions in the primary chamber by limiting the air to about 40% of that theoretically required for complete combustion.[1] The pyrolysis process which occurs converts most of the fuel nitrogen to molecular nitrogen. This nitrogen does not react and form NOx in the secondary chamber because temperatures are below those required for producing thermal NOx.

Controlled-air incinerators are very similar to starved-air units, except that the requirement of maintaining sub-stoichiometric conditions in the primary chamber may be relaxed.

Slide 21-4

```
POSSIBLE NOx CONTROL TECHNIQUES FOR MWCs

  3.  Three-Stage Combustion Design
          Gas Reburning
          Controlled Mixing - Low NOx Burner
```

Gas reburning is a three-stage NOx control technique which has been applied in various fossil fuel power plants. Conventional gas reburning techniques are not generally used as a control technique for MWC NOx.

In gas reburning, the first stage of combustion is under excess air conditions. The second stage occurs downstream where an auxiliary fuel is injected into the combustion product gases. The auxiliary fuel is typically natural gas or some other low nitrogen content fuel. Reburning is generally designed to occur in the radiant section of the furnace, so that auxiliary fuel is part of the overall energy input.

Reburning creates a reducing atmosphere with about 90 percent of the theoretically required air.[2] The reburn fuel and NO are primarily converted to CO, N_2, and H_2O. A third combustion stage is required after reburning in order to convert the CO to CO_2.

It is possible for reburning to occur with the use of a conventional auxiliary fuel burner. However, auxiliary fuel burners typically operate under excess air conditions and are designed to increase combustion gas temperatures. Modifications would be required to produce the required reducing atmosphere and the subsequent downstream addition of air for complete combustion.

Low-NOx burners for conventional fossil fuels feature controlling the mixing of the fuel and air, so as to limit the delivery of oxygen to the fuel and reduce combustion intensity (hot spots).

Rotary waterwall combustors appear to have some features of a low NOx burner, in that they have been able to meet the NSPS NOx limit of 180 ppm without the need for flue gas treatment.[3,4]

The rotary waterwall combustors have a different gas flow geometry from other grate burning MWC systems. As the product gases flow down the rotating chamber toward the exit, they mix with the volatile and other gases from the downstream rotary grate sections. Undoubtedly there are reactions of the combustion product gases with the volatile gases. These appear to result in a form of reburning, where the volatile MSW gas is the reburn fuel. Although excess air conditions are found in the gases leaving the rotary chamber, local conditions in the tumbling fuel bed may approximate the reburning conditions.

Slide 21-5

```
FLUE GAS NOx CONTROL

Selective Non-Catalytic Reduction (SNCR)

Selective Catalytic Reduction (SCR)
```

The selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR) techniques have some important similarities to gas reburning. Materials are injected into the product gases to create a reducing atmosphere for the dissociation of NO into molecular nitrogen, water and carbon monoxide.

The contrasting feature is that gas reburning provides an additional fuel input into the furnace combustion zone, whereas the SNCR and SCR reagents are generally injected after the combustion zone.

```
┌─────────────────────────────────────────────────────────┐
│                                                         │
│        BEST DEMONSTRATED CONTROL TECHNOLOGY             │
│                                                         │
│        Selective Non-Catalytic Reduction (SNCR)         │
│                                                         │
│        Reagents:   Ammonia, Urea, Other Compounds       │
│                                                         │
└─────────────────────────────────────────────────────────┘
```

NOx emission limits are included in the federal New Source Performance Standards for new MWC units. The USEPA has established that selective non-catalytic reduction (SNCR) is the Best Demonstrated Technology for NOx control for large MWCs.

The operation of SCNR systems requires the injection of a reagent material which can react with nitrogen oxide (NO) to produce nitrogen gas (N_2). A number of reagent materials can be used. Ammonia and urea are the most widely used reagents. The process using ammonia for SCNR is generally known as Thermal de-NOx, which is patented by EXXON. The process using urea for SNCR is patented by the Electric Power Research Institute. Chemicals such as hydrazine hydrate, methanol, ammonium sulfate and other compounds are also effective SNCR reagents.

```
┌─────────────────────────────────────────────────────────┐
│                                                         │
│              SNCR PERFORMANCE FACTORS                   │
│                                                         │
│     Reagent Selection                                   │
│     Temperature Region:   1,600° - 1,800°F              │
│     CO Concentration                                    │
│     Residence Time                                      │
│     Reagent Injection Rate Keyed to NO                  │
│     Gas Mixing Efficiency                               │
│                                                         │
└─────────────────────────────────────────────────────────┘
```

The major operational factors which influence the performance of SNCR are listed above. A properly designed SNCR system is required to have controls which take into consideration the influences of these factors.

The most important constraint is the temperature of the flue gases into which the reagent is injected.[5,6] Although the process will often work in the design temperature window from 1,600° to 1,800°F, the temperature at which the process works best will vary depending upon which reagent is used and on the specific features of the application.

For instance, a complicating factor is that as the concentration of CO increases, there is a shift of the effective range for the reduction reaction to lower temperatures. Because of the variability of the combustion conditions, the practical limit of NO reduction is considerably less than would occur under ideally controlled mixture conditions.

Under steady conditions, the relative rate of reagent injection must be set to obtain the amount of NO reduction desired. However, the fuel burning rates and combustion gas temperatures will vary as the fuel properties change. Corresponding variations will occur in residence times and NO concentrations. Therefore, the injection rate must be metered in response to demand.

In addition, mixing of reagent and combustion gases must be appropriately controlled. The usual application includes a heater for the reagent and a carrier gas stream to enhance injection of the reagent into the furnace.

Either steam or compressed air can be used as the carrier gas. In some applications the reagent is mixed with recirculated flue gas before being injected into the flue gas stream. An air compressor or blower can be used to deliver the mixture to various damper controlled nozzles which will control the injection location and to regulate its delivery and mixing rate.

Slide 21-8

```
COMPETING REACTIONS OF AMMONIA

Reduction:
    NH₃ + NO + 0.25 O₂ ---> N₂ + 1.5 H₂O

Oxidation (Flue Gas too Hot):
    NH₃ + 1.25 O₂ ---> NO + 1.5 H₂O

No Reaction (Cool Flue Gas, Ammonia Slip):
    NH₃ ---> NH₃
```
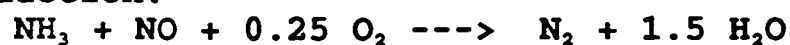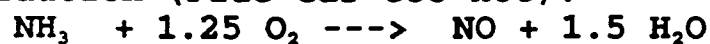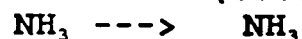
Operators should be aware that there are three possible reactions which can occur when reagents are injected into the flue gas. The reduction reaction, oxidation reaction, or neither type of reaction may dominate, depending upon the combustion gas temperature and local mixture conditions.

Ammonia will be used to illustrate the three types of reactions because it undergoes a fairly simple set of chemical reactions. The first reaction in Slide 21-8 is the reduction reaction, in which the ammonia causes the NO to be reduced back to molecular nitrogen. As noted below, this reduction process generally occurs if the gases are in the right temperature range.

However, if the gas temperatures are too high (e.g. above 2,000 °F), the ammonia will undergo an oxidation process, forming additional NO.

If the gas is too cool, the ammonia will simply flow out with the combustion gases, or "slip" through (or break through) without being reacted or influencing nitrogen oxide.[6]

If excessive ammonia is injected, some of it may react with HCl or sulfur compounds, forming ammonium chloride or ammonium sulfate. These two products cause the formation of a white or blue smoke, respectively, as discussed in Learning Unit 15.

Slide 21-9

+---+
| CHEMICAL DECOMPOSITION OF UREA, $CO(NH_2)_2$ |
| |
| $CO(NH_2)_2$ ---> NH_3 + HNCO (Iso-cynauric acid) |
+---+

Upon being injected into the furnace, urea decomposes to ammonia and iso-cyanuric acid (HNCO). The ammonia fraction performs in much the same way as in the thermal de-NOx process. The iso-cyanuric acid can also react with NO to cause its reduction.

Slide 21-10

+---+
| SELECTIVE NON-CATALYTIC REDUCTION (SNCR) |
| |
| Operational Problems |
| Furnace Temperature Variations |
| Spacial and Temporal Variations |
| NO Increases if T > 2,000 °F |
| Ammonia Slip - Can React to Form |
| Ammonium Chloride & White Smoke |
+---+

If too much reagent is injected or if the mixing or temperature levels are inappropriate, some of the reagent can slip through unreacted.[6] This reagent can subsequently react into such compounds as ammonium chloride, ammonium sulfide,

or ammonium bisulfide. These materials may cause plume opacity and/or corrosion problems. White smoke from ammonium chloride is often observed in the plume from a MWC unit using this control technology.

If hydrogen gas is blended with the ammonia, the operating window of gas temperatures can be expanded to include lower temperatures.[5] Although, this technique is not commonly used in MWC applications, it could help compensate for the flue gas variability found at MWC units.

Slide 21-11

```
┌─────────────────────────────────────────────────┐
│                                                 │
│     SELECTIVE CATALYTIC REDUCTION (SCR)         │
│                                                 │
│          Reagent:   Ammonia                     │
│                                                 │
└─────────────────────────────────────────────────┘
```

In the selective catalytic reduction (SCR) process, ammonia is injected into properly selected locations of the flue gas path where a catalyst bed is installed. Many metals such as copper, iron, chromium, nickel, molybdenum, vanadium and cobalt can be used as the catalyst material. In general, catalyst systems have high capital costs.

The major problem with catalyst systems is that the gas must be cleaned before the catalyst is used. If any dirty gas were to come in contact with the catalyst, its surface would become fouled by the particulate and/or condensable materials. The conversion performance would be considerably decreased by fouling of the catalysts.

Therefore, a designer would have to provide for flue gas cleaning and for controlling the formation of dioxins/furans on the fly ash, before the gases enter the SCR process. Assuming that a spray dry absorber and fabric filter system is used, the flue gas would be cooled to somewhere around 400°F. This temperature is below the optimum operating temperature range for the catalysts, which generally range from 530° to 800°F.[6]

Therefore, the flue gas would have to be reheated, requiring either a considerable expenditure for auxiliary fuel or the application of a air-to-air heat exchangers. Either of these would require increased capital and operating costs. Because of the associated costs, SCR has not been widely adopted for NOx control at MWC installations.

REFERENCES

1. W. R. Seeker, W. S. Lanier, and M. P. Heap, "Municipal Waste Combustion Study, Combustion Control of Organic Emissions," U.S. Environmental Protection Agency, EPA-530-SW-87-021-c, June 1987, pp. 4.8 to 4-14 and 7-1 to 7-14.

2. Craig A. Penterson et al., "Natural Gas Reburning Technology for NOx Reduction from MSW Combustion Systems," Proceedings of 1990 ASME National Waste Processing Conference, Long Beach, CA, June 1990, pp. 185-191.

3. David S. Beachler and Nancy M. Hirko, "Air Emission Test Results from the Dutchess County Resource Recovery Facility," Proceedings of 1990 ASME National Waste Processing Conference, Long Beach, CA, June 1990, pp. 405-416.

4. David S. Beachler and Nancy M. Hirko, "Nitrogen Oxide Emission Rates from Waste-to-Energy Plants Using Westinghouse O'Conner (Rotary) Combustors," Proceedings of 1990 ASME National Waste Processing Conference, Long Beach, CA, June 1990, pp. 235-247.

5. Michael Medock, "An Overview of Non-Catalytic NOx Control," Solid Waste and Power, February 1990, pp. 46-51.

6. Ramon Li et al., "Identifying and Controlling WTE Stack Emissions," Solid Waste and Power, February 1990, pp. 16-22.

22. AUTOMATIC CONTROL SYSTEMS

Slide 22-1

```
┌─────────────────────────────────────────────────┐
│                                                   │
│       MWC SYSTEMS REQUIRING CONTROL               │
│                                                   │
│       1.   Crane Operation                        │
│       2.   Combustion Control System              │
│       3.   Ash Handling System                    │
│       4.   Flue Gas Cleaning System               │
│       5.   Turbine-Generator                      │
│       6.   Feedwater Demineralizer Plant          │
│       7.   Boiler Feedwater & Condensate          │
│       8.   Motor Controllers                      │
│       9.   Cooling Water                          │
│                                                   │
└─────────────────────────────────────────────────┘
```

Many important systems or processes within MWC units, such as those listed above, require some appropriate combination of manual and automatic controls to achieve stable and safe unit operations.[1]

Manual controls include the simple on/off and variable switches which are used by operators to power electrical equipment and to position valves and dampers.

For example, the operator of an overhead crane will control the movement of the crane, the location of each grapple load, and where it is to be deposited. However, the pressure exerted by the grapple, the height the grapple load is lifted, and its claw movements are generally automatically controlled. In addition, the crane often has provisions for a load cell and a microprocessor-based data processing unit to automatically weigh the load before it is deposited in the charging hopper. The operator may be required to manually record the weight of each grapple load.

Slide 22-2

```
┌─────────────────────────────────────────────────┐
│                                                   │
│       AUTOMATIC CONTROLS SYSTEM FUNCTIONS         │
│                                                   │
│       1.   Modulating Control                     │
│       2.   Sequential Control Logic               │
│       3.   Process Monitoring                     │
│                                                   │
└─────────────────────────────────────────────────┘
```

Automatic controls provide for the automatic modulation of control variables, the control of sequences of logical events, and the monitoring of the operational status of various processes and/or systems. Modulating controls use variable equipment settings for operation under various load conditions.

Sequential logic controllers are used to assure safe and appropriate operations during transient conditions such as start-up, materials charging, soot blowing, ash removal and shut-down operations.

Monitoring of the operational status of various systems or processes can be accomplished with the aid of panel-mounted indicating lights, alarm annunciators, instruments and recorders for selected physical parameters (e.g., fluid flow rates, temperatures, pressures, and gas concentrations). Monitors can provide a warning of potential upset conditions as well as associated data which may be used to evaluate the possible causes and remedies for such conditions.

Slide 22-3

```
TYPES OF AUTOMATIC CONTROL SYSTEMS

1.  Pneumatic
2.  Hard-wire Electronic Analog
3.  Programmable Logic Controllers
        Microprocessor-Based
        Distributive Control Systems
```
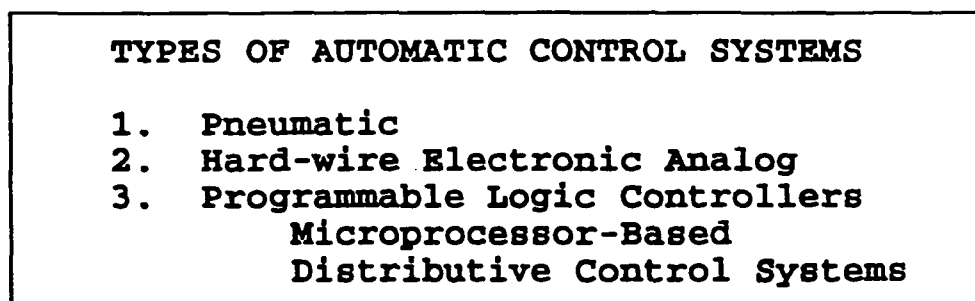
Modulation of a particular system variable can be obtained through use of either dedicated pneumatic controllers, hard-wired electronic analog controllers or programmable logic controllers (PLCs).

Slide 22-4

PNEUMATIC CONTROL LOOP: FLOW CONTROL
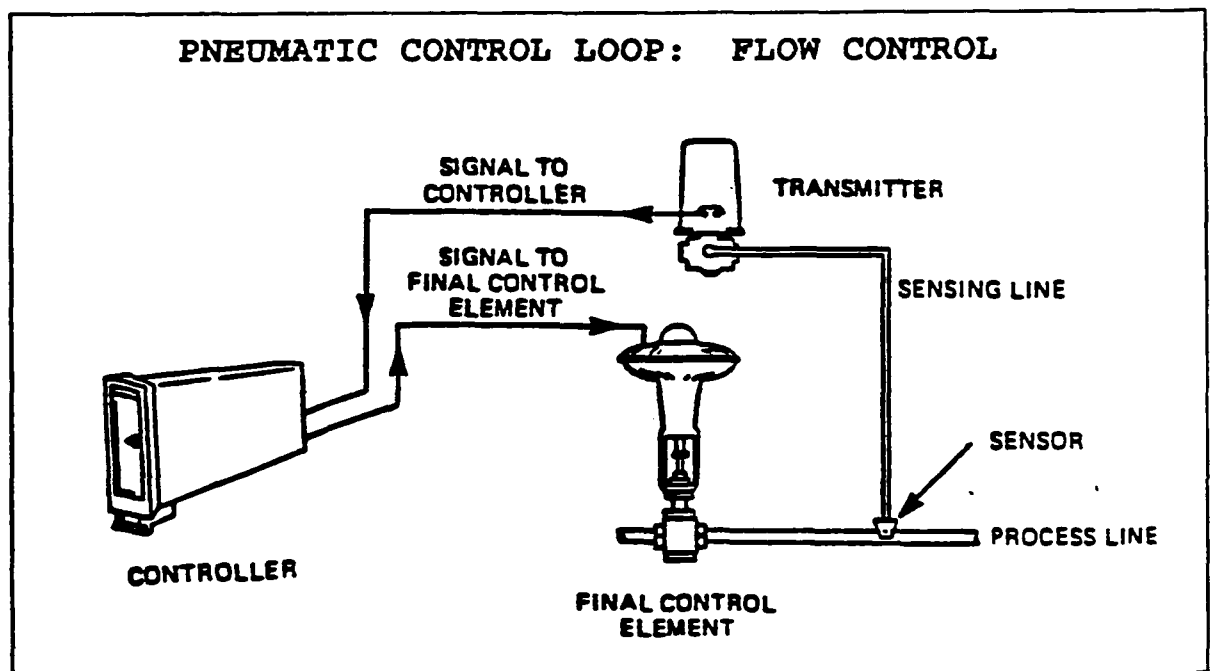
Dedicated pneumatic systems, such as shown in the above slide, and hard-wired controllers have been widely used in combustion units.

Microprocessor-based distributed control systems with PLCs are most often used in new MWC applications. A distributive control system is one where a number of micro-computers or PLCs are distributed around the unit to provide local control of specific equipment.

The various PLCs are then tied together by a data highway into a computer network. This allows the control and sensor signals to be accessed from throughout the system. The system also allows for self-checking and redundancy, so that a unit may be able to continue to operate with a malfunctioning controller or sensor. The operator is notified of the malfunction by light indicators and alarm annunciators.

Slide 22-5

```
AUTOMATIC CONTROL SYSTEM ELEMENTS

1.   Manipulated Variable (Parameter)
2.   Measuring Device (Transducer)
3.   Feedback Signal
4.   Set Point (SP)
5.   Controller
6.   Actuating Signal
7.   Final Control Element (FCE)
8.   Status Indicator
```

The typical elements of a control system are listed above. An electronic-based control system will be assumed in the following presentation, although pneumatic control systems use almost the same principles.

A simple control system measures the difference between a feedback signal and its set point (SP) or reference value to determine the appropriate change in equipment operation. The manipulated variable is the control parameter being regulated. It is generally measured by a sensor and transducer device which produces an electrical feedback signal for comparison with the set point signal.

A controller produces a signal which is sent to a final control element (FCE) to modify the operation of the equipment. The status indicators could include indicating lights, alarm annunciators, and instrument recorders and readout devices.

Control systems are designed to respond to transient operating conditions by automatically correcting the equipment settings. Under various system disturbances, operators will need to make modifications such as: changing the set point, changing the controller gain (bias), or switching to the manual mode to control the equipment.

Slide 22-6

```
┌─────────────────────────────────────────────────┐
│        GAS-SIDE CONTROL PARAMETERS              │
│                                                 │
│     1.  Air Flow Rate                           │
│     2.  Opacity                                 │
│     3.  Oxygen Content                          │
│     4.  Carbon Monoxide                         │
│     5.  Draft                                   │
│     6.  Combustion Temperature                  │
│     7.  Flue Gas Temperature at APCD            │
└─────────────────────────────────────────────────┘
```

The gas-side parameters listed above may be used as control parameters in automatic combustion control systems. Each combustion equipment vendor will have a unique combustion control system which probably considers at least four of the above parameters.

Slide 22-7

```
┌─────────────────────────────────────────────────┐
│        WATER-SIDE CONTROL PARAMETERS            │
│                                                 │
│     1.  Steam Temperature                       │
│     2.  Steam Pressure                          │
│     3.  Steam Flow Rate                         │
│     4.  Drum Level                              │
│     5.  Feedwater Flow Rate                     │
└─────────────────────────────────────────────────┘
```

The water-side parameters listed above may be used as control parameters for combustion control systems. In addition, pH is an important water treatment control parameter for maintaining optimum heat transfer and system performance.

Slide 22-8

```
┌─────────────────────────────────────────────────┐
│        FINAL CONTROL ELEMENTS                   │
│                                                 │
│     1.  Grate Speed/Ram Speed                   │
│     2.  Timer Delay Period (Dwell Time)         │
│     3.  Valve Position                          │
│     4.  Damper Position                         │
│     5.  Motor/Fan/Pump/Turbine Speed            │
│             Variable Speed Drive                │
└─────────────────────────────────────────────────┘
```

The final control elements listed above may be used by control systems to achieve the desired equipment operational changes.

SINGLE-ELEMENT CONTROL SYSTEM: DRAFT[2]
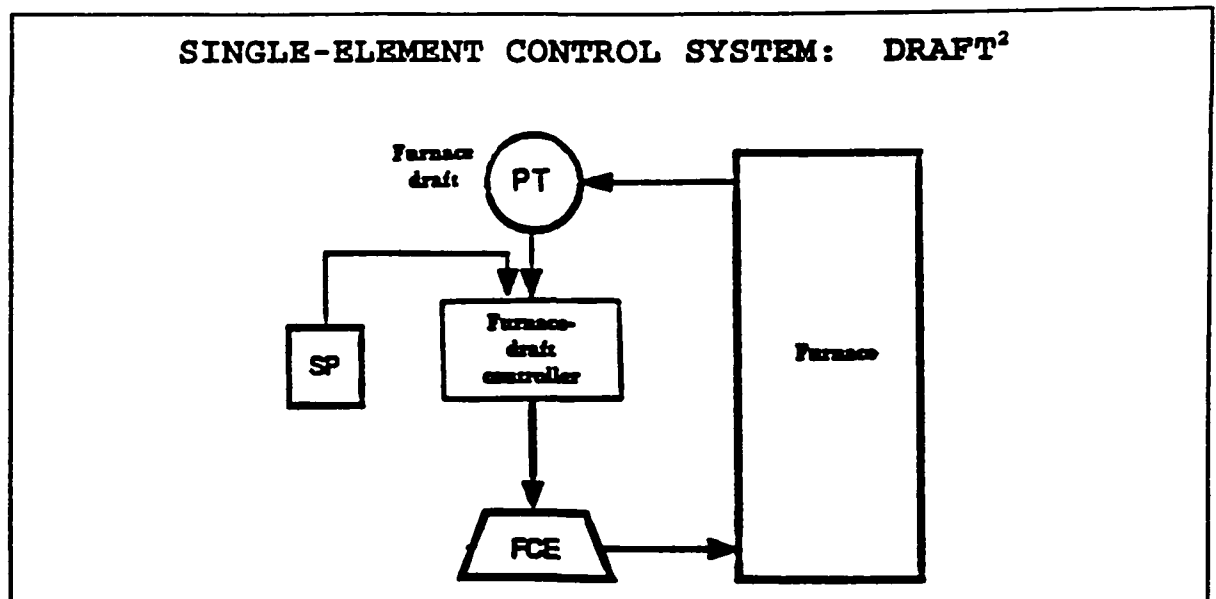
Adaptation of a Figure of the Instrument Society of America

A furnace draft controller is an example of a simple, single-element control system which generally operates very well. An internal damper or flow control device can be used to restrict the flow of gases through the furnace. The pressure transducer (PT) measures furnace pressure above atmospheric conditions. The controller compares the value with the set point (SP) and then sends a signal to a final control element (FCE).

Slide 22-10

SINGLE-ELEMENT CONTROL SYSTEM: DRUM LEVEL[2]
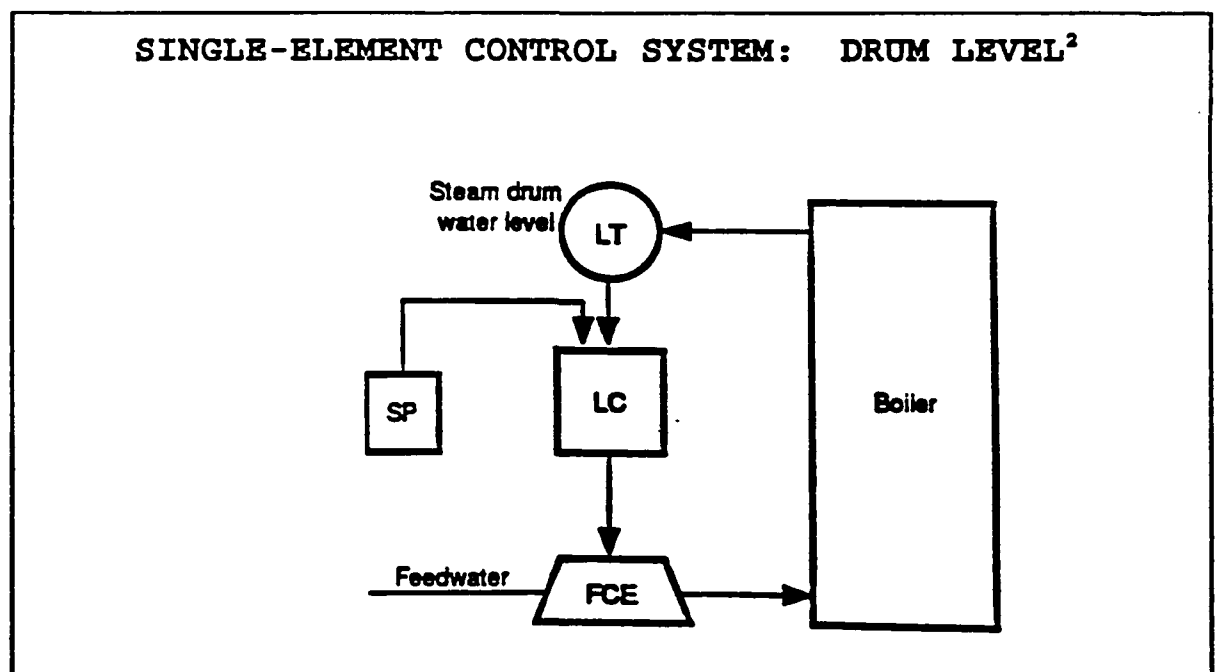
Courtesy of the Instrument Society of America

The drum level requirement is that the level of liquid in the boiler be maintained, so that the boiler neither runs dry nor delivers liquid into the superheater coils.

A single-element drum level controller (LC) would receive a signal from a level transducer (LT) for comparison with the set point. Single-element drum level controllers, however, produce unstable drum level conditions because they are incapable of considering logic based on the phenomena of "shrink and swell."

When steam flow increases (e.g., throttle valve is opened), the boiler steam pressure drops. The reduced pressure causes the mixture of vapor and water in the boiler to expand. This phenomenon, called "swell," results in an increase in the level of water in the boiler drum. A single-element controller would sense this act and reduce the feedwater flow into the boiler.

However, a simple mass balance tells us that as steam flow goes up the feedwater flow should be increased. Incidentally, increasing the flow of relatively cold feedwater into the boiler will also decrease the average temperature and increase the mixture density in the boiler, which could somewhat offset the "swell" condition.

The alternate problem is that of "shrink," which occurs during a reduction of steam flow. Shrink occurs with an increase of steam pressure and density and a decrease in drum level.

Slide 22-11

TWO-ELEMENT CONTROL SYSTEM: DRUM LEVEL[2]
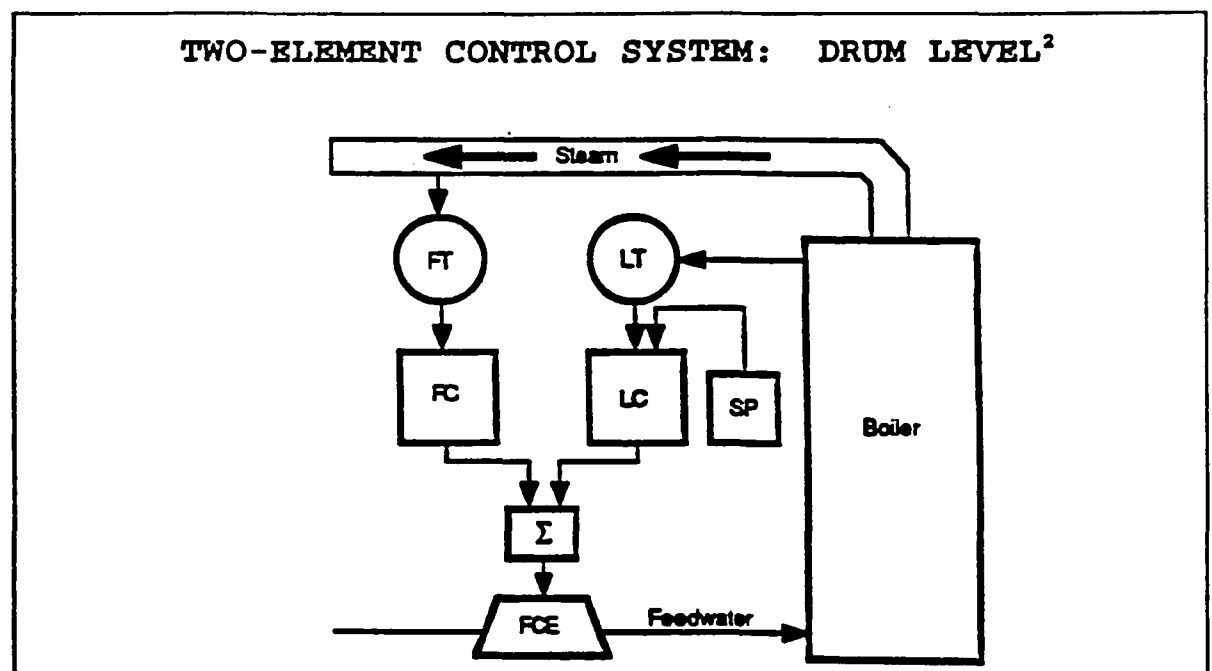
Courtesy of the Instrument Society of America

Two-element controllers improve the stability of the drum level by sensing the rate of steam flow as well as the drum level. A signal from a flow transducer (FT) produces an actuating signal from a flow controller (FC) which is compared with the actuating signal from the level controller.

For instance, under an increasing steam flow condition, the flow controller produces a positive signal while the level controller produces a negative signal. The two signals are added, producing a null output signal which temporarily maintains the feedwater flow rate into the boiler. After a period of time, the pressure will stabilize and the drum level will drop, causing the flow to be appropriately increased.

Slide 22-12

THREE-ELEMENT CONTROL SYSTEM: DRUM LEVEL[2]
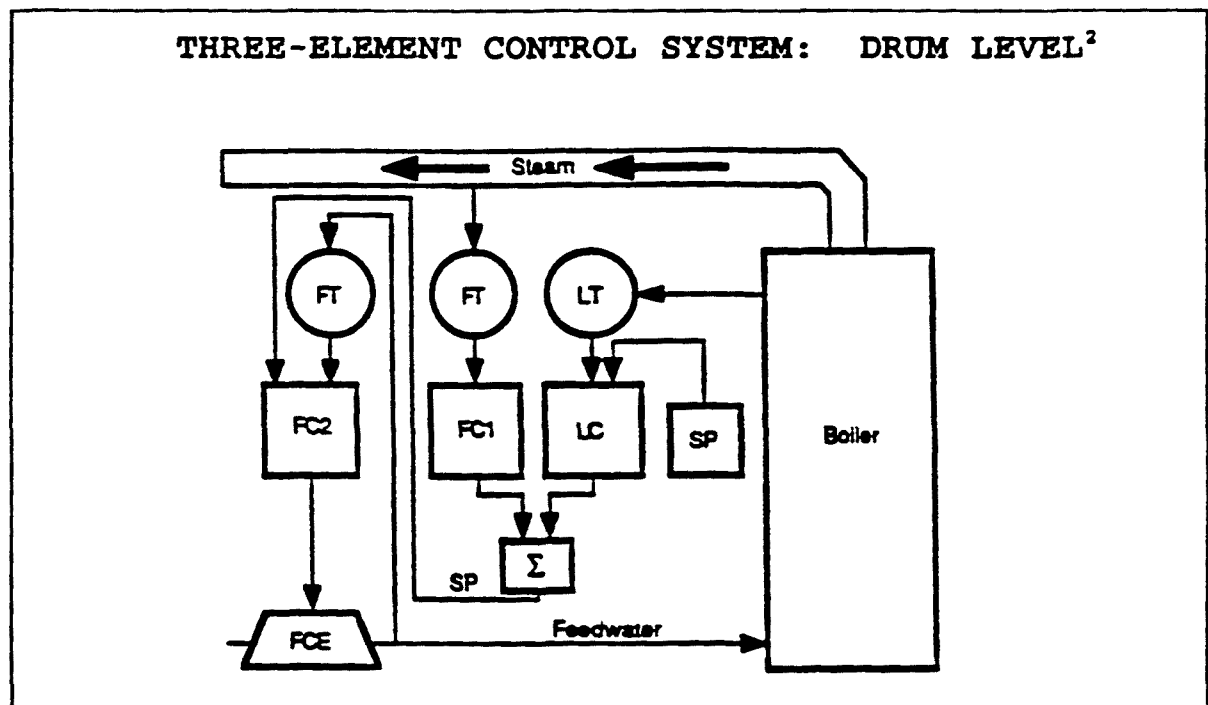
Courtesy of the Instrument Society of America

A three-element control or cascade control system makes use of the output from one control loop to provide the set point for another. In the example, the steam flow and boiler water level are used to correct the set point for the feedwater flow controller.

Although cascade control logic may appear to be complicated, it has been routinely used for many years in industrial- and utility-sized combustion equipment. It is particularly applicable in modern microprocessor-based PLC control systems.

Slide 22-13

MICRO-PROCESSOR BASED CONTROL SYSTEM
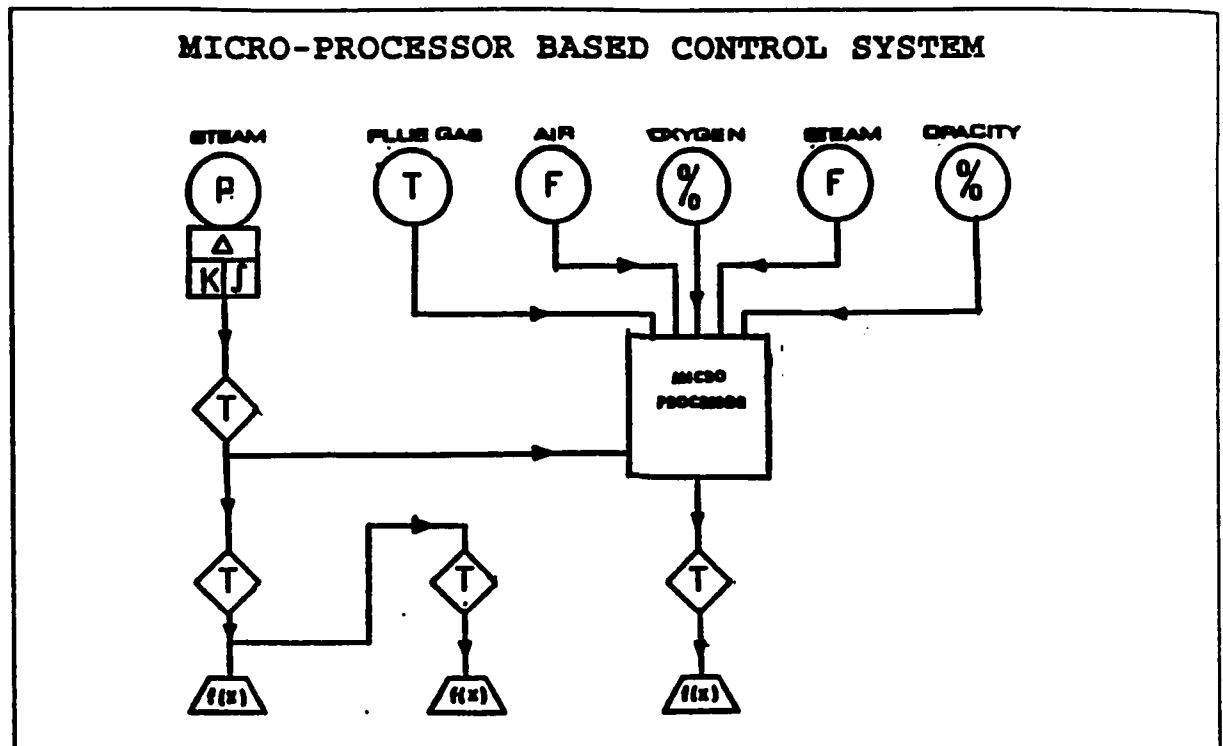
The above slide illustrates the features of a microprocessor-based combustion control system. The input variables include both steam pressure and flow as well as air flow, flue gas temperature, oxygen content and opacity.

Because of the increased computational ability, computational algorithms can be used to take into account additional special features. The features of variable gain, differential control and integral control are design features which will not be considered further in this training program.

The illustration does indicate that steam pressure would be the major indicator of load and the corresponding demand for fuel and air flow. However, the combustion restraints require that air flow be modified to take into consideration the flue gas conditions as well as the corresponding steam flow rate.

Slide 22-14

TRIM CONTROL FEATURES

1. Oxygen Trim Control
2. Flue Gas APCD Temperature Control
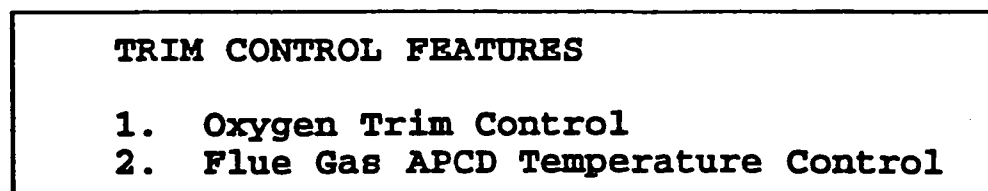
A trim control system uses special microprocessor-based control logic to modify combustion conditions so as to maintain some required operating condition. The normal control units would allow air and fuel to change in response to demand, but the trim control units would fine-tune the air delivery to maintain certain desired conditions.

For instance, an oxygen trim control system can be used to control the level of excess air or oxygen level in the flue gas. The primary motivation for such control systems could be either to control NOx emissions or to reduce the energy loss associated with excessive amounts of flue gas.

A different trim control unit could limit the flue gas temperature at the entrance to the APCD as a dioxin/furan control requirement. This control could be achieved through delivering heat sink materials such as excess air or water sprays into the flue gas after combustion.

Slide 22-15

```
CONTROL SYSTEM COMPARISONS

Conventional Fuels
     Gas & Fuel Oil
     Coal
     Municipal Solid Waste
```

The control systems for conventional fuels are capable of creating a steady combustion condition which can respond to transient demands for load. In general natural gas is the easiest conventional fuel to burn and to control. Oil is also fairly easy to control. Coal presents a more difficult control problem because of the specific fuel properties of volatility and fixed carbon. For this reason, coal combustion units may be base-loaded, if natural gas or oil-fired units are available to meet the swing loads.

MSW is a considerably more variable fuel than the conventional fossil fuels. The moisture content and other combustion properties can vary widely from one grapple load to the next, in spite of the mixing which is done before charging into the combustion unit.

The MWC combustion control system is required to accommodate the widely varying fuel properties. This is partially achieved by using more excess air than would be typically used for conventional fuels. It is also achieved by using longer residence times for the solid fuel on the grates.

```
┌─────────────────────────────────────────────────────┐
│                                                       │
│         WATERWALL MWC CONTROL FEATURES                │
│                                                       │
│         Base Load                                     │
│         Steady Combustion Temperatures                │
│                                                       │
└─────────────────────────────────────────────────────┘
```

A very important combustion control method is to limit the demand driven load transients. MWC combustion units are typically designed as base load units, so that the combustion environment is as steady as possible.

Such control systems can establish a priority of either constant combustion temperature or constant load. Under either case, air delivery will need to only respond to variable fuel properties and not primarily to transients in the combustion chamber thermal environment caused by changing steam flow rates and the corresponding changes in waterwall temperatures.

Of course, overall increases in combustion intensity will result from increasing both the fuel volatization and its mixing with the air. Therefore, grate agitation and charging ram operation will be controlled as well as the air supply.

Each MWC vendor may have its own unique control system features. However, the major control variable is generally either under-fire or over-fire air flow. As was illustrated earlier, the PLC features of modern control systems allow other variables to be used to trim the air supply to achieve desired combustion and exit gas conditions.

Slide 22-17

```
┌─────────────────────────────────────────────────────┐
│                                                       │
│         STARVED-AIR UNIT CONTROL SYSTEMS              │
│                                                       │
│         Two-Stage Combustion Design                   │
│    '    Steady Combustion Temperatures                │
│         Low Primary Air Flow                          │
│         Long Solids Residence Time                    │
│         Air Controlled in the Secondary               │
│                                                       │
└─────────────────────────────────────────────────────┘
```

Starved-air units achieve combustion control by separately regulating the air flow rates and the corresponding fuel/air stoichiometries in the primary and secondary combustion chambers. The primary chamber is maintained under substoichiometric conditions.

The control strategy attempts to limit the fuel volatilization rate by controlling the primary chamber temperature. However, a variable rate of evolution of volatile matter will occur because of fuel characteristics. This is in spite of the fact that primary temperatures are limited so that the rate of volatilization is fairly slow and the solid fuel residence time is fairly long.

As was presented in Learning Unit 10, an increase in air supply under sub-stoichiometric conditions will increase the equilibrium temperature. Therefore, the main controller response is to regulate the delivery of air so as to obtain desired primary chamber sub-stoichiometric conditions which in turn regulate the primary chamber temperature.

Additional control features can regulate the dwell time between delivering new fuel charges and the amount of fuel bed agitation.

Slide 22-18

```
CONTROL SYSTEM INTERLOCKS

CEMS Operational Requirement
High Carbon Monoxide
Auxiliary Burner Flame Sensor
Fan Running during Pre-Ignition Purge
```

Many control systems are required to have system interlocks to prevent operation under upset conditions. For example, the ram feeders for the waste charging system may be prevented from delivering waste if the CEMS is not operating properly. Some units have provisions to shut down the feeders in the event of a high carbon monoxide reading. Other provisions in the control system design should anticipate this condition and regulate the delivery of air or start up an auxiliary burner.

Some interlock systems are provided to assure the safe operation of the equipment. During start-up operations, a timer generally prevents the flow of fuel to the auxiliary burner until after an adequate time period for purging the combustion chamber with fresh air. If the fans fail to operate, an interlock would disable the start-up cycle.

After auxiliary burner start-up, a flame detector must sense the burning of the fuel, or else the burner's fuel flow will be automatically stopped.

REFERENCES

1.   George R. Kotynek and Calvin L. Hartman, "Using State-of-the-Art Electronic Controls for Controlling Boiler/Furnaces in Refuse-to-Energy Plants," Proceedings of 1990 ASME National Waste Processing Conference, Long Beach, CA, June 1990, pp. 123-133.

2.   Reprinted by permission. Copyright@ Instrument Society of America 1988. From "Boiler Feedwater and Steam - Controlling for Safety and Efficiency," Videotape from ISA's Boiler Control Series.

23. CONTROL ROOM OPERATIONS

Slide 23-1

```
┌─────────────────────────────────────────────┐
│         OPERATOR CONTROL FUNCTIONS          │
│                                             │
│   1.  Monitor System Operations             │
│   2.  Evaluate Conditions                   │
│   3.  Institute Appropriate Changes         │
└─────────────────────────────────────────────┘
```

Operators provide critical functions of monitoring system operations, evaluating current conditions and trends and instituting appropriate changes. These functions are required even though the unit's automatic control systems may have many designed features which provide for automatic corrections of undesirable operating conditions.

Slide 23-2

```
┌─────────────────────────────────────────────┐
│       OPERATING SYSTEMS                     │
│                                             │
│       MSW Handling                          │
│       Combustion                            │
│       Boiler & Feedwater                    │
│       Power Generation                      │
│       APCD & Ash Removal                    │
│       Electrical Service                    │
│       Water Treatment                       │
│       Cooling Water                         │
│       Fire Protection                       │
└─────────────────────────────────────────────┘
```

The major unit operations centered in the control room will typically include the MSW handling, combustion, boiler and feedwater, power generation, APCD and ash removal systems. Many auxiliary systems are also operated from the control room, including the unit electrical service, water treatment, cooling water, lube oil, and fire protection systems.

Some of the above mentioned systems may have their control functions operated through remote control rooms or stations. Remote operations may have the advantage of allowing auxiliary operators to be located closer to the equipment, which should facilitate prompt equipment inspections and trouble shooting.

Slide 23-3

```
┌─────────────────────────────────────────────┐
│      CONTROL ROOM COMMUNICATIONS             │
│                                              │
│   Operator/Unit Interface                    │
│       Receive Operating Information          │
│       Transmit Instructions                  │
└─────────────────────────────────────────────┘
```

The control room is the location of the central communications system where the operators receive information about the unit's operational status and transmit instructions to the equipment or other operating personnel.[1] The communications interface is sometimes called the control board or control panel.

The control room is analogous in function to the cockpit of an airplane where the pilot and other officers receive information and perform unit operations. Information about status of system operations is obtained from the available instruments, indicator lights, annunciators and alarms.

Communications with auxiliary operators and support staff may be crucial in developing the basis for the operator's decisions. Valuable information is often obtained by dispatching individuals to confirm instrument readings and to check for abnormal equipment symptoms such as material blockages, leakages, vibrations, noise and surface temperatures. Personal conversations in the control room are augmented through the use of telephones, intercoms and radio devices. Operators must not only give clear instructions, they must also listen carefully to understand what others are saying.

Slide 23-4

```
┌─────────────────────────────────────────────┐
│      PANEL MOUNTED INSTRUMENTS               │
│                                              │
│   Analog Displays                            │
│   Digital Displays                           │
│   Status Indicator Lights                    │
│   Annunciators                               │
│   Alarms                                     │
│   Television Monitors                        │
│   Recording Devices                          │
│       Circular Charts                        │
│       Strip Charts                           │
└─────────────────────────────────────────────┘
```

Panel mounted instruments may include analog and digital instrument readouts, status indicator lights, annunciators, alarms, TV monitors and recording devices.[2]

Status lights indicate whether the equipment is operating or off-line.

Annunciators are the back-lighted messages which light up to indicate operating status, such as when a given system parameter is outside its normal operating limits. The annunciator light is shut off automatically when its parameter returns to a normal operating value.

Audible alarms are additionally used to alert operators to the existence of selected upset conditions. After an alarm has been sounded, it may be shut off by the operator to avoid being a continued distraction.

TV monitors can provide visual information about unit operations such as MSW handling, combustion conditions, ash removal and visual stack emissions.

Recording devices include circular and strip chart recorders. These can provide a continuous record of the values of selected parameters such as opacity, steam flow, steam pressure, combustion temperatures, gaseous emissions, etc.

Slide 23-5

```
GRAPHIC SCREEN DISPLAYS

Alpha/Numeric
     Menus, Lists, Warnings
Two-Dimensional Equipment
     Schematic with Data
Individual Component
Groups of Equipment
Overview of Performance
Trends of Selected Data
```

Some sophisticated installations will have terminal units which provide access to the unit's microprocessor-based distributed control system. Information can be obtained from graphic screens which can display data in a number of forms.[1] The software is generally menu-driven and includes other alphanumeric displays which provide messages and warnings.

Two-dimensional displays can provide current operating data arranged logically on a graphical sketch of the equipment, system, process or instrument. Detailed displays of individual instruments and controllers can be obtained with indicators of current and maximum readings as well as the set point. An interactive graphics feature may allow the changing of set points by touching the graphic screen.

Group displays typically indicate a series of bar graphs indicating levels of operations of selected groups of controllers along with their set points.

Overview displays are generally designed to provide indications of equipment operations in such a way that abnormal conditions are obvious from deviations in the pattern of displays.

Trend displays can provide a graph of the continuous record of a selected variable over a period of time. Displays of multiple parameters on the same graph can be enhanced by the use of different colors for each parameter.

Slide 23-6

```
COMBUSTION SYSTEM MONITORS

Opacity
Carbon Monoxide
Oxygen
Acid Gas Concentrations
Air & Flue Gas Temperatures
Television Monitors
```

A number of instruments which are typically used as combustion monitors are listed above. Most of these were previously presented in Learning Units 13 and 14.

Slide 23-7

```
BOILER & FEEDWATER MONITORS

Steam Pressure & Temperature
Steam Flow Rates
Water Pressure & Temperature
Feedwater Flow Rates
Feedwater pH & Conductivity
```

Typical boiler and feedwater monitors are listed above. Principles and techniques of water treatment will be presented in Learning Unit 26.

```
┌─────────────────────────────────────────────────┐
│           OPERATOR-INITIATED CHANGES            │
│                                                 │
│     Transmit Direct Signals                     │
│          Motor, Pumps, Switches                 │
│     Transmit Signals to Controllers             │
│          Modify Set Points                      │
│          Initiate Start-Up or Shutdown          │
│     Request Maintenance                         │
└─────────────────────────────────────────────────┘
```

When a system disturbance is observed, the operator must evaluate the severity of the condition, consider possible remedies, and make a proper response. Operator responses include transmitting instructions to the equipment through manual manipulations which override or modify the settings of the control system.

The unit may be restored to proper operating conditions by changing the control system set points or by switching to the manual mode to make specific operational equipment modifications. Operator-initiated control signals can be sent to either specific equipment or controllers through microcomputer keyboards, touch-screens, and/or panel mounted controller knobs and switches.

Other operator initiated changes include unit start-up and shutdown operations, which will be described in Learning Unit 24.

Operator's instructions include requesting verification of operating conditions. Operators also have the tasks of assuring that routine maintenance is performed and that proper requests are made for major maintenance, which will be described in Learning Unit 29.

REFERENCES

1.	J. A. Moore, "The Man/Machine Interface," Standard Handbook of Power Plant Engineering, Thomas C. Elliott, editor, McGraw Hill Book Co., NY, 1989, pp. 6.125-6.145.

2.	J. A. Moore, "Key Systems and Components," Standard Handbook of Power Plant Engineering, Thomas C. Elliott, editor, McGraw Hill Book Co., NY, 1989, pp. 6.95-6.123.

24. OPERATING PRACTICES

Slide 24-1

```
┌──────────────────────────────────────────────┐
│           OPERATING RESPONSIBILITIES          │
│                                                │
│   1.  Maintain Safety of People                │
│   2.  Maintain Safety of Equipment             │
│   3.  Operate Within Legal Regulations         │
│   4.  Optimize Equipment Performance           │
└──────────────────────────────────────────────┘
```

This learning unit presents the general operating features of MWC units, including start-up and shutdown operations. Additional consideration will be given in subsequent learning units to operator practices associated with combustion system upsets, water treatment, turbine/generator systems, maintenance and safety.

The primary responsibility of the operator is to operate the plant in a safe and efficient manner.[1,2] This will assure the protection of the plant personnel and reduce the potential damage to the equipment and surrounding environment. Once these are assured, the optimization of equipment performance will require a balance between the desire for operation at a maximum production rate and the minimization of operating cost.

Slide 24-2

```
┌──────────────────────────────────────────────┐
│           OPERATOR JOB FUNCTIONS               │
│                                                │
│   Automatic Control System Manager             │
│   Equipment Operator                           │
│           What is Happening?                   │
│           Why?                                 │
│           What are the Options?                │
│           What are the Consequences?           │
└──────────────────────────────────────────────┘
```

The operator is considerably more than an automatic control system manager.[3] Automatic control systems are designed to aid operators in making routine responses to system variables. Such systems are designed to account for the complex interactions between the MWC system components and monitors. Control systems generally operate very rapidly and have safety features included in their logic.

Operators are often required to take manual control of the equipment. This can occur because the control logic does not cover a particular situation or because a sensor or control system component has failed.

Operators must be able to know what is happening in the unit, why it is happening, what can be done, and the consequences of the various actions.

Slide 24-3

```
┌─────────────────────────────────────────────────────────┐
│          TYPICAL WALK-DOWN CHECK-LIST                    │
│                                                          │
│     1.   Fuel Charging & Pit Operations                  │
│     2.   Fuel Bed Uniformity                             │
│     3.   Fuel Bed Clinkering                             │
│     4.   Slag Deposits on Waterwalls                     │
│     5.   Equipment Noise/Overheating                     │
│     6.   Ash Leaks, Blockages, Conditions                │
│     7.   Pumps, Fans & Dampers                           │
│     8.   Water & Oil Leaks (Valve Packing)               │
│     9.   Safety Valve Leaks                              │
│    10.   Soot-Blowers (Confirm Operation)                │
│    11.   Hydraulic Systems (Temp., Pressure)             │
└─────────────────────────────────────────────────────────┘
```

Operators can identify some aspects of unit performance by maintaining and reviewing a comprehensive log sheet of component equipment operating conditions.

A daily log sheet can be used to tabulate selected operating conditions. For instance the specific components' pressures, temperatures, flow meter readings, indicator positions and levels may be recorded as well as an indication of whether the equipment is operating or not.[4]

Such log sheets are generally maintained at specified time intervals (e.g., every four hours or at the beginning of each shift).

Slide 24-4

```
┌─────────────────────────────────────────────────────────┐
│          OPERATOR REQUIREMENTS                           │
│                                                          │
│     1.   Know the System Characteristics                 │
│     2.   Assess the Operating Conditions                 │
│     3.   Identify Potential Modifications                │
│     4.   Make Timely Decisions                           │
│     5.   Establish Proper Procedures                     │
│     6.   Keep Proper Records                             │
└─────────────────────────────────────────────────────────┘
```

The operators are required to understand the special system design features, which include the operating limits of the component equipment and the important

influences of one component on another.[5] Operators must conduct operations within the limitations of the site-specific equipment. Of course, the operational and control features of the equipment will vary from plant to plant.

Operators gain much of their knowledge through on-the-job experiences of operating and inspecting the equipment. Additional knowledge comes from discussing issues with knowledgeable personnel, studying the site-specific training manuals, and reviewing the instructions and drawings found in plant documentation manuals.

Operators must assess the operating conditions through the surveillance of both the instruments and the equipment. Operators must also judge the importance of deviations from normal operating conditions.

When an upset condition is detected, the possible remedies must be considered and a decision made in a timely manner. The operator must be prepared to respond to all situations which may arise. If appropriate decisions are delayed and/or corrective actions taken at inappropriate times, it is probable that the operating conditions will deteriorate. Inappropriate actions could cause the system to operate outside its design limits, leading to an unsafe condition, unit trip (shutdown) and/or a violation of the applicable regulations.

Slide 24-5

```
+--------------------------------------------------+
|                                                  |
|        POTENTIAL MAJOR HAZARDS                   |
|                                                  |
|     1.   Loss of Water                           |
|     2.   Explosive Mixture of Fuel/Air           |
|     3.   High Pressure Steam Pipe Rupture        |
|                                                  |
+--------------------------------------------------+
```

As has been the case for generations, the two most dangerous conditions in power plants are the loss of water in the boiler and the existence of explosive mixtures in the furnace.

Drum water level control is important because the water is the major provision for removal of heat from combustion. The drum level represents the balancing of the inflow and outflow of water from the unit. Therefore, a drum level problem can result in problems with the control system, a failure in the feedwater system, excessive steam flow or steam leaks.

If an operating boiler loses water, overheating will occur in the boiler drums, pipes and waterwall regions. This will cause increased thermal stress in the metal members, which can result in cracks and tube failures. The extent of the damage can be controlled by restoring the water flow and/or reducing the level of combustion.

24-3

If the lost water is due to tube failures, the unit will generally need to be taken off-line for tube replacement or plugging. The steam or water escaping from a tube leak could result in the cutting of adjacent tubes and/or the overheating of other sections of the boiler circuit.[5] In addition, thermal stress problems may be increased by the inflow of large quantities of relatively cool feedwater.

Explosive mixtures are avoided by purging the unit with air prior to lighting the burners. A minimum air flow should be maintained at all times after the purge process. The combustion chambers should be pre-heated prior to the charging of MSW. This improves initial combustion and reduces the possibility of the quenching of combustible gases, which could lead to the accumulation of explosive gas mixtures.

The third hazard is a steam pipe rupture. Steam pipes may rupture under the uncontrolled conditions of either high thermal stress or water hammer. Water hammer occurs when slugs of liquid water and steam flow together in a steam pipe.[5] General protection against excessive pressures in pipes is provided by the installation of safety valves, which should be regularly tested.

Slide 24-6

```
STANDARD OPERATING PROCEDURES

1.  Safe Practices & Systems
2.  Emergency Procedures
3.  General Operations
4.  Routine & Major Maintenance
5.  Start-Up and Shutdown
6.  Testing and Calibration
```

Operator actions should generally be consistent with established plant procedures, such as in those areas listed above. For instance, operators must promptly respond to potentially hazardous safety conditions to reduce the possibility of injury to personnel or damage to equipment. Particular diligence is required during start-up and shutdown, as these transient operations may provide opportunities for uncontrolled conditions.

The operators typically participate in the development and refinement of standard operating procedures. In addition, the operator must consider measures which will maintain or improve the equipment's ability to perform continuously and efficiently. These measures include making arrangements for routine inspections, and preventive maintenance and the scheduling of major maintenance.

Slide 24-7

```
POLLUTANTS INFLUENCED BY OPERATIONS

1.   Air Pollutants
         Smoke
         Particulates
         Gases
2.   Waste-Water Discharge
3.   Odor
4.   Noise
```

Operators have responsibilities for maintaining operations within all relevant permit conditions. These include both air pollutant emissions and waste-water discharges. Operators are responsible for operating the combustion, heat recovery, and APCD systems so as to control the smoke, particulates, CO, NOx, organics, acids and heavy metal emissions from the unit. In addition, operators have responsibilities for limiting the nuisances of odor and noise in the neighborhood.

Slide 24-8

```
NORMAL OPERATING SYSTEM CONTROLS

1.   Combustion
2.   Boiler
3.   Boiler Water Treatment
4.   Air Pollution Control Devices
```

Operators are responsible for controlling all major and auxiliary systems found in MWC units. This learning unit, however, focuses on the combustion and boiler systems.

Slide 24-9

```
COMBUSTION CONTROL

Air and Fuel Transients

Operator Activities
      Review System Performance
      Improve Equipment Setting
```

Operators will need to continually review the combustion conditions by monitoring the gas temperatures in the fully mixed region (above the overfire air jets) or the primary and secondary combustion chambers. In addition, the steam pressure, temperature and flow rate, as well as smoke and all CEMS for flue gas concentrations should be monitored.

As discussed in Learning Unit 22, the combustion control systems will vary depending upon design concepts and individual unit features. However, all systems are designed to follow a desired combustion profile as the materials pass through the unit. This profile includes the MSW being dried and heated, the evolution of the various gases, ignition of the combustible gases within or above the bed, and the burning of the fixed carbon on the grate.

Slide 24-10

```
GRATE BURNING OPERATOR CONTROL

1.    Underfire Air to Each Zone
           Damper Controls
           Supply Air Pressure
           Draft
2.    Fuel Bed
           Waste Feed Rate
           Bed Thickness & Uniformity
           Bed Agitation
3.    Overfire Air Supply Pressure
```

The grate burning system is considered to have a drying zone, a pyrolysis zone, a burning zone and a burn-out zone. Ideally, the active burning region will be appropriately located relative to the main furnace geometry. The distribution of underfire air will affect the location of the burning region and the rate of waste burn-out. The ash should appear to be completely burned as it falls from the grate.

Combustion control is generally achieved by modulating air supply, grate agitation, and fuel delivery. Operators may exercise control on the underfire (or under-grate) air using dampers which are designed to maintain the desired air flow distribution and draft conditions.

In many systems, the overfire and underfire air supplies are coupled parameters, so that adjustments of a damper for one will influence the other. Operators must know how these system characteristics will affect unit performance.

The solid MSW must be properly moved through each zone by grate actions so that the bed thickness and bed uniformity are maintained. A non-uniform air supply

can be caused by the plugging of air nozzles or by the influence of bed thickness on air distribution. Thicker bed regions have more resistance to air flow than thin bed regions, so the thick beds get less than the desired air flow and the thin beds get too much. The channelizing of air leads to local hot spots of intense combustion, causing glass melting and clinker formation. Clinkers then act to restrict the air flow.

Operators can improve the uniformity of bed combustion conditions by maintaining the integrity of the MSW mixing and feeding and by controlling the underfire air distribution and grate conditions.

The waste feed rate will determine the total heat input and must be matched to the air flow rate. However, waste feed has a fairly slow response time, whereas changes in underfire can have an immediate impact upon the overall combustion conditions. The unique response time characteristics of the unit must be considered in the adjustments of combustion control systems.

The overfire air supply must be appropriately operated to provide the mixing of combustible gases and oxygen for complete combustion. Overfire air nozzles are generally designed to provide adequate penetration and mixing in the gaseous region above the grates. Operators can maintain the air plenum pressures, damper settings and fan performance to assure that mixing is adequate.

Slide 24-11

```
BOILER CONTROL

        Drum Level
        Load
        Steam Temperatures
        Feedwater Conditions

Operator Activities
        Review System Performance
        Make Furnace Observations
        Soot Blowing (Automatic/Manual)
        Detect Tube Failures
```

Drum level controllers and the control features of conventional fossil fuel and MWC-fired power boilers were introduced in Learning Unit 22.

MWC combustion performance is greatly improved when the operating load (steam flow) is as steady as possible. Conventional power plants are designed to meet transient demands, but MSW fuels have such large variability in fuel properties that meeting transient demands is difficult. Most MWC units, however, have control systems which can meet the anticipated fluctuations in steam demand.

The temperature of the steam delivered from the unit is dependent upon a number of variables such as the following: steam flow, steam pressure, cleanliness of the radiant and convective heat absorbing surfaces, level of excess air, air preheating, and general flame conditions, as well as the combustion control system. In general, changes in the fuel charging rate occur too slowly to be primary elements in temperature control. Most plants use steam or water attemperators to achieve steam temperature control.

Operators are able to maintain appropriate steam temperature conditions by reviewing performance results and making regular furnace observations to check the condition of the deposits on the heat exchange surfaces. Although rapping or soot blowing may be performed automatically, supplemental manual operations may be able to improve steam temperature control and combustion system performance.[3]

Operators will want to compare the feedwater and steam flow rates. An increased feedwater rate which is not in response to an increased steam supply could be an indication of a boiler tube failure or other steam system leakage. Because of the pressure associated with such leakage, adjacent steam pipes may be cut by the leaking steam. In addition, steam tube failures can release steam into the combustion zone, lowering the flue gas temperature and causing a deterioration in the combustion conditions. A significant increase in carbon monoxide could also be caused by a boiler tube failure.

If a tube failure is confirmed by other evidence, such as a visual observation or hearing the steam leak, the normal operator response is to take the unit off-line as soon as possible to inspect and repair or plug the ruptured tube(s).

Slide 24-12

```
BOILER WATER TREATMENT

        Oxygen & Dissolved Gases
        Carbonates
        Acidic or Alkali Conditions

Operator Activities
        Monitor Conditions
        Chemical Treatment
        Blowdown
```

Boiler water treatment is introduced in this learning unit and will be covered in greater depth in Learning Unit 26.

Operators must pay particular attention to the conditions of the water in the boiler. Water contains various impurities which can cause corrosion and pitting of metal as well as scale build-up. If left untreated, these conditions can lead to metal failure and the formation of blisters, bags and/or burned out heat exchange surfaces.[2]

Oxygen, carbon dioxide and other dissolved gases can cause corrosion and pitting. The gases released from the water in the deaerating feedwater heater are typically purged by venting. To be most effective, the temperature must be as high as possible, although not so high as to cause the feedwater pump to become steambound.

To avoid scale formation, calcium carbonate and magnesium carbonate in the water supply must be treated and removed. These compounds generally enter by the leaking of raw water through cracks in the condenser. The carbonates can be treated by the addition of an alkali substance, such as sodium hydroxide or caustic soda, which converts the carbonates to a precipitate. Note that high alkali levels can cause caustic embrittlement of metals.

The alkali level in the feedwater can be monitored using a pH meter, which can also indicate any acidic condition. The monitoring of pH in both boiler water and in feedwater is very important because significant damage due to scale build-up and/or acid corrosion can occur in a short period of time.[3] The pH levels in boiler water[5] should range between 8.0 and 9.5. The pH number of 7.0 indicates a neutral condition, with larger values indicating alkaline (basic) conditions and values below 7.0 being acidic.

Raw water often has dissolved solid impurities, which cannot be removed by conventional settling, clarification and filtering techniques. These impurities are concentrated in boiler water, because the steam (pure water) leaves the impurities behind.

The dissolved solids in the boiler water must be removed by blowdown, a process where a portion of the water is discharged from the boiler and replaced by treated make-up water. Such impurities could cause foaming or the trapping of steam bubbles below the water surface in the steam drum. Foaming also can cause the carryover of slugs of water into the steam lines, which create water hammer and the rupture of steam headers and steam lines and damage to steam turbines.

```
          COMBUSTION SYSTEM START-UP

    1.   Prepare Boiler For Ignition
              Inspect Boiler
              Test Components:
                   Fans, Pumps, Safety Valves
              Clean Gas-Side of Boiler
              Chemically Clean Water-Side
              Fill Boiler with Water
              Static Test Boiler at Pressure
              Adjust Control System Settings
```

The start-up procedure depends upon how long the boiler has been off-line and the existing conditions within the boiler (hot water, cold water, or empty). The standard operating procedures should be followed, including the manufacturer's recommended procedures.

During the initial system start-up, steam leaks can be detected by conducting a full-scale hydrostatic test. This test includes filling up the boiler with water and pressurizing the boiler section to 50% above its rated pressure.[2]

Special gas-side cleaning, boiler chemical cleaning and/or static testing with at the system pressure may be required, depending on the conditions. In addition, the routine testing of various components, such as fans, pumps and safety valves, may be required. Inspection includes using the proper procedures for clearing safety tags from breakers and on hatch doors.

Valves should be correctly positioned for start-up according to the manufacturer's standard operating procedures. This generally includes provisions for blocking off and draining appropriate portions of the steam-circuit headers. The superheater and reheater vents should be opened so that any residual moisture will be boiled off.

Prior to starting up or restarting a unit, the boiler should be inspected. For instance, during an annual outage, ultrasonic testing (UT) is generally performed to identify the locations where the tube thicknesses has been substantially reduced due to corrosion and erosion.

Water should be added to the boiler up to the proper level on the glass water level indicator. The water should be warm enough to prevent condensation on the gas-side of the metal surfaces.

```
┌─────────────────────────────────────────────────┐
│                                                   │
│         COMBUSTION SYSTEM START-UP                │
│                                                   │
│   2.   Warm Up Boiler                             │
│            Purge Air & Ignite Burner              │
│            Maintain Minimum Air Flow              │
│            Vent Air from Drum & Headers           │
│              Limit Thermal Stresses               │
│            Vent Steam from Economizer             │
│            Boil-Out the Superheater               │
│                                                   │
└─────────────────────────────────────────────────┘
```

Prior to auxiliary fuel ignition, the gases in the furnace are generally purged with fresh air for five minutes. The auxiliary fuel burners are then used to heat the combustion chamber, with some minimum air flow supplied at all times to avoid explosive conditions.

The auxiliary fuel burner generally has an ignition sensor which will trip the fuel flow if the flame is extinguished. A purge period will again be required before attempting to relight the burner.

During warm-up, there will be little or no steam flow through the superheater. Special care will be required to vent air and steam and to prevent the occurrence of water hammer and other unsafe conditions.

To protect boiler metals from thermal stresses, the gas temperatures leaving the furnace should be limited as recommended by the manufacturer. The temperature rise profile is generally specified by the manufacturer, with heat-up values typically limited to around 200 °F per hour.[3] When the manufacturer-specified operating conditions are met, steam flow to the superheater and other parts of the steam circuit can be initiated.

```
┌─────────────────────────────────────────────────┐
│                                                   │
│         COMBUSTION SYSTEM START-UP                │
│                                                   │
│   3.   Begin to Charge MSW                        │
│            Ignition                               │
│            Enable Automatic Controls              │
│            Monitor Auxiliary Systems              │
│                                                   │
└─────────────────────────────────────────────────┘
```

The charging of MSW can only begin after the unit has been brought up to the required temperature conditions.

The sequence of events associated with increasing the level of underfire air, overfire air, and MSW charging will vary from unit to unit. This condition may be controlled manually until the unit is up to load before switching on the automatic combustion control system. Some units may have automatic combustion controls which operate through the start-up process.

Slide 24-16

```
COMBUSTION SYSTEM UNIT SHUTDOWN

Stop Feeding Waste into Unit
Burn the Fuel on the Grate
Operate Auxiliary Burners as Necessary
Allow Steam Pressure to Decay
Limit the Cool Down Rate
Maintain APCD Temperatures
```

The procedures and time requirements for shutting down a boiler depend upon the design of the unit and the nature of the shutdown. Shutting down a boiler can occur as a result of an emergency, or as a planned shut down from normal operations to either hot stand-by or cold conditions.

The general shutdown procedures provide for terminating the MSW charging and maintaining temperatures through the use of auxiliary fuel firing equipment. The ash handling equipment should remain operational until after the ash from the bed material has cleared the grate.

Depending upon how quickly the unit is to be shut down, the boiler pressure can be allowed to decay naturally (e.g., a bottled-up unit) or the fans can be operated to accelerate the boiler's cooling process. Normally, the boiler will not be drained unless the drum is to be entered. A special wet lay-up procedure must be initiated if the unit is to be down for more than a week.

The shutdown procedures for a modular, refractory-wall unit include locking out the loader, maintaining chamber temperatures with the auxiliary burners, and continuing blower operation until after residue burn-out has been obtained.

Removal of solid residues from the grate or hearth areas are typically accomplished by operation of the movable grates or ram devices. To avoid being burned, personnel should enter the grate or hearth area only after assurance that the ash has been removed or sufficiently cooled below the bed surface.

```
┌─────────────────────────────────────────────────────┐
│                                                       │
│     APCD SYSTEM START-UP, SHUTDOWN, UPSET             │
│                                                       │
│     Water Freeze Protection                           │
│     Preheat Fabric Filter                             │
│     Dew Point Controls                                │
│     Flue Gas Redirection upon Bag Rupture             │
│     Controls to Prevent Slurry Solidification         │
│     High Temperature Protection of Bags               │
│                                                       │
└─────────────────────────────────────────────────────┘
```

APCD systems have a number of unique features associated with their operation under normal, start-up, shutdown, and upset conditions. Potential problems range from preventing the freezing of liquids to the prevention of acid gas corrosion of metal surfaces and the protection of fabric filters against blinding.

Depending upon the design of the freeze protection application, operators may be required to monitor the system to assure that it is operating properly or to be assured that the protection system has been enabled.

A special type of freeze problem is the solidification of the slurry in the SDA's delivery system. If the slurry is cooled below normal hot water temperatures (140°F), there is a chance that the liquid will solidify. This is particularly a problem when the flow stops. SDA designs generally include provisions for heating (electric resistance or steam tracing) and recirculating the flow. If maintenance is required, such as the replacement of a spray nozzle, the procedures should be accomplished in a planned manner so as to minimize the potential solidification problems.

Fabric filters (FF) can become "blinded" by small particulates becoming lodged within the fabric. During start-up the potential for blinding is worse than normal, due to the fact that the FF must generally be heated from ambient to operating temperatures, and in the process pass through the dew point. Condensation of moisture on the fabric can cause particulates to solidify, resulting in blinding.

Provisions to avoid blinding include using the auxiliary fuel pre-heat cycle to preheat the APCD system before flue gas from waste combustion is introduced. Other provisions may allow for the use of a by-pass duct for a limited time period during start-up.

In the event of a rupture in a fabric filter bag, the baghouse pressure will fall and the opacity will go up. An automatic control system with pressure and/or opacity sensors may redirect the flue gas to an adjacent fabric filter module. Alternately, this function may be performed manually by an operator. Of course, care must be taken during bag replacement, to avoid human exposure to hazardous conditions.

If the flue gas temperature were to rise above the maximum operating range of the fabric filters, some protection feature will be required to avoid melting the fabric. Many systems will initiate an upstream water spray into the flue gas to provide evaporative cooling.

Another form of temperature protection would be to open the damper to a by-pass duct. Of course, the operator will need to determine what caused the upset to occur and take corrective measures.

APCD systems can have special heaters (electrical or auxiliary fuel fired) to maintain temperatures above the dew point. Other designs will emphasize thermal insulation and damper controls to prevent moist gases entering the unit during a shutdown.

REFERENCES

1. E. B. Woodruff, H. B. Lammers and Thomas F. Lammers, Steam Plant Operations, Fifth Edition, McGraw-Hill Book Company, New York, 1984, pp. 259-265.

2. Frederick M. Steingress and Harold J. Frost, Stationary Engineering, American Technical Publishers, Inc., Homewood, IL, 1991, pp. 87, 181-192, 177-293.

3. Joseph G. Singer, Combustion, Fossil Power Systems, 3rd Edition, Combustion Engineering, Inc., Windsor, CT, 1981, pp. 20-1 to 20-31.

4   PEI Associates, Inc., Combustion Source Inspection Module, Student Reference Manual, Submitted to U.S. Environmental Protection Agency, September 1990, pp. 242-245, 272-291.

5. Steam, Its Generation and Use, 39th Edition, Babcock and Wilcox, New York, 1978, pp. 34-1 to 34-14.

25. TROUBLESHOOTING OF COMBUSTION UPSETS

Slide 25-1

```
┌─────────────────────────────────────────────┐
│    TYPICAL COMBUSTION UPSETS                  │
│                                               │
│    1.   MSW/RDF Charging System               │
│    2.   Grates                                │
│    3.   Combustion Air Supply                 │
│    4.   Waterwalls/Tubes                      │
│    5.   Ash Handling                          │
│    6.   Power Failures/Excursions             │
│                                               │
└─────────────────────────────────────────────┘
```

The troubleshooting of combustion upsets generally focuses on corrective actions associated with the component equipment listed above.

Components may malfunction because of a number of reasons, including: normal wear, operation outside of design conditions, improper lubrication, blockages, and electrical failures (unit kicked off line, frequency excursions).

Upsets may also be caused by operator error, such as by reacting to a situation before thinking of all the ramifications of the action or by reacting too slowly to an emergency situation.

Slide 25-2

```
┌─────────────────────────────────────────────┐
│    INDICATORS OF COMBUSTION QUALITY           │
│                                               │
│    1.   Opacity                               │
│    2.   Carbon Monoxide                       │
│    3.   Temperature (Furnace & APCD)          │
│    4.   Oxygen                                │
│    5.   Visual Appearance of Fire             │
│    6.   Total Hydrocarbon                     │
│    7.   Furnace Draft                         │
│    8.   Air Supply Pressures                  │
│                                               │
└─────────────────────────────────────────────┘
```

A number of instruments can be used to indicate the quality of the combustion conditions. Typically, opacity is used to indicate combustion and/or APCD system performance. Combustion quality is primarily indicated by carbon monoxide and temperature monitors.

In addition, furnace draft, supply air pressure, and oxygen monitors can provide important information about combustion conditions.

```
┌─────────────────────────────────────────────────┐
│         PERSONAL COMBUSTION OBSERVATIONS          │
│                                                   │
│        Combustion Conditions                      │
│        Bottom Ash                                 │
└─────────────────────────────────────────────────┘
```

Personal visual observations of the fuel bed and in the above-bed regions can provide valuable information as to the combustion conditions. Viewing the combustion region through observation ports or with the aid of TV monitors can provide information about the movement of the burning zones, intensity of combustion, bed thickness and uniformity, clinkers and slag deposits, and the presence of undesirable oversized materials which were included in the feed.

Sparklers in the flue gas convection passes indicate excessive entrainment.

Information about combustion quality can also be obtained by observing the ash color and consistency and by laboratory testing of the ash to determine its carbon content. The ash should be gray in color and have no recognizable combustible components, such as paper materials.

In addition to visual observations, operators will detect some component malfunctions by hearing abnormal equipment noises and sensing vibrations. For example, a high pressure steam leak associated with a tube failure may be heard.

Slide 25-4

```
┌─────────────────────────────────────────────────────┐
│     FUEL PREPARATION & HANDLING                       │
│                                                       │
│     1.  Wide Swings in Fuel Properties                │
│             Fuel Moisture: Mix Wet & Dry MSW          │
│     2.  Feed Hopper/Conveyor - Bridging               │
│             Maintain Proper Charging Level            │
│             Redirect Undesirable Materials            │
│     3.  Grapple/Loader Breakdown                      │
│     4.  Pit Fire                                      │
│             Charge Into Unit                          │
│             Extinguish with Water/CO₂                 │
└─────────────────────────────────────────────────────┘
```

As discussed in Learning Unit Number 8, a number of general conditions must be maintained to avoid combustion upsets associated with the fuel preparation and handling system. Problems associated with wide swings in fuel properties can be avoided by mixing the waste in the pit before it is charged into the combustor.[1]

Inspection, removal, and redirection of undesirable materials can prevent some of the problems of system blockages and explosions. If a conveyor or hopper blockage occurs, the standard remedy should be consistent with the design of the unit and should include consideration for the safety of personnel.

A jammed charge hopper is the major cause for an upset condition in the combustor. Avoiding overloading should help prevent the bridging and jamming of the charge hopper.[1] Maintaining the appropriate level of MSW in the charge hopper is generally required for obtaining a uniform distribution of fuel on the fuel bed.

Hopper fires can be caused by improper combustor operations which allow combustion to move from the fuel bed into the feed hopper. To avoid hopper fires, feeder systems are required to maintain a proper air-lock condition. Such design provisions can include a water-cooled guillotine or resistance door which maintains the proper level of compaction of the charge in the hopper.

The maintenance of the applicable grapples and cranes or loaders is important to continuous operations. Inspection and routine maintenance of crane/grapple units will include routine consideration of cable or hydraulic system replacement.

Pit fires can be caused by breakage of chemical bottles, spontaneous combustion, and smoldering ashes from fireplaces and barbecues. Ashes have good insulating properties and may be hot enough to cause ignition for hours after being discarded. Pit fires can be difficult to put out, with the operator's response dependent upon the situation. Remedies include placing the smoldering material into the charge hopper and extinguishing the materials with water[2] or other extinguishing material.

Pit fires are not a typical problem in RDF plants because the MSW is normally processed into RDF fairly soon after it is received. However, RDF processing plants have their own problems, including the potential for serious shredder explosions.

Design features will determine the tendency of a grapple to be damaged by exposure to burning materials. The hydraulic lines of hydraulic grapples may be destroyed by hot materials, whereas cable-operated grapples may be undamaged by such activity.

Slide 25-5

```
┌─────────────────────────────────────────────────────────┐
│         UPSETS ASSOCIATED WITH FUEL PROBLEMS             │
│                                                          │
│   1.  Improper Feed Rate                                 │
│           Too High  - Excessive Gas Temperatures         │
│                     - High Steam Production              │
│                     - Poor Burn-out of the Ash          │
│           Too Low   - Insufficient Fuel                  │
│                     - Low Combustion Temperatures       │
│                     - Low Steam Production              │
│   2.  Improper Fuel Bed Thickness                        │
│           Too High  - Improper Air, Poor Burn-Out       │
│           Too Low   - Entrainment                       │
│   3.  Sudden Change in Fuel Properties                   │
│           High Moisture  - Reduced Temperatures         │
│           High Volatiles - Increased Temperatures       │
│           High Inorganics - Reduced Temperatures        │
└─────────────────────────────────────────────────────────┘
```

In most MWC systems, the feed rate is controlled by the steam demand. To obtain increased energy production, the energy release rate must be increased. Agitation of the burning grate and the delivery of underfire air to the burning grate zone are the major parameters used to control the energy release rate.[3]

Slide 25-6

```
┌─────────────────────────────────────────────────────────┐
│         UPSETS ASSOCIATED WITH FUEL PROBLEMS             │
│                                                          │
│   REMEDIES:                                              │
│        Regulate Grate Agitation                          │
│        Regulate Underfire Air Supply                     │
│        Regulate Charging Rate                            │
│        Change MSW Mixing Conditions                      │
│        Modify Trim Control System Settings               │
└─────────────────────────────────────────────────────────┘
```

The production of steam actually responds fairly slowly to changes in the fuel charging system. This is because of the relatively long residence time on the grate, which is caused by the need for fuel drying and heating before the new fuel contributes to the combustion process. In fact, a new charge of MSW fuel can be thought of as a temporary heat sink.

However, if the fuel has a high plastic content, it could cause a burst of volatiles to be emitted. High rates of volatilization of plastic bags can be a special problem if large quantities are charged without mixing with other waste.

Trim control units are required to fine-tune the air delivery system to control combustion gas temperatures and carbon monoxide. An oxygen trim control system has been typically provided, although carbon monoxide trim systems are available with modern microprocessor-based combustion control systems.

A sudden charge of wet MSW can upset the combustion conditions by acting as a heat sink. In general, this upset is responded to by increasing the underfire air supply and reducing the fuel charging rate. Another technique is to reduce the fuel bed thickness so that better drying can occur.

Of course, the crane operator can be requested to provide better mixing of the MSW. Mixing is not generally a problem in RDF systems.

Slide 25-7

```
              COMBUSTION AIR UPSETS

Underfire Air Supply
      Low Pressure   - Inadequate Oxygen
      High Pressure - Excessive Entrainment
      Poor Distribution (Front/Rear)
Overfire Air Supply
      Low Pressure   - Inadequate Mixing
      High Pressure - Excessive Gas Cooling
      Poor Distribution, Mixing
Fuel Bed Thickness, Clinkers
      Too Thick - Delayed Burning
      Too Thin - Particulate Entrainment
      Clinkers - Prevents Air Flow
Air Intrusion from Feed Hoppers
```

Inadequate control of combustion air will generally be detected through excessive carbon monoxide and/or smoke emissions. Abnormal combustion temperatures could also indicate problems with the air supply and distribution. Air control problems include those caused by fan and damper failures. Clinkers are formed because the temperatures often exceed the ash fusion temperature.

```
┌─────────────────────────────────────────────────────────────┐
│                  COMBUSTION AIR UPSETS                       │
│                                                              │
│       REMEDIES:                                              │
│                Check Draft Gage Readings                     │
│                Adjust Fan Controls/Dampers                   │
│                Modify Fuel Charging Rate                     │
│                Remove Clinkers                               │
│                                                              │
└─────────────────────────────────────────────────────────────┘
```

Operators should be cautioned that control of combustion air upsets will depend upon the site-specific design features of the air supply and the combustion systems. The comments presented below are designed to be general in nature, and as such will not apply to every situation.

Poor combustion air conditions can result from improper operation of the control system or a fan/damper failure. Such conditions are generally detected by observing the draft and air pressure gages. Fan dampers may have pneumatic actuators which mechanically provide the adjustments. A pneumatic system leak can cause a deteriorated response. Many fan applications include both electric and steam turbine drives, so shutdown will not be caused by a single energy source failure.

If the fuel bed is too thick, the air flow through the bed will be reduced. If the bed is too thin, the air flow will be excessive. In either case, improper mixing conditions can occur. The regions of increased air flow will tend to burn more intensely and have a tendency for particle entrainment. Compensation for variations in fuel bed thickness may be obtained by modifying the underfire air flow rate and its distribution. An obvious response would be to modify the fuel charging rate. Usually, both the fuel charging rate and the underfire air flow rate are adjusted together to obtain an optimal bed thickness.

Clinkers on the fuel bed will interrupt the normal air flow and cause inadequate mixing and combustion. The related ash fusion temperatures are generally lower under reducing conditions than under oxidizing conditions.[4] Once the clinkers are formed, air flow will be restricted and the conditions will tend to deteriorate. It is possible to turn the entire fuel bed into a fused mass that requires the boiler to be shut down for removing the clinker from the grates (sometimes with a jackhammer).[4]

Excessive carbon monoxide and/or smoke can also be caused by fuel property variations. For instance, when a charge of wet MSW is delivered, incomplete combustion may occur due to reduced gas temperatures.

```
┌─────────────────────────────────────────────────────┐
│         COMBUSTION TEMPERATURE UPSETS                │
│                                                      │
│    1.  High Temperature in Upper Region              │
│            Refractory or Metal Damage                │
│            Excessive Slagging                        │
│        Remedy:                                       │
│            Increase Overall Air Supply               │
│            Reduce the Underfire Air Supply           │
│            Reduce the Feed Rate                      │
│                                                      │
└─────────────────────────────────────────────────────┘
```

Abnormal combustion temperatures, carbon monoxide, and smoke can be caused by improper air delivery and distribution.

In many excess-air units, the general control system is designed to modulate the secondary air to control combustion temperature. Since excess air is a heat sink, adding more air will decrease the overall combustion temperatures. However, an increase of the underfire air will generally tend to increase the rate of production of volatiles and the intensity of combustion in grate-burning systems.[3]

Combustion temperatures are typically indicated through the use of shielded thermocouples which measure the temperature of the adjacent flowing gases.[1] The thermocouples should be shielded or placed in a location where they cannot "see" the flames of the radiant section. In general multiple thermocouples are provided, so that a malfunction of one unit will not cause an upset condition. Broken thermocouples can be routinely replaced. Slag deposits on thermocouples will act as insulation, causing the thermocouples to give low readings.

Slagging conditions on the heat exchanger surfaces can reduce heat transfer to steam and cause an increase in flue gas temperatures leaving the convective section.

```
┌─────────────────────────────────────────────────────┐
│         COMBUSTION TEMPERATURE UPSETS                │
│                                                      │
│    2.  Low Temperature in Upper Region               │
│            Inadequate Combustion                     │
│            Inadequate Energy Production              │
│        Remedy:                                       │
│            Increase Underfire Air Supply             │
│            Decrease Overfire Air Supply              │
│            Increase the Feed Rate                    │
│            Increase Auxiliary Fuel Burning           │
│                                                      │
└─────────────────────────────────────────────────────┘
```

Low combustion gas temperatures can be caused by low fuel feed rate and by the delivery of low quality fuels. Fuels having excessive moisture or inorganic content will have reduced heating values.

MSW/RDF feeder and auxiliary fuel burner control systems can be used to help maintain combustion gas temperatures. Auxiliary burners are generally provided for pre-heating the combustion chambers prior to the introduction of waste by the charging systems.

Some combustion units use flue gas recirculation as a heat sink to control temperatures. If flue gas is recirculated, the automatic controls will control the combustion temperatures by regulating the damper positions to modulate the amount of recirculated flue gas.

Slide 25-11

```
FURNACE DRAFT CONDITION UPSETS

1.  Excessive Draft
        High Velocities and Poor Mixing
        Excessive Particulate Entrainment
2.  Inadequate Draft
        Low Velocities and Pressure
        Transients, Puffing
3.  Operation with Positive Pressure
        Exterior Fly Ash Accumulation
        Gases/Smoke Leaking Out of Furnace
            Combustion Quenching
            Pollutant Exposure to Personnel
            Damage to Furnace Structure
        Torching - Flames Down Thru Grates
            Damage to Grates & Air System
```

In addition to the reading of draft gages, a general indication of improper draft control would be smoke emissions from cracks or openings in the combustion chamber walls and/or the unexpected build-up of fly ash around the unit's exterior.

Transients in the gas velocities are associated with improper fan/damper and/or fuel charging system operations. These conditions can lead to poor mixing and cause products of incomplete combustion to be formed.

Operating a furnace at an improper draft or at a pressure greater than ambient can cause problems with the combustion unit. The recommended amount of draft is designed to assure that appropriate gas velocities are maintained. If

pressure changes occur, gases can not only change their speed but also their direction.

Puffing is the condition which occurs when the combustion chamber pressure becomes positive and gases reverse their directions. Torching is the name of the condition where the combustible gases flow downward through the grate, causing damage to the grate, structural members, and underfire air supply system.

Slide 25-12

```
FURNACE DRAFT CONDITION UPSETS

REMEDY
     Balance Forced Draft Fan/Dampers
     and Induced Draft Fan/Dampers
```

The remedy for improper draft conditions is to restore the controlled operation of the forced draft and induced draft fans and the associated dampers.

Combustion problems are also expected when the unit operates above design capacity. Many operators will try to operate their unit at the upper levels of its rated capacity. This could be a problem if the fans are unable to supply adequate air. Fan performance may be compromised if the fans are not well maintained or if unplanned air resistance occurs in the dampers or ducts.

REFERENCES

1. <u>Municipal Waste Combustion Systems Operations and Maintenance Study</u>," U.S. Environmental Protection Agency, EPA-340/1-87-002, June 1987, pp. 4-18.

2. Joseph G. Singer, <u>Combustion, Fossil Power Systems</u>, 3rd Edition, Combustion Engineering, Inc., Windsor, CT, 1981, pp. 20-1 to 20-31.

3. W. R. Seeker, W. S. Lanier, and M. P. Heap, "Municipal Waste Combustion Study, Combustion Control of Organic Emissions," U.S. Environmental Protection Agency, EPA-530-SW-87-021-c, June 1987, p. 8-1 to 8-25.

4. PEI Associates, Inc., <u>Combustion Source Inspection Module, Student Reference Manual</u>, Submitted to U.S. Environmental Protection Agency, September 1990, pp. 242-245, 272-291.

26. SPECIAL SYSTEM CONSIDERATIONS I: WATER TREATMENT

Slide 26-1

```
┌─────────────────────────────────────────────────┐
│              IMPURITIES OF RAW WATER              │
│                                                   │
│      Composition Varies with Source               │
│             Chemical Wastes                       │
│             Organic Wastes & Bacteria             │
│             Oxygen & Dissolved Gases              │
│             Dissolved or Suspended Minerals       │
│             Suspended Solids                      │
└─────────────────────────────────────────────────┘
```

Water treatment has many complex aspects which are developed in various references, including those listed at the end of this learning unit. The emphasis of this learning unit will be on summarizing boiler water treatment features. Cooling water and wastewater treatment are also important operator responsibilities.

Water impurities include those items listed above. Impurities generally get into boiler water systems through the raw water supply and through the leakage of the condenser's cooling water into the condensed steam (condensate) which is recirculated into the boiler as feedwater. For example, in applications where coastal water is used for condenser cooling water, salt water (chloride) can leak into the condensate, and the chloride content of the leakage will often vary with the tides.

Slide 26-2

```
┌─────────────────────────────────────────────────┐
│              CHEMICAL COMPOUNDS                   │
│                                                   │
│      Acids:   Hydrogen Ions in Solution           │
│      Bases:   Metal-Hydroxyl Ions in Solution     │
│      Salts:   Compounds of Acids & Bases          │
└─────────────────────────────────────────────────┘
```

When materials dissolve in water, they dissociate into ions. The positively charged ions are called cations and the negatively charged ions are called anions.[1]

The chemical compounds found in water are classified as acids, bases (alkalis) and salts. Examples of acids include hydrogen chloride, nitric acid and sulfuric acid. When acids are dissolved in water, hydrogen ions (H^+) and negatively charged anions such as: Cl^-, NO_3^- and SO_4^- are formed.

Bases are those liquid solutions characterized by the presence of metal ions (e.g., Ca^{++}) and hydroxyl ions (e.g., OH^-). These may be referred to as basic, alkali, and caustic solutions. Examples of basic materials include water solutions such as calcium hydroxide or hydrated lime which are formed when lime (calcium oxide) reacts with water.

Salts are formed when acids and bases react together. Examples of salts are calcium sulfate, calcium carbonate ($CaCO_3$, limestone), magnesium carbonate ($MgCO_3$), and sodium chloride (table salt).[2]

Slide 26-3

```
        BOILER WATER IMPURITIES

    1.  Dissolved Gases
    2.  Dissolved Minerals - Hardness
    3.  Dissolved and Suspended Solids
```

The major impurities in boiler water can be grouped as: dissolved gases, dissolved minerals, and dissolved and suspended solids.

Many materials have increased solubility in water as the temperature increases. However, oxygen, carbon dioxide and salts, such as calcium sulfate, calcium carbonate and magnesium carbonate, have reduced solubility as the temperature increases. This leads to the important phenomena of deaeration and scale formation which will be discussed below.

Slide 26-4

```
    BOILER WATER PROBLEMS

    Corrosion of Metal Tubes
    Scale Build-Up Inside Tubes
    Contamination of Steam:
        Deposits in Tubes & Turbine
```

Operators must pay particular attention to the conditions of the water in the boiler. Boiler water contains various impurities which can cause corrosion and pitting of metal, as well as scale build-up and contamination of the steam. If left untreated, these conditions can lead to boiler tube failures and damage to steam turbines.

Scale formation is most difficult in the high temperature regions of the boiler, due to the decreased solubility which results in precipitation of scale materials. The typical compounds found in scale deposits include calcium carbonate, iron oxide, alumina, calcium phosphate, magnesium hydroxide, magnesium silicate, and silica.[1]
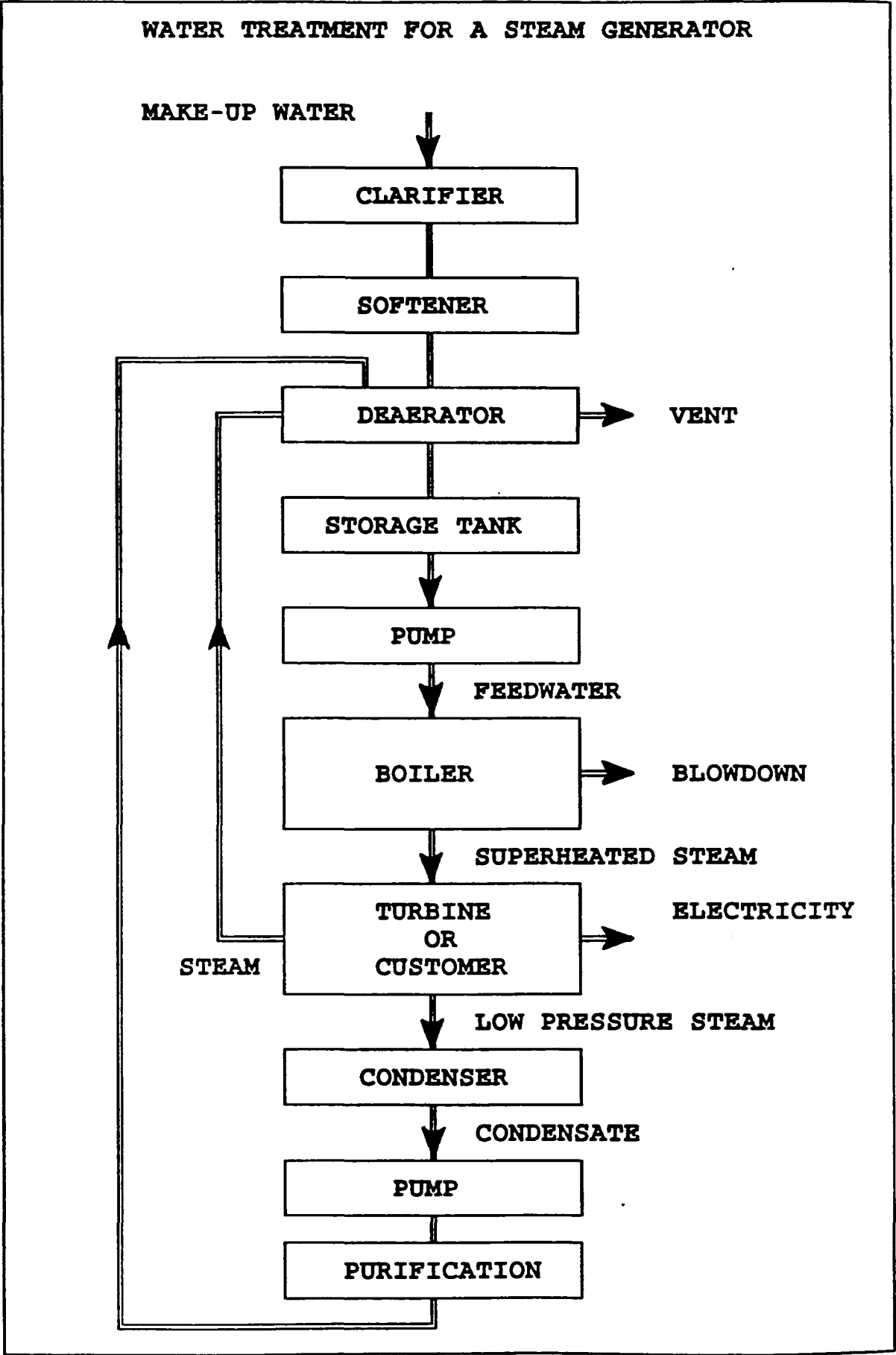
Slide 26-5
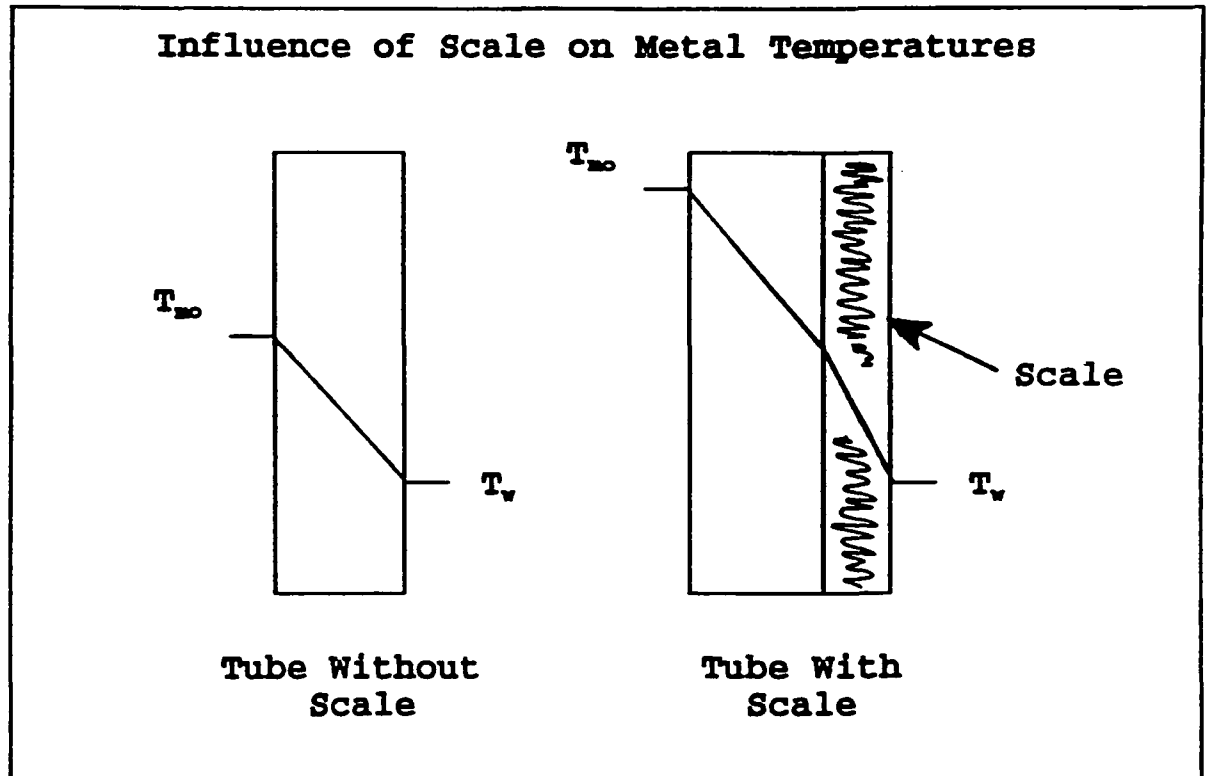
The tube failure mechanisms include the long-term, repetitive formation of scale which acts as insulation and causes increased metal temperatures and thermal expansion of the metal.[1,3,4,5]

As indicated in Slide 26-5, the outside metal temperature (T_{mo}) is increased considerably as a result of the insulating properties of built-up scale.

When the scale cracks off, the metals are suddenly cooled and undergo contraction. This process results in the formation of bulges or blisters which eventually lead to tube failures. Another mode of tube failure is associated with rapid accumulation of scale deposits which causes overheating to the point that the metal undergoes plastic flow and ruptures.[6]

The water treatment at each site must be appropriate for the water conditions of the individual sources of contamination and the operating steam pressure and temperature requirements of the particular MWC unit.[7]

WATER TREATMENT FOR A STEAM GENERATOR

The condensate, boiler feedwater, and steam circuit generally follows the flow path indicated in the slide. Note, however, that the actual plumbing system can be considerably more complicated than indicated in Slide 26-6 in order to accommodate all the features of water treatment.

The clarifier is a conventional element of a water treatment system, which is used to remove suspended matter from the raw water. Removal can be accomplished through the application of coagulation, flocculation and sedimentation concepts.[1] The particles suspended in the water have electrical charges which cause the particles to repel each other. Coagulation works by neutralizing these charges; flocculation works to cause the materials to agglomerate; and sedimentation is the physical settling process.

Softening and deaeration will be introduced below. However, note that the deaerator acts as a feedwater heater, using steam extracted at an intermediate pressure from the turbine to heat the condensate and make-up water mixture enough to control the amount of dissolved gases. In addition to water treatment benefits, the system thermodynamic efficiency also is increased by this feedwater heating operation in that the latent energy which would otherwise be lost to the condenser is delivered to the feedwater.

Slide 26-6 indicates that a condensate purification system can be located downstream of the condenser. Depending upon the application, condensate purification may be necessary, particularly if steam is reclaimed from an industrial application. Such condensate conditioning systems may take different forms, including that of a water softener or condensate polishing (demineralizer) system.

Although not indicated in the sketch, various chemical additives or conditioners may be added to the water in the deaerator storage tank, boiler, or main steam supply line to achieve the desired changes in water or steam properties.

Slide 26-7

```
  BOILER WATER PROBLEMS & REMEDIES

  1.   Dissolved Gases
          Metal Corrosion & Pitting
       Remedy:
          Deaeration
          Chemical Scavengers
```

Oxygen, carbon dioxide and other dissolved gases can cause corrosion and pitting. For example, oxygen can react with the protective iron oxide (magnetite) on metal surfaces to form a non-protective oxide (hematite) which allows pitting to occur.[7] This oxidation can be controlled by reducing the amount of dissolved oxygen in the water and creating a slightly basic water solution.[3]

Gases are removed by heating water enough to cause the gases to be vaporized in a deaerating feedwater heater. The operating principle is that the solubility of oxygen decreases significantly as the water temperature increases.

In addition, chemical deaeration can be achieved by the addition of chemicals (scavengers) such as sodium sulfite or hydrazine.[7] In MWC boilers, sodium sulfite is often added to the water in the deaerator storage tank. It reacts with the traces of oxygen leaving the deaerator, and the residual sodium sulfite is maintained in the boiler to remove any un-reacted oxygen.

Hydrazine works well as an oxygen scavenger in high pressure boilers (where sodium sulfite breaks down and becomes corrosive), but hydrazine can cause undesirable health problems.[7]

Slide 26-8.

TRAY-TYPE DEAERATING FEEDWATER HEATER[2]
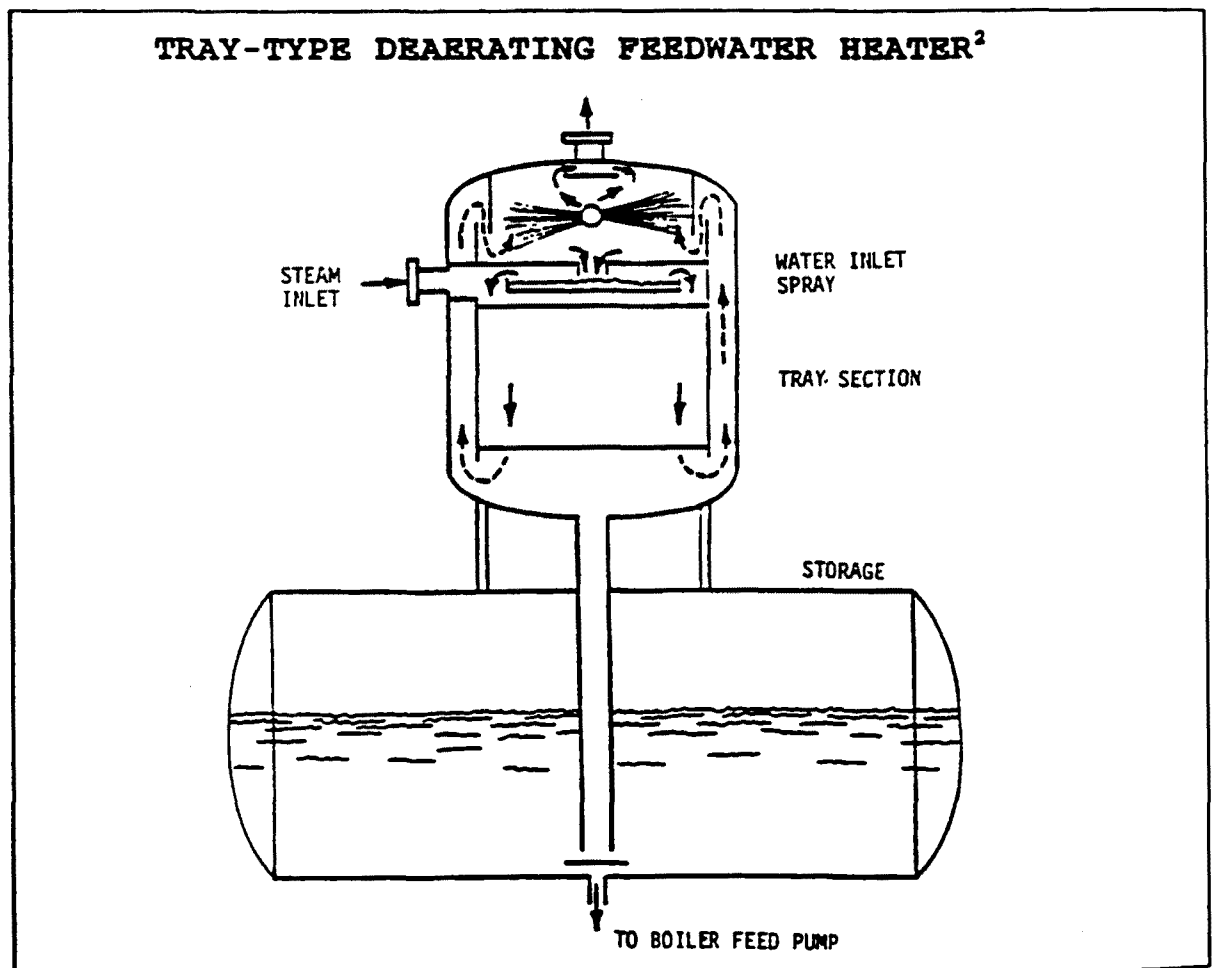
Courtesy of Boiler Efficiency Institute

The deaerating heater is an "open feedwater heater" which is used to remove dissolved gases.[4] The gases are forced out of solution by heating the water with steam. In general, the heating is provided by steam. The steam is extracted from the turbine at an intermediate pressure between the condenser pressure and the throttle pressure. Deaerator pressures are often found between 5 and 75 psig.

The gases released by heating can be purged by opening a vent valve at the top, since the unit is pressurized. The water collected in the storage tank becomes boiler feedwater.

Slide 26-9

DEAERATING FEEDWATER HEATER & FLASH TANK[4]
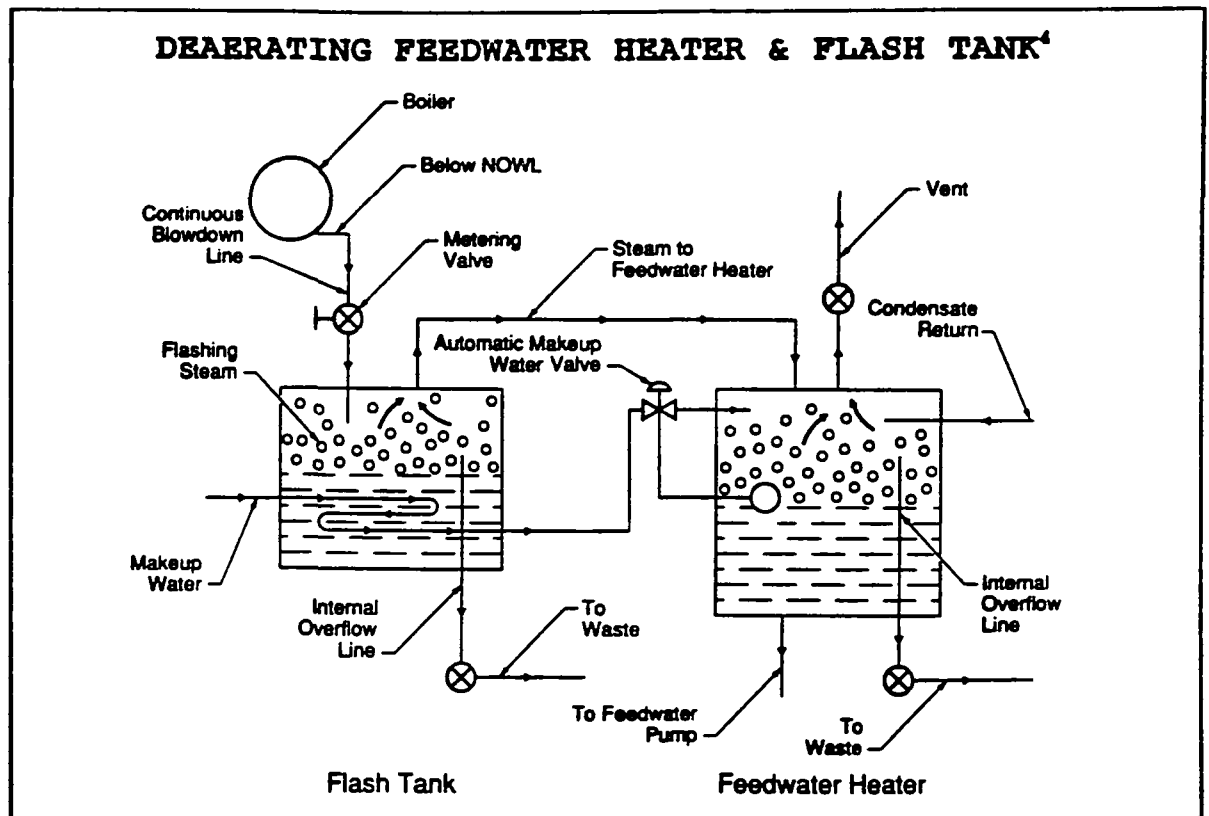
From Frederick M. Steingress and Harold J. Frost, Stationary Engineering, American Technical Publishers, Inc., Homewood, IL, 1991, printed with permission.

The steam for the deaerating heater can be extracted from the steam turbine, or it can come from the boiler blow-down after it has passed through the flash tank.

In general, the extraction steam pressure will vary with the design. However, as larger pressures are specified, the corresponding feedwater temperatures and vapor pressures are increased.[4] To avoid cavitation problems (pump becoming steam-bound), the design must provide for the net positive suction head (NPSH) requirements of the pump. Cavitation can be avoided if the height of the deaerator storage tank above the feedwater pump is adequate to compensate for the frictional losses in the supply pipe, the losses of the fittings, and the fluid's vapor pressure.

The flash tank is a special evaporative heat exchanger which heats feedwater and also evaporates part of the blowdown water from the boiler[4]. In the flash tank, the contaminants from the blowdown are concentrated in the waste water and pure steam is delivered to heat the feedwater.

```
┌─────────────────────────────────────────────────┐
│         BOILER WATER PROBLEMS & REMEDIES         │
│                                                  │
│     2.   Dissolved Minerals - Hardness           │
│               Increase Metal Corrosion           │
│               Form Scale & Sludge                │
│          Remedies:                               │
│               Water Softeners                    │
│             ·   Condensate Purification          │
└─────────────────────────────────────────────────┘
```

Minerals dissolve in water as ions that carry an electrical charge.[8] The ions can be indicated by measurements of conductivity and hardness. Minerals often enter from the water supply or as cooling water which leaks through seals and connections in the condenser. Minerals such as calcium and magnesium must be treated and removed to avoid scale formation.

These minerals are typically found as calcium carbonate and magnesium carbonate. Such carbonates (or salts) are generally detected by testing for hardness,[4] which relates to the ability of water to dissolve soap.[2]

Mineral salts can be treated by the addition of an alkali substance, such as sodium hydroxide (caustic soda) and calcium oxide (lime), which converts the carbonates to a precipitate.[4] The precipitates can be removed by filtration. Other methods include conversion to a calcium phosphate and magnesium phosphate sludge, which does not adhere to metal surfaces.

The monitoring of pH in both boiler water and in feedwater is very important because significant damage due to scale build-up and corrosion can occur in a short period of time.[3] Note that high alkalinity levels can cause deposits which weaken metal and lead to cracking, called caustic embrittlement.

Demineralizers are used in some MWC operations to remove ionized mineral salts (hardness).[1] Cations (pronounced as "cat-ions") such as calcium, magnesium, and sodium can be removed in a hydrogen cation exchanger. Anions (pronounced as "an-ions") such as bicarbonates, sulfates, chlorides, and soluble silica are removed in the anion exchanger.

A sodium zeolite ion-exchange water softening process is one of the simplest methods of removing hardness. The zeolite can be thought to act like a sponge material that gives up its sodium ions in exchange for calcium carbonate, magnesium carbonate, and ferrous oxide. When the zeolite has been exhausted of sodium ions, it can be regenerated by flushing with common table salt (sodium chloride).[4]

Synthetic cation and anion exchange resins, which can be regenerated, are often used. Demineralizers can involve two-vessel systems as well as mixed bed units.[4] Generally, mixed bed units are more difficult to operate and not as efficient as systems with separate vessels for the cation and anion resins.

Slide 26-11

```
            BOILER WATER PROBLEMS & REMEDIES

     3.   Dissolved & Suspended Solids
             Causes Carry-Over of Impurities
             Damages Superheater, Valves, Turbine
          Remedy:
             Boiler Water Blowdown
```

Impurities such as dissolved and suspended solids in the water are removed by blowdown, a process where a portion of the water is discharged from the boiler and replaced by treated make-up water. Note that these impurities are non-volatile, so they will not evaporate and leave the boiler with the steam.

If these impurities are not removed, their concentration will build up in the boiler water. High concentrations of impurities will cause foaming, which is the trapping of steam bubbles below the water surface in the steam drum.

Foaming can cause the carry-over of slugs of liquid water with dissolved and suspended solids into the steam lines. The solids may be deposited in the superheater tubes, valves, and steam turbine, resulting in considerable damage and loss of production.[6] For instance, high concentrations of silica can cause severe turbine blade fouling.

The level of such impurities may be indicated by high alkalinity, the total dissolved solids, and suspended solids which should be kept below the recommended limits that depend upon the unit's design (boiler pressure).[3,7]

```
┌─────────────────────────────────────────────────────────────┐
│              INDICATORS OF WATER QUALITY                      │
│                                                              │
│     1.  pH - Indicates Acidic/Alkali Quality                 │
│              <7: Acidic;  7: Neutral;  >7: Basic             │
│     2.  Conductivity of Steam & Feedwater                    │
│              Microsiemens/cm                                 │
│     3.  Total Dissolved Solids in Boiler Water               │
│              Microsiemens/cm                                 │
│     4.  Alkalinity                                           │
│              Equivalent Calcium Carbonate, ppm               │
│     5.  Hardness - Ability to Dissolve Soap                  │
│              Calcium & Magnesium Salts, ppm                  │
│     6.  Silica - Silicon Dioxide, ppm                        │
└─────────────────────────────────────────────────────────────┘
```

There are a number of laboratory tests and continuous indicating instruments which can provide an indication of water quality. The most common are the pH and conductivity meters.

A pH meter monitors the acidic or basic characteristics of a solution. The optimum pH levels in boiler water will depend upon the application.[9] A pH number of 7 indicates a neutral condition, with larger values indicating basic (alkaline) conditions and smaller values indicating acidic conditions.

The pH in the condensate is generally lower than that in the drum water. The pH of the boiler water at one typical MWC with 100% condensate return ranges from 9.3 to 10.4, and that in the condensate ranges from 9.0 to 9.5.[10] Feedwater pH often ranges between 8.0 and 9.5.[9]

Electrical conductance is the reciprocal of electrical resistance. Conductance relates to the flow of electrons through the water, with more impurities causing electrons to flow more easily. Conductivity meters measure the reciprocal of electrical resistance of water, with low conductance and high resistance being an indication of pure water. High conductance would therefore be an indication of a high level of impurities. Conductivity meters can be mounted on the steam and feedwater tubes to provide a continuous reading.

The typical conductivity instrument provides direct reading in microsiemens/cm or microhms/cm (siemens and ohms are equivalent).[11] A typical boiler water conductivity range is from 75 to 100 microhms/cm, whereas the feedwater range is from 10 to 15 microhms/cm.[10]

The meter for total suspended solids operates exactly as a conductivity meter. It is used to measure the quality of water leaving the boiler in the blowdown.

Alkalinity, hardness and silica can also be measured as an equivalent concentration of calcium carbonate, calcium and magnesium salts, and silicon dioxide, respectively. Silica monitors are typically mounted on the main steam line to the turbine, giving measurements in mass-based parts per million (ppm). For instance, 1 ppm of silica would indicate that a pound of silicon dioxide would be found in a million pounds of water.[4]

The example hardness, silica, and iron numbers which follow were measured at a MWC unit which has 100% condensate return.[10] The hardness in the feedwater was limited to 0.1 ppm. The measured silica in the boiler water was around 3 ppm, with the silica in the feedwater limited to 0.1 ppm. Similarly, the iron in the boiler water was around 1 ppm, and the corresponding iron in the feedwater was 0.02 ppm.

REFERENCES

1. Frank N. Kemmer, <u>Nalco Water Handbook</u>, The Nalco Chemical Company, Second Edition, published by McGraw Hill Book Company, 1988, pp. 3.3 to 3.15, 12.24 to 12.45, 39.1 to 39-66.

2. David F. Dyer and Glennon Maples, <u>Boiler Efficiency Improvement</u>, Boiler Efficiency Institute, Auburn, AL, 1981, pp. 8.1-8.32.

3. Joseph G. Singer, <u>Combustion, Fossil Power Systems</u>, 4th Edition, Combustion Engineering, Inc., Windsor, CT, 1991, pp. 20-1 to 20-45.

4. Frederick M. Steingress and Harold J. Frost, <u>Stationary Engineering</u>, American Technical Publishers, Inc., Homewood, IL, 1991, pp. 83-87, 277-293.

5. E. B. Woodruff, H. B. Lammers and Thomas F. Lammers, <u>Steam Plant Operations</u>, Fifth Edition, McGraw-Hill Book Company, New York, 1984, pp. 264-270.

6. <u>Betz Handbook of Industrial Water Conditioning</u>, Eighth Edition, Betz Laboratories, Inc., Trevose, PA, 1980.

7. James A. Baumbach, "Key Treatment Chemicals," <u>Standard Handbook of Power Plant Engineering</u>, Thomas C. Elliott, editor, McGraw Hill Book Co., NY, 1989, pp. 4.217-4.237.

8. David S. Beachler, <u>APTI Course SI:428A, Introduction to Boiler Operation</u>, U. S. Environmental Protection Agency, EPA 450/2-84-010, 1984, pp. 4-13 to 4-16.

9. <u>Steam, Its Generation and Use</u>, 39th Edition, Babcock and Wilcox, New York, 1978, pp. 34-10 to 34-18.

10. Personal Communication, Vicki Barnhart, York Resource Energy Systems, Inc., York, PA.

11. J. A. Moore, "Pollution Instrumentation," <u>Standard Handbook of Power Plant Engineering</u>, Thomas C. Elliott, editor, McGraw Hill Book Co., NY, 1989, pp. 6.45-6.57.

27. SPECIAL SYSTEM CONSIDERATIONS II: ELECTRICAL THEORY

Slide 27-1

```
BASIC ELECTRICITY

Ohms Law
DC vs. AC Current
Electrical Phases
Power
Transformer
Rectifier
```

A basic understanding of electrical principles is necessary for informed operation, maintenance, and troubleshooting.[1] This learning unit will present the basic principles of electricity. It will focus on the basic knowledge required for the understanding of transformers, rectifiers, and electric generators.

This learning unit will generally follow the development of electrical principles presented in the book, Stationary Engineering, by Steingress and Frost.[1]

Slide 27-2

```
             ELECTRICITY & CURRENT

Electricity
        Flow of Electrons
Direct Current:  DC
        Steady Flow of Electrons
Current
        Rate of Electron Flow
```

We will begin by defining electricity and some of its related properties. Initially, we will focus on steady "direct current" (DC), such as that associated with battery powered systems.

Current is the flow of electrons. When we say, "electric current or electricity can flow through a wire," we mean that electrons can flow through the wire. The electrons of steady DC current flow in one direction.

Current is measured in amperes or amps. Current can be thought of as the rate of electron flow, where one ampere is a very large number of electrons per second.[2]

Slide 27-3

ELECTRICITY - FLUID FLOW ANALOGY

Parameter	Electricity	Fluids
Flow Rate	Electron Flow/Current (amps)	Fluid Flow (gpm)
Driving Force	Electrical Potential or Voltage Difference (volts)	Pressure Difference (psi)

We will use the fluid flow analogy to help our understanding of electricity.[3] Current is analogous to fluid flow rate, which can be expressed in gallons per minute (gpm).

We know that fluid flow is caused by a pressure difference, such as that developed by a pump. The electrical driving force is called the electrical potential or voltage difference. It causes current to flow through a conductor. Electrical potential is measured in volts and is analogous to pressure, which can be measured in pounds per square inch (psi).

Slide 27-4

VOLTAGE OSCILLATIONS OF ALTERNATING CURRENT
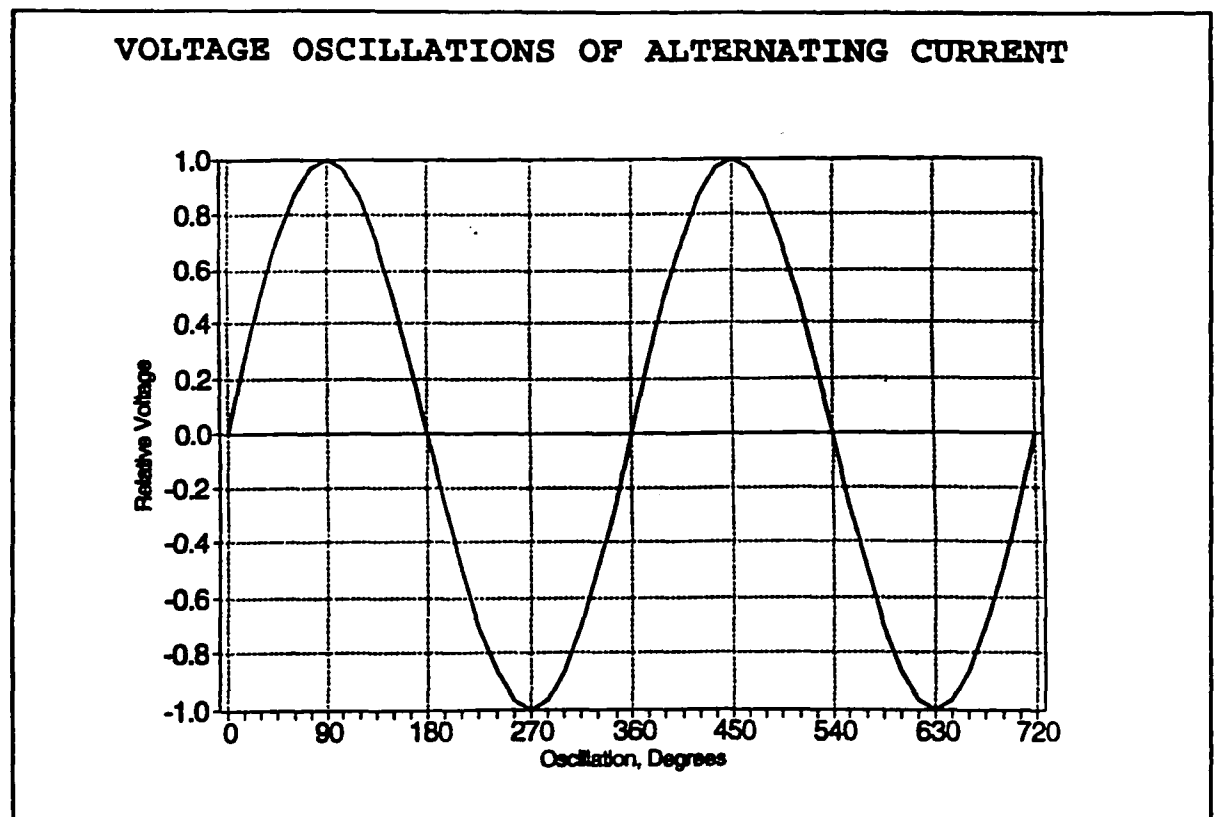
The voltage of alternating current (AC) electricity periodically changes, as illustrated above. AC is the traditional form of commercial electricity which is produced by most steam turbine generators and is delivered to customers through interconnecting electrical transmissions lines (the grid). The voltages for standard A.C. electricity in the United States oscillates at 60 cycles per second (60 Hz), where each cycle would correspond to an oscillation occurring over 360 degrees, as illustrated above.

Because of the oscillations, the actual time-average AC voltages and the corresponding AC currents have values of zero. However, conventional AC instruments measure representative voltages and currents. The instruments are designed to give "root-mean-square" values, which are the average of the square of the values over time. It may be interesting to note that the oscillating features of AC voltages and currents can be measured by oscilloscopes.

Slide 27-5

```
+-----------------------------------------------------------+
|          OTHER BASIC ELECTRICAL PARAMETERS                |
|                                                           |
|    1.  Conductor    - Material Which Permits              |
|                       Electrons to Flow                   |
|    2.  Resistance   - Measures Opposition to Flow         |
|    3.  Ohm          - Unit of Electrical Resistance       |
|    4.  Insulator    - Material with High Resistance       |
|    5.  Circuit      - The Path of Electrical Current      |
|                       From a Source Through Various       |
|                       Conductors and Devices              |
+-----------------------------------------------------------+
```

Conductors are materials with properties that permit the flow of electrons. Materials are generally ranked according to their relative resistance to electrical flow. Electrical resistance is generally measured in units of ohms.

The resistances of conductors depend upon chemical composition, size (diameter), and length. Glass objects generally have enough electrical resistance to be called insulators, whereas metal wires are called conductors. Large diameter (small gage) copper wires have much lower electrical resistance than thin copper wires. Electrical conductors must be properly selected so that they will not overheat and fail (melt) under high current conditions. The current carrying capacity of wire conductors is dependent upon size (gage) and electrical insulation design.

An electrical circuit is composed of at least one electrical source, various conductors (or resistors) and/or other electrical devices (e.g., motors) which are connected together. A battery or some other electrical source is required to provide the voltage which will cause electricity to flow through a circuit.

Slide 27-6

```
+-----------------------------------------------------+
|                     OHMS LAW                        |
|                                                     |
|        Voltage = Current x Resistance               |
|                                                     |
|              E   =   I   x   R                      |
|        or                                           |
|              I   =    E                             |
|                      ---                            |
|                       R                             |
+-----------------------------------------------------+
```

Ohms law establishes the basic relationship of steady electrical flow. The electrical potential (measured in volts) is equal to the current (measured in amps) times the resistance (measured in ohms). Ohms law uses "E" as the standard symbol for the voltage or electrical potential. The symbol for current is "I", and the symbol for resistance is "R".

If any two of these variables are known, the third can be found from Ohms law by using simple algebra.

Ohms law can be conveniently used in steady applications which involve both large and small electrical quantities. Many power applications involve high voltages, measured in kilovolts (thousand volts) or megavolts (million volts). By contrast, instruments often produce small voltage signals which are measured in millivolts (one-thousandth of a volt) or current signals which are measured in milliamperes (one-thousandth of an amp). It is recommended that conversions be made to the standard units of volts, amps, and ohms before Ohms law is used for calculations.

Slide 27-7

```
+-----------------------------------------------------+
|                 ELECTRICAL POWER                    |
|                                                     |
|         Watt - Unit of Electrical Power             |
+-----------------------------------------------------+
```

The basic unit of electrical power is a Watt. In power generation, we often are concerned with large quantities of power which can be measured in kilowatts (kW, thousand Watts) or megawatts (MW, million Watts). As described later, the alternative units often used in AC electric generation applications are volt-amps (VA), kilovolt-amps (kVA), and megavolt-amps (MVA).

```
              DC ELECTRICAL POWER

Power    =  Voltage  x  Current

      P  =   E   x   I
or
      P  =   (I x R) x I
         =   I² x R
or
      P  =   E x ( _E_ )
                   R

         =    E²
             ____
              R
```

Electrical power is generally defined as the product of the voltage times current. The electrical power unit is a Watt which has dimensions equivalent to a volt-amp (VA). Other formulas listed above were obtained using Ohms law substitutions.

The power relationships can be applied to the example of the resistance heating of a conductor. If the resistance of the conductor and the voltage across it can be calculated or measured, the rate of resistance heating can be determined.

AC VOLTAGE AND CURRENT RELATIONSHIPS
(EXAMPLE WITH CURRENT LAGGING)
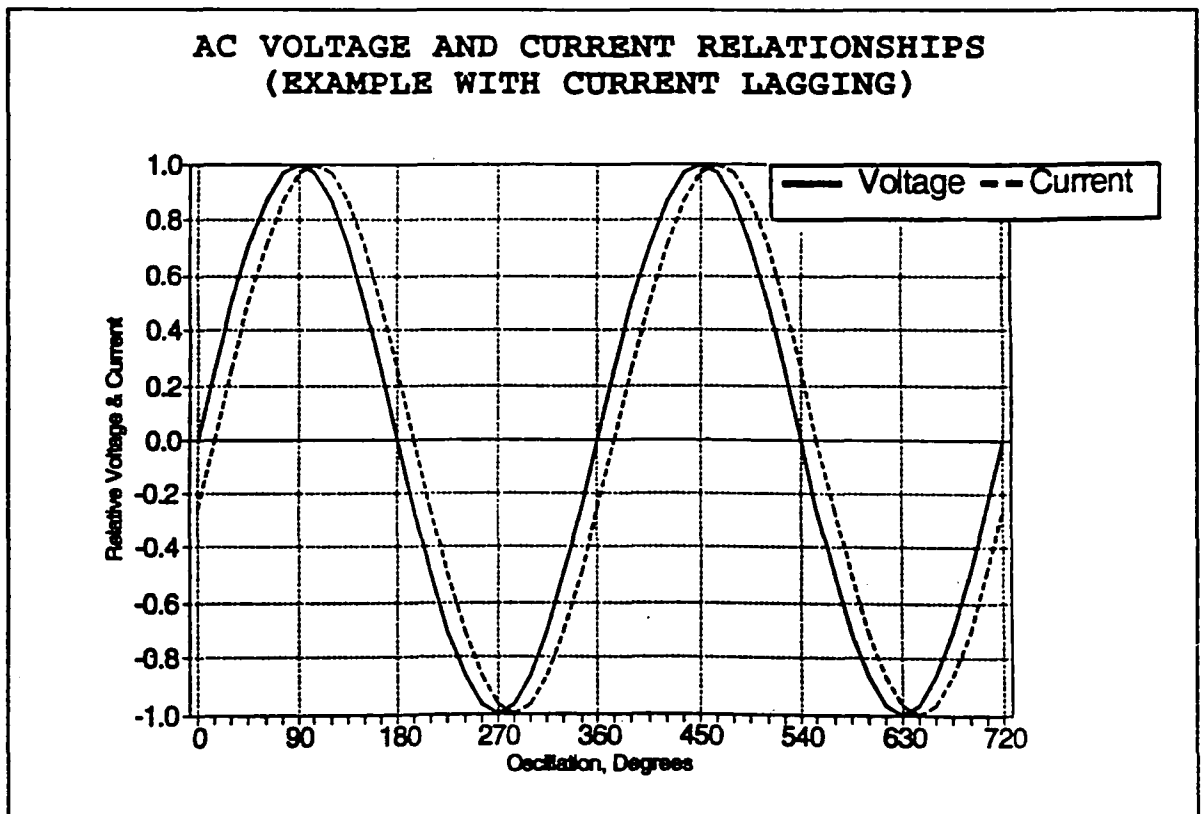
Note that the AC current is generally not exactly "in phase" with the voltage. In the example illustrated above, the current is shown to be lagging the voltage by 15 degrees. This is because the horizontal axis is basically time, with the current reaching its peak value a short time after the voltage peaks.

Slide 27-10

```
                      AC ELECTRICAL POWER

     Power      = Voltage x Current x Power Factor

             P  =  E x I x cos Θ
     or
             P  =  (I x R) x I x cos Θ
                =  I² x R x cos Θ
     or
             P  =  E x ( E )  x cos Θ
                          R
                =  E²  x cos Θ
                   R
```

The previously developed DC power equations require modification for AC power, as indicated above.

Slide 27-11

```
                     AC ELECTRICAL POWER

          Apparent Power is Current times Voltage

              P_apparent  =  E x I,   [KVA]

     Power Factor:

          Power Factor = cos Θ = P/P_apparent

     Reactive Power is Imaginary Power

              P_reactive  =  E x I x sin Θ,  [KVAR]
```

The "power factor" is the correction factor required because the current and voltage generally are slightly out of phase with each other. If steady current and voltage readings are obtained across a component of an AC circuit, they may be multiplied together to yield the "apparent power."

In electric power generation, the apparent power is often expressed in MVA units, as it represents an upper production limit. The power factor is defined as the ratio of the "real power" divided by the "apparent power." The conventional representation of a power factor is "cos Θ," where Θ represents the phase angle difference between the voltage and current.[4] For the example where the phase angle difference was 15 degrees, the power factor would be 0.96.

"Reactive power" is imaginary power which is defined as being equal to the "apparent power" times "sin Θ." For the example of a 15 degree phase angle, the reactive power is 0.26 times the voltage-current product. "Reactive power" can be expressed in units of VARS (volt-amperes reactive)[5], KVARs (kilovolt-amperes reactive), or MVARs (Megavolt-amperes reactive).

MWC units often sell electric power to utilities who stipulate in the contract the purchase of "real power" (MW). Utilities will typically include a penalty in the contract if adequate VARs are not produced. VARs requirements are equivalent to requiring the generated energy to have a particular power factor. An example contract specifies a 0.9 "lagging" power factor (current lagging the voltage).

The VARs output can be controlled by varying the field excitation of the generator. The generator can be "overexcited" to produce VARs which can flow to the plant's motors, providing their excitation and reducing the VARs drawn from the utility system. Many generators make use of special power-factor controllers which work in conjunction with the voltage regulator. Also, power-factor drawn by the in-plant motors from the utility grid can be controlled by using special capacitors.[5]

Slide 27-12
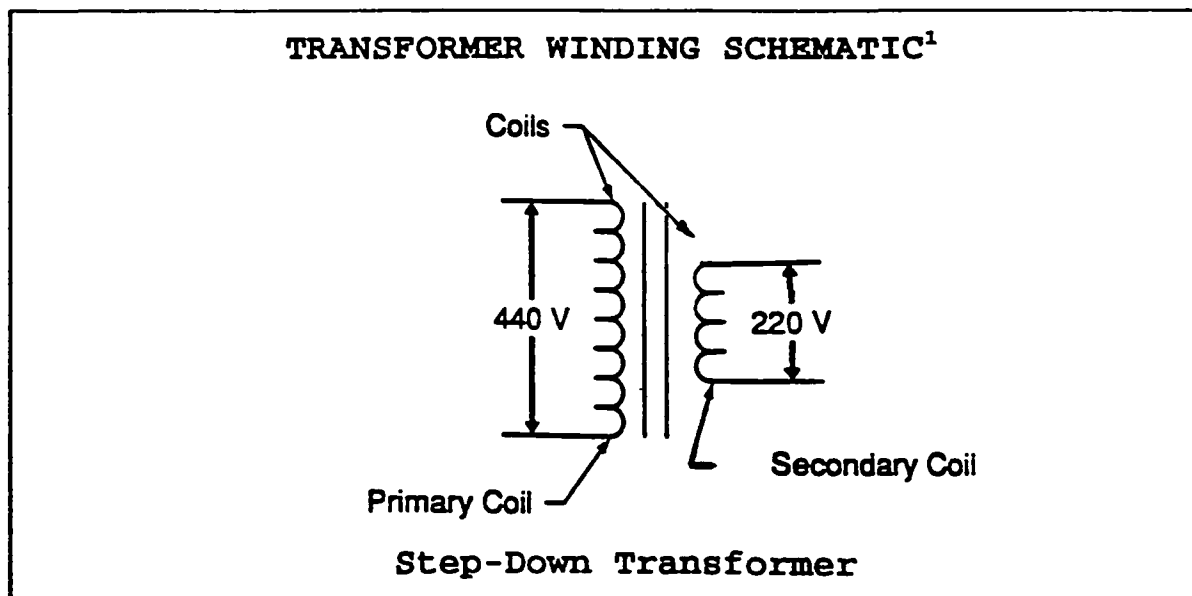
TRANSFORMER WINDING SCHEMATIC[1]

Coils

440 V   220 V

Primary Coil

Secondary Coil

Step-Down Transformer

From F. M. Steingress and H. J. Frost, <u>Stationary Engineering</u>, American Technical Publishers, Inc., Homewood, IL, 1991, printed with Permission.

Slide 27-12 illustrates the basic wiring of a transformer, which uses the phenomenon of electrical induction. Transformers are designed to increase or decrease voltage in AC circuits. A step-up transformer delivers a higher voltage from the secondary coil than is received by the primary coil, and a step-down transformer will deliver a reduced voltage.

The fractional increase or decrease in voltage of a transformer is proportional to the ratio of the windings of wire in the primary and secondary coils. If there are twice as many windings on the primary coil as on the secondary coil, the transformer will function as a step-down transformer with the resulting voltage at one-half that of the supply voltage, as illustrated in the slide.

Transformers are essential elements in the connection between the utility grid, MWC electric generator, and in-plant distribution system. However, the wiring of the transformers and their protection systems are much more complex than indicated above.

Design considerations include the wiring of transformers (using either the wye-delta, delta-wye, wye-wye, or delta-delta configurations) with their special grounding provisions.[5] These electrical design features are beyond the scope of this training program.

Slide 27-13

SCHEMATIC OF 3-PHASE ELECTRIC CURRENT
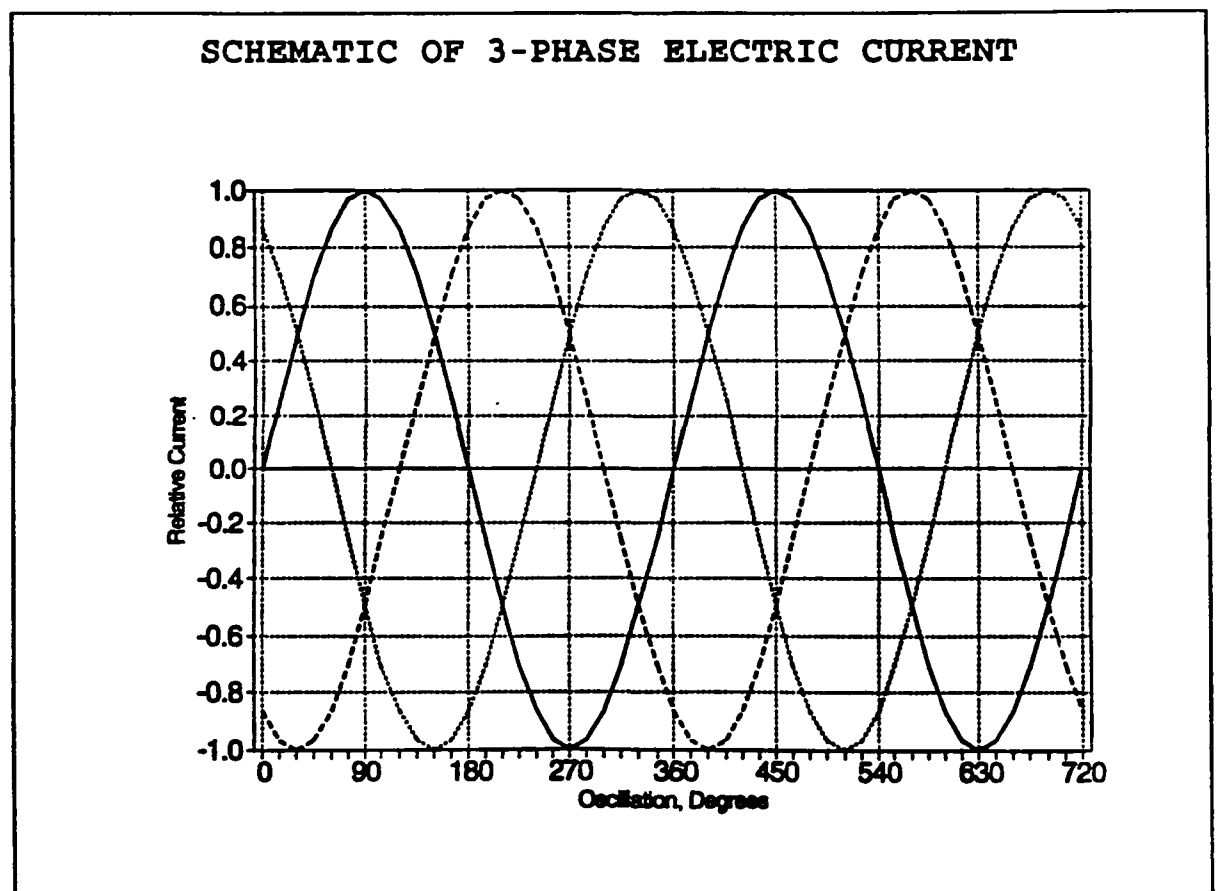
Operators should be aware that the utilities transport 3-phase, high voltage, AC power. Therefore, the MWC units which generate electricity for sale to utilities produce 3-phase power. Three-phase generation uses three primary conductors which carry AC currents whose cycles are timed in a regular offset pattern, as illustrated above. Many circuit designs will use four conductors in order to accommodate a ground requirement.

The electrical system design is required to accommodate both the utility and plant requirements. The voltages and voltage differences between the conductors will depend upon the wiring design. Also, the grounding, transformer connections, voltage regulation, and circuit breaker systems will be dependent upon the special design features which are selected.[5]

The design, wiring, and operational features of 3-phase motors will be left to the electrical system designers and in-plant training programs.

Slide 27-14

```
CIRCUIT BREAKER:
Controls the Flow of Electricity

RECTIFIER:
Converts AC Electricity to DC

INVERTOR:
Converts DC Electricity to AC
```

Special electrical power equipment such as circuit breakers, rectifiers, and inverters are commonly used in MWC units.

Circuit breakers[5] are designed to provide the switching required in electrical generation and electrical service. Some circuit breakers are provided primarily to protect the utility grid, whereas others function as a local safety device. The utility can trip the main circuit breaker as part of the normal and correct functioning of the network protective system.

Circuit breakers are switches that are mechanically closed after a heavy spring is compressed and held in place by a latch. Circuit breakers are designed to open automatically when an external tripping signal is received. The signal may signify that the current flow on the circuit is too high, the voltage is too high or too low, or that some fault condition has occurred.

The signals are often actuated by the action of a relay. For example, a directional relay is designed to prevent the reversed flow of electricity, such as the case when a generator receives grid power which causes it to act as a motor.

A rectifier is an electronic device which receives an AC electrical supply and produces DC electricity. Rectifiers are used to produce the DC electricity which is used to produce the electrical fields required for particle collection in electrostatic precipitators. Rectifiers can also be used for charging the batteries which store energy for emergency power supply systems.

Inverters are used to convert the DC electricity into AC electricity. Emergency power supply systems are generally designed around storage batteries and inverters. These are required because AC power is generally required to drive almost all the electric motors and controls used in MWC units.

REFERENCES

1. Frederick M. Steingress and Harold J. Frost, Stationary Engineering, American Technical Publishers, Inc., Homewood, IL, 1991, pp. 301-328.

2. Basic Electricity, Field Manual, FM 55-506-1, Department of the Army, Washington, DC, 22 April 1977, p. 32.

3. Electricity, Theory and Fundamentals, Student Workbook 52C10, US Army Engineer School, Fort Belvoir, VA, June 1979, pp. 5-7.

4. W. A. La Pierre and B. M. Jones, "Electrical and Electronics Engineering," Mark's Standard Handbook for Mechanical Engineers, Eighth Edition, Edited by T. Baumeister, et al., McGraw Hill Book Company, NY, 1978, pp. 15-1 to 15-6.

5. John Reason, "Electrical Interconnections," Standard Handbook of Power Plant Engineering, Thomas C. Elliott, editor, McGraw Hill Book Co., NY, 1989, pp. 5.3-5.24.

28. SPECIAL SYSTEM CONSIDERATIONS III: TURBINE GENERATOR

Slide 28-1

```
ENERGY RECOVERY/CONVERSION OPTIONS

Produce and Sell Steam
Produce and Sell Both Steam & Electricity
Produce and Sell Electricity
```

Modern MWC facilities are equipped with a variety of systems for converting heat energy in the waste into a usable and sellable form. A growing portion of new, large MWCs are being equipped with steam turbines and electrical generators. Such systems allow either a portion or all of the thermal energy generated in the boiler to be converted to electrical power.

Three basic system configuration options considered in the initial design of the facility include a MWC unit which (1) sells only steam, (2) sells both steam and electricity, and (3) sells only electricity.

The design selection will obviously depend on local economic considerations (e.g., the sale price of steam and electricity) and the general demand characteristics of a steam customer. As covered in previous learning units, optimal MWC performance is achieved when the combustor is operated at its design load on a nearly continuous basis. Many steam customers will have a varying demand, which implies that either the boiler load is modulated or that process steam be dumped.

Several facilities have been designed to serve steam customers but have elected to account for varying steam demand by adding turbine generator sets. In this manner, the combustor is operated at nearly constant conditions and the amount of electricity generation is set by the difference between steam customer demand and the total energy generation by the MWC boiler.

The third option provides for all of the heat release from the boiler to be converted to electricity and sold to a customer such as the local electric power utility. This system design option generally permits the MWC boiler to be operated at its design load capacity on a continuous basis.

Slide 28-2

```
TURBINE GENERATOR SYSTEM CONFIGURATIONS

Steam Turbine
Electrical Generator
Condenser, Hotwell, & Air Ejector
Condensate Pump & Heater
Deaerator
Feedwater Pumps & Heaters
```

A typical turbine generator set will consist of a variety of major components and system ancillary components. Steam from the boiler first passes through a throttle valve which modulates the flow rate and pressure of steam being delivered into the steam turbine.

Slide 28-3

```
STEAM TURBINE TYPES & FEATURES

Impulse Steam Turbine
Reaction Steam Turbine
Impulse-Reaction Steam Turbine

Multiple Stages
Conversion of Thermal Energy
Production of Mechanical Energy
```

Three types of turbines are commonly used: the impulse, reaction and impulse-reaction turbines. Their designs have many similarities, as described below.

Steam turbines consist of many stages of airfoil blades which convert energy in the steam to rotating shaft power. Steam pressure and temperature decrease from stage to stage in a steam turbine.

As the pressure is decreased, the density drops which causes the steam to expand and occupy more volume. This results in the progressive increases in turbine wheel diameter and blade length as steam moves through each successive stage.
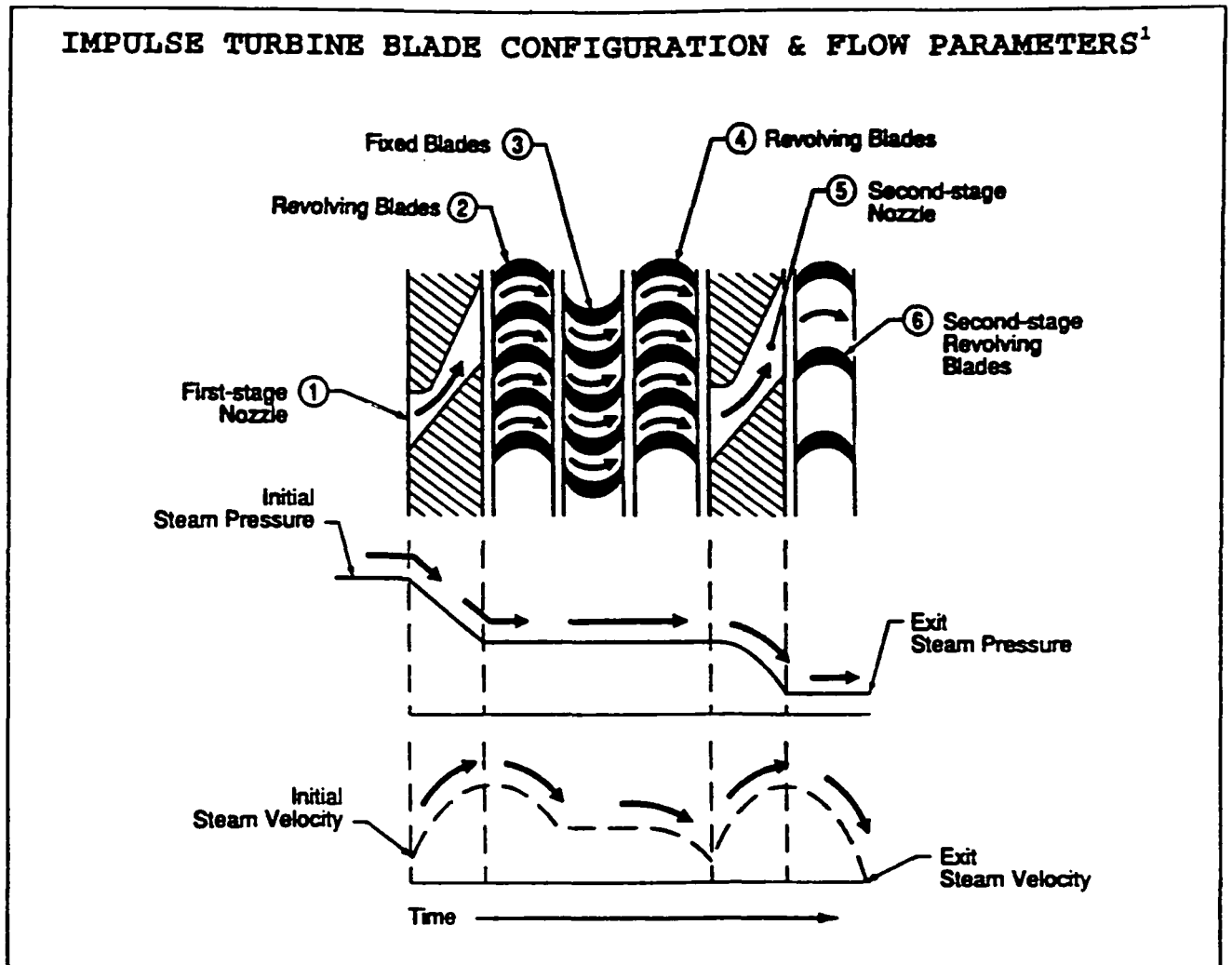
IMPULSE TURBINE BLADE CONFIGURATION & FLOW PARAMETERS[1]

From F. M. Steingress and H. J. Frost, Stationary Engineering, American Technical Publishers, Inc., Homewood, IL, 1991, printed with Permission.

Impulse steam turbines use the impact of high velocity steam to create a force acting on a blade mounted on a wheel. As illustrated in the above slide, impulse turbines have multiple stages consisting of a nozzle, two rows of rotating airfoil blades and one row of stationary blades. The system is designed so that most of the pressure drops occur through the nozzles rather than the blades. Although the pressure within a blade section is nearly constant, the velocity drops-off considerably.

The rotating blades are attached to disk wheels which are mated to the rotor shaft while the fixed blades, or stators, are attached to the turbine casing. Expansion of the steam through the turbine causes the shaft to rotate and converts the high pressure thermal energy of steam into mechanical energy (shaft work). The stationary blades act mainly to change the direction of the steam flow, so the optimum angle of steam flow exists as the steam enters the second set of rotating blades.
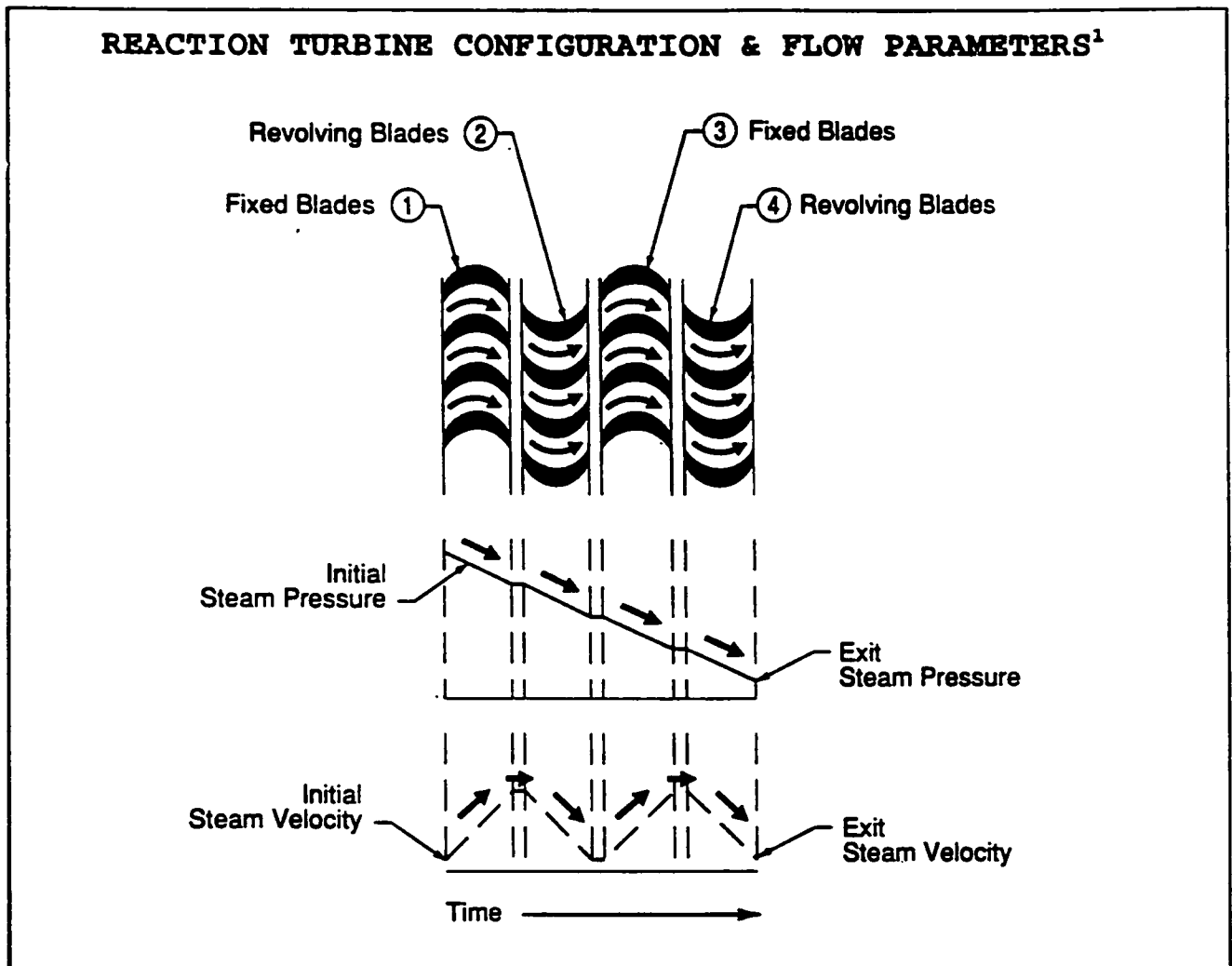
REACTION TURBINE CONFIGURATION & FLOW PARAMETERS[1]

From F. M. Steingress and H. J. Frost, <u>Stationary Engineering</u>, American Technical Publishers, Inc., Homewood, IL, 1991, printed with Permission.

Reaction steam turbines make use of reaction forces produced by a flow of steam through the turbine blades. The difference in the momentum of the flow entering and leaving the rotating blades causes a mechanical force on the blades which is transferred to the shaft. The high velocity steam gives up its kinetic energy (velocity) as it flows through the revolving blades.

The reaction turbine uses fixed blades to act as nozzles. As illustrated above, steam enters the first set of fixed blades and has its velocity increased as its pressure drops. The fixed blades also change the direction of the steam flow so it enters the rotating blades at the optimum angle. The process then repeats itself at succeeding stages.

Impulse-reaction turbines combine impulse and reaction blading. There are several stages of impulse blades in the high pressure end of the steam turbine and reaction blades in the low pressure end of the turbine.

Steam turbines used in large MWC installations will typically have many stages. For example, the turbine generator at the Mid Connecticut RDF plant is rated at 45 MW and has 21 turbine stages. In typical MWC applications, the electrical generator shaft is directly coupled to the turbine shaft, so that the generator rotates at the same speed as the turbine.

The amount of power generated by the turbine is proportional to the flow rate of steam through the turbine and the steam pressure drop across the turbine. By modulating the main throttle valve, the total flow of steam and the steam pressure at the first stage nozzle can be adjusted to provide the required rotor speed at the desired power output level.

Slide 28-6

STEAM GENERATOR EQUIPMENT & FLOW SCHEMATIC[2]
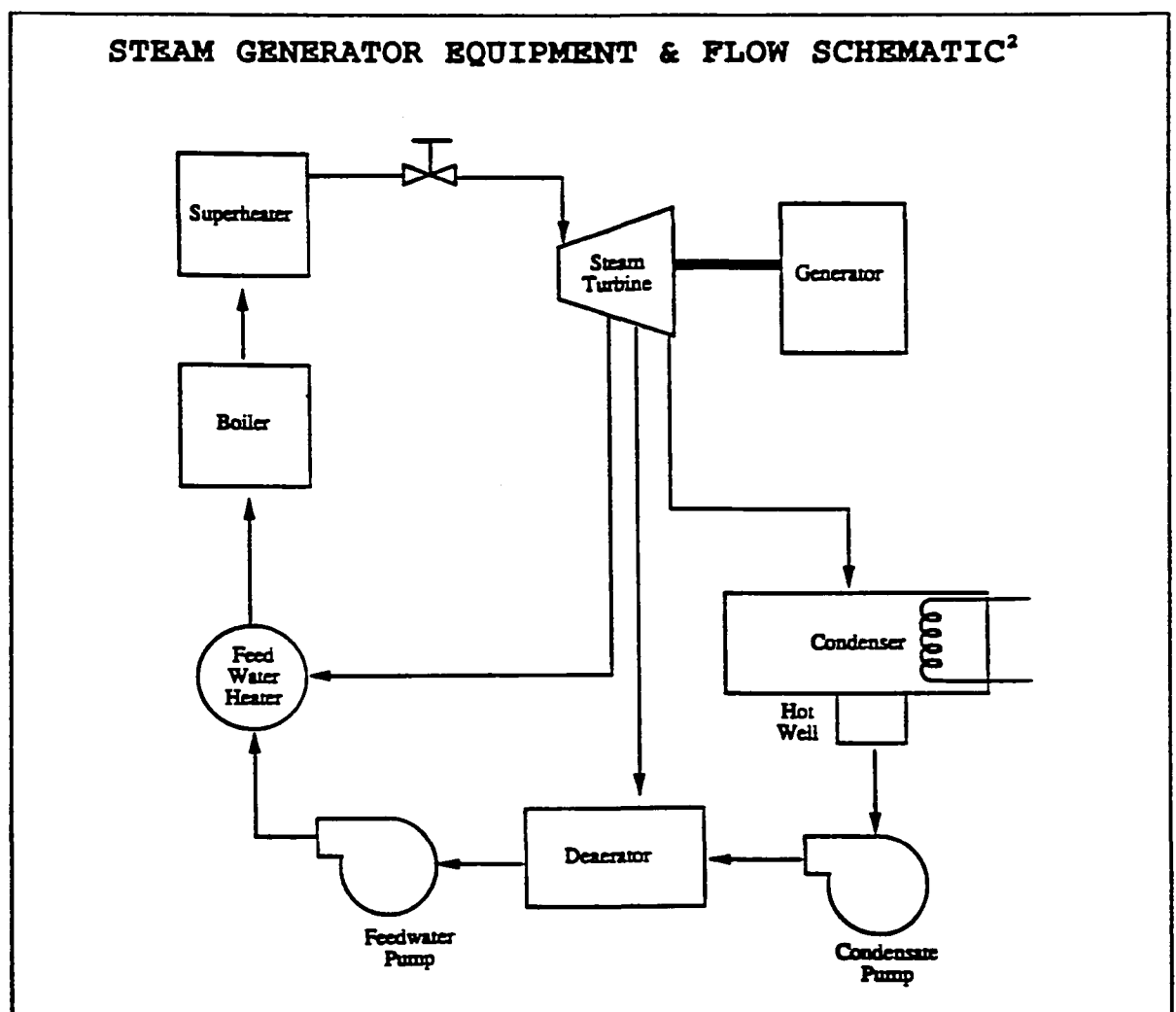
The above slide illustrates the typical arrangement for the steam side of a boiler and turbine generator set and its auxiliary components. As pressure and temperature drop through the turbine, the steam loses its superheat and approaches conditions where it will condense.
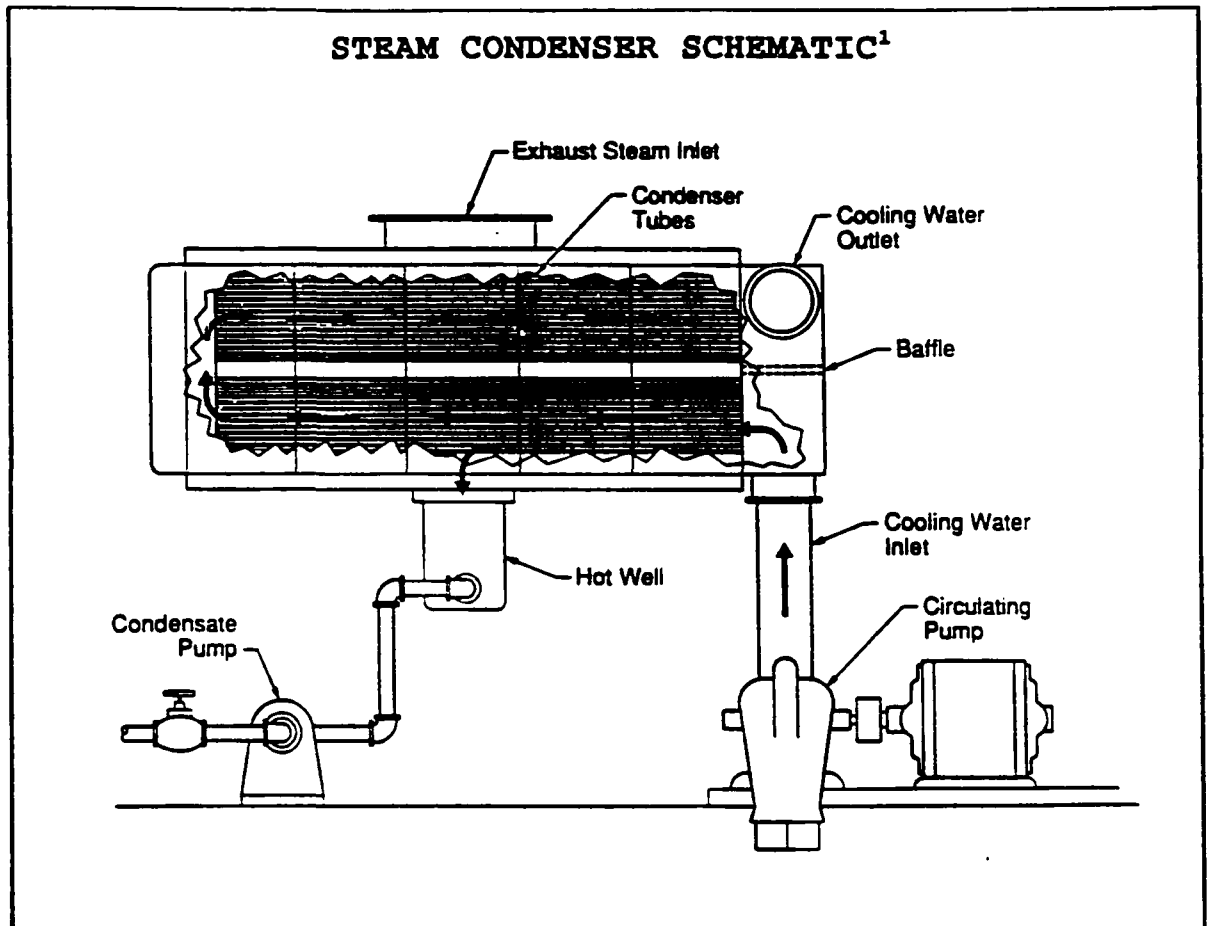
STEAM CONDENSER SCHEMATIC[1]

From F. M. Steingress and H. J. Frost, <u>Stationary Engineering</u>, American Technical Publishers, Inc., Homewood, IL, 1991, printed with Permission.

Outlet flow from the turbine is directed into a condenser, which is basically a series of cooled tubes that cause the steam to condense. Water then drips from the condenser tubes into a lower chamber known as a hotwell. A minimum level of water must be maintained in the hotwell at all times.

The condensate pump extracts the water from the hotwell and directs it to a device known as a deaerator. The purpose of the deaerator is to remove dissolved gases from the water before it is pumped to the boiler. To accomplish that objective, the condensate is heated to its saturation point where dissolved gases will boil off. Released gases are then vented to the atmosphere. The deaerator operates at a pressure ranging from around 5 to 75 psig, depending on the particular design of the plant.

The boiler feedwater pump increases the pressure of deaerated water to the full boiler operating level. Also at this stage, the feedwater is preheated before it enters the boiler economizer. As illustrated in the previous slide, heat for operation of the deaerator and the feedwater heaters is often supplied by extracting steam from various stages of the turbine.

Because the functions of the feedwater pump are so critical to unit operations, a parallel set of pumps is generally installed. This allows switching between the pumps to provide for maintenance, without having to take the boiler off-line.

Slide 28-8
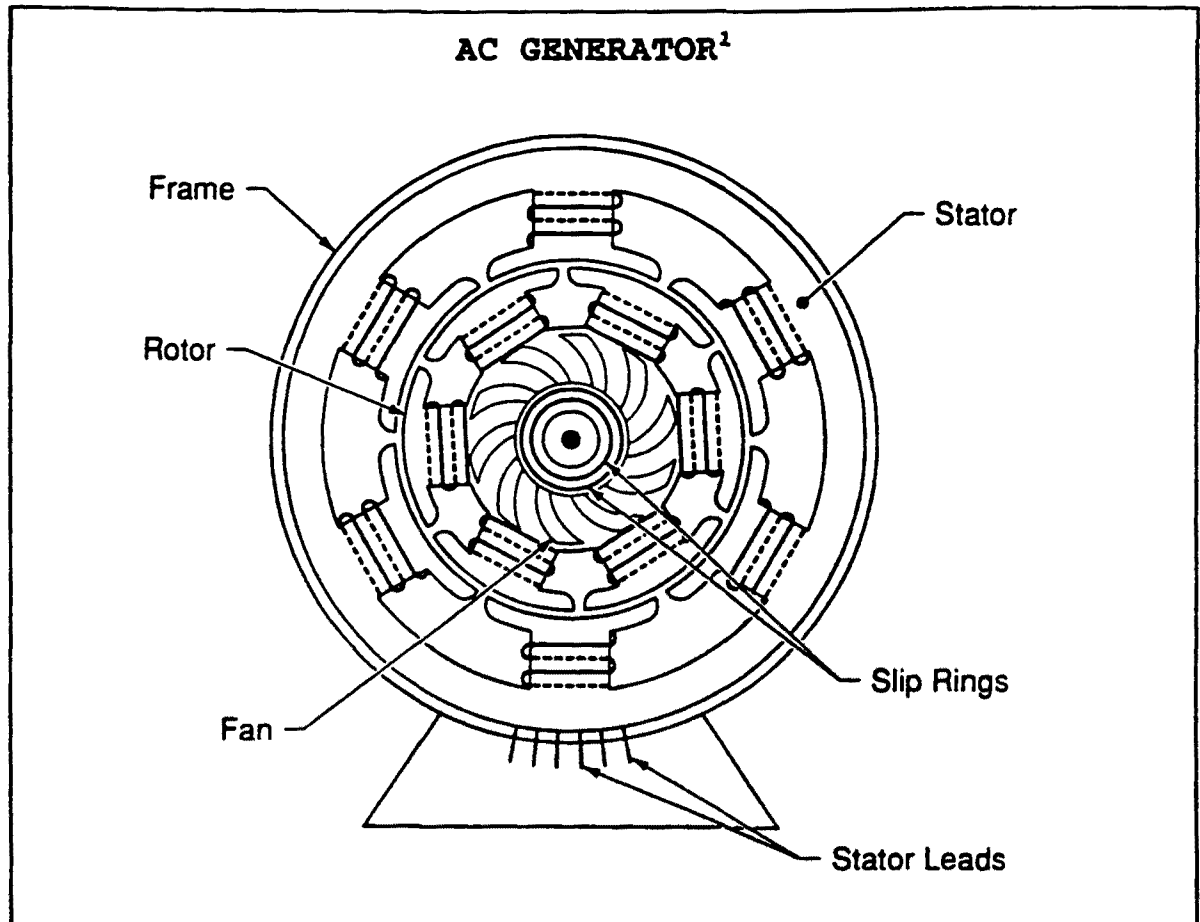
AC GENERATOR[1]

Frame — Stator

Rotor — Slip Rings

Fan — Stator Leads

From F. M. Steingress and H. J. Frost, Stationary Engineering, American Technical Publishers, Inc., Homewood, IL, 1991, printed with Permission.

In addition to the steam cycle described above, other key ancillary components of the turbine/generator are the oil heating and cooling systems and the turning gear.

The shaft in the turbine and generator rotates on bearings which are bathed in oil. The oil is provided at a pressure (by a lift pump) high enough to maintain an oil film which carries the load of the rotor. To avoid serious bearing friction, the oil must continually flow through the system at a proper viscosity. Under no load or cold start conditions, the viscosity considerations require oil heating. Under full load operation, oil coolers are used to maintain viscosity by rejecting heat. Because of the critical nature of the oil flow, turbine generators will be supplied with a redundant set of pumps and will generally have an emergency system operated by an alternate power supply, such as DC powered pumps with a battery pack.

Once the turbine generator set is placed into operation, the shafts should be kept in continual rotation, even when the unit·is down and no power is being generated. The rotor is kept turning to maintain the turbine and generator shaft alignment and to minimize vibrations in the shaft. The turning gear is a motor driver which provides rotation of the main shaft, generally less than 10 rpm. Typically,.a centrifugal clutch mechanism disengages the turning gear whenever steam flow through the turbine causes the rotor to turn at higher speeds.

The purpose of the slip rings, shown in Slide 28-8, is to transmit DC electric energy as excitation current to the rotor. The stator leads are connected to switching devices which transmit the three-phase AC energy from the coils on the stator to the utility grid.

Slide 28-9

```
TURBINE GENERATOR OPERATION

     Cold Start
     Synchronization
     Shut-Down
```

Each turbine generator set will be provided with a detailed set of operating instructions developed by the vendor.

In large installations, there will typically be an area operator at the turbine generator as well as remote control from the main control room. In the main control room, the operator will usually have a major panel devoted to instrumentation and control of the turbine generator set. Redundant measurements and controls may be provided for the area operator.

It is critically important that the control room and area operators remain in close contact especially during system start-up and shut-down.

During start-up, the generator will provide no load to the turbine and the turbine will be relatively cool (or cold). Bringing the system from that state to full operational status is a critical responsibility of the operator.

All system components such as condensate pumps, deaerator, feedwater pumps, feedwater heaters, control valves, recirculation valves, vent valves, and emergency systems must be sequentially brought to operational status or standby status. All liquid supply system components must also be at their proper level and automatic control systems operational.

A key responsibility of the operator is to bring the turbine generator to its operational state at a rate specified by the manufacturer. During the start-up cycle, the turbine metal temperature will rise to the temperature of the steam supplied by the boiler. That process can cause severe thermal stress to build within the turbine and will cause a differential expansion of the casing and internal components. From a cool start, manufacturers generally require that the casing be warmed at a rate of about 100 °F per hour and at all times the temperature difference across any metal wall should not exceed about 150 °F. Procedures associated with preheating of the steam supply lines and assuring proper operation of emergency and auxiliary systems may cause the time required for the start-up process to extend over more than a single operating shift.

In addition to metal temperature concerns, care must be exercised to prevent the turbine rotor from accelerating too rapidly. After coming off the turning gear, the rotor is often limited to an acceleration of about 100 rpm/minute until a mid-range speed is reached. Then a hold period is often required to prewarm the rotor and casing. Typical mid-range rotor speed will be on the order of 1000 rpm, and a hold time on the order of a half hour or more is not unusual. The manufacturer will also specify the acceleration rate for the turbine rotor which will assure safe operation through the rotor's critical speed points. Compliance with the start-up cycle is vitally important.

The generator rotor will begin to turn as the turbine rotor begins to turn. Fine adjustments of the rotor speed and excitation will be required to match the generator electrical voltage and phase characteristics with those of the utility grid. The proper rotational speed will typically be 3600 rpm to provide 60 Hz, three phase power output, although some generators are designed to operate at 1800 and 1200 rpm.

Generation of electricity by the system requires that an array of electrical subsystems be in operation. Provisions will be made for an excitation system and for adjusting the generator side voltage. During start-up, careful adjustment of generator side voltage may be required to prevent possible feedback to the generator end when the generator is synchronized.

Picking up load on the generator must be accomplished in a gradual fashion and coordinated with adjustments on the steam flow side of the turbine generator. The rate at which load can be added will depend upon the turbine starting conditions. For colder starts, the load should be added at a very gradual rate (about 0.5% of rated capacity per minute). For hot starts, load can be added at a much faster rate (about 2 to 3 % of rated capacity per minute is typical).

Unit shut-down must rigorously follow a schedule of events which will basically be a reverse of the start-up procedures. The operator is responsible for assuring that the sequencing of events in the shut-down schedule are appropriately fulfilled.

The preceding material only addresses the broad general features of that operation. It is the responsibility of the operator to become familiar with the detailed instructions provided by the turbine generator manufacturer. These instructions should also be incorporated into a detailed operating procedures manual which is specific to the overall MWC facility configuration and characteristics.

Slide 28-10

GENERATOR SYNCHRONIZATION WITH UTILITY GRID[3]
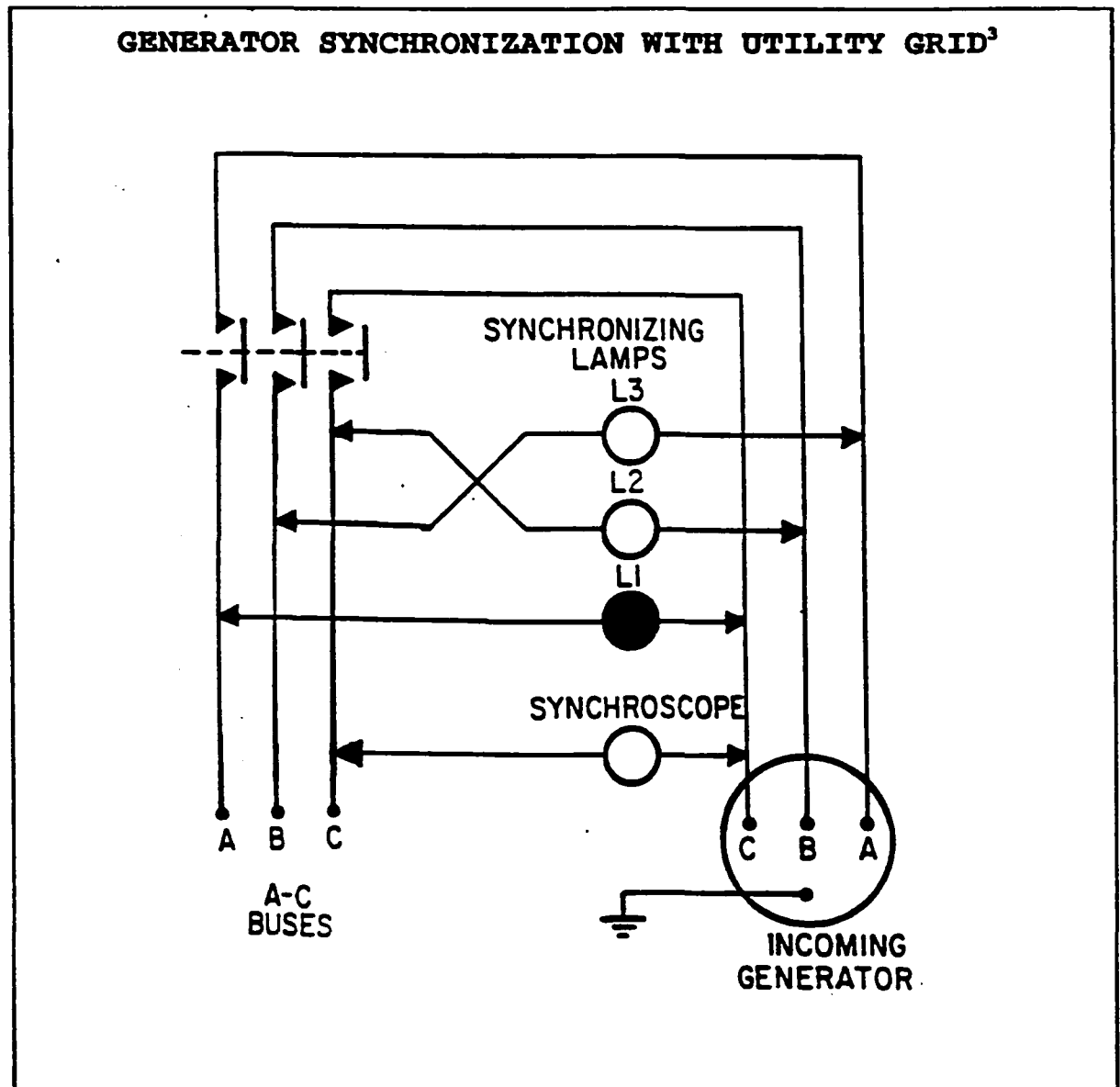
The synchronizing process requires that the three phases of electricity generated exactly match with the three phases of the AC buses of the utility grid before the breaker switch is closed.

The three phases are indicated in the above sketch as "A," "B" and "C." For the wiring diagram shown, the first synchronizing light (L1) will be off and the other two will be on when the three phases of electricity are appropriately oriented.[3]

Slide 28-11

```
┌─────────────────────────────────────────────────┐
│                                                 │
│    TURBINE GENERATOR SYNCHRONIZATION            │
│                                                 │
│    Synchroscope:  Phase Angle Meter             │
│             Clockwise Rotation                  │
│             Counterclockwise Rotation           │
│             Stationary Indicator                │
│             Indicator Pointing Upward           │
│                                                 │
└─────────────────────────────────────────────────┘
```

A synchroscope is a phase angle meter which is provided to indicate any frequency mismatch and the difference in the phase angle between that of one leg of the generated power and the corresponding leg of the grid.[4] The operator uses information from the synchroscope to adjust turbine speed and excitation energy, thereby synchronizing the generator to the grid before closing the switch gear.

If the synchroscope indicator rotates counterclockwise, it is an indication that the frequency of the generated energy ("incoming" to the grid) is greater than that of the grid.[4] A clockwise rotation would indicate a lower generator frequency than that of the grid.

A stationary synchroscope pointer indicates that the frequencies are matched. The angular displacement of the pointer is an indication of the phase difference between the incoming and grid energy. The indicator is stationary and points directly upward when the phase of the incoming energy is matched to that of the grid.[4]

Slide 28-12

```
┌─────────────────────────────────────────────────┐
│                                                 │
│    TURBINE GENERATOR ABNORMAL CONDITIONS        │
│                                                 │
│            Water Induction                      │
│            Excessive Vibration                  │
│            High Bearing Temperatures            │
│            High Back-Pressure                   │
│            Speed Control                        │
│                                                 │
└─────────────────────────────────────────────────┘
```

A number of potential abnormal turbine generator operating conditions are listed above.

Water induction can be caused by the flow of relatively cold vapor or liquid water from the feedwater heater through the steam extraction line and into the turbine casing.[5] Water induction can cause severe thermal stress problems which can cause distortion of the casing and destruction of turbine blades. It can be controlled by installing automatic block valves and proper feedwater heater maintenance.

Excessive vibration of the turbine-generator may be an indication of potential problems, which can cause serious damage to the unit. Many modern turbine-generators are instrumented to "trip" if pre-set vibration limits are reached.

Likewise, high bearing temperatures can be caused by an inadequate cooling water flow rate, excessive cooling water temperature, or by the lack of lubrication. Most modern turbine-generator sets have bearing temperature controllers which will "trip" the unit if excessive temperatures occur. If this happens, the turbine manufacturer should be contacted for assistance.

It is possible for the generator to act as a synchronous motor and drive the turbine. This phenomena, which is called "motoring," may occur during low load operations, such as during the turbine generator start-up and shutdown.[5] The turbine blades can become overheated and damaged due to the lack of steam flow, which normally controls the blade temperatures. Modern systems generally incorporate reverse power relays to automatically prevent this occurrence.

High steam turbine back-pressure or low vacuum in the condenser can be caused by inadequacies in the cooling water system. High back-pressure can result in overheating of the low pressure blading if the problem is not corrected. Temperature sensors or vacuum gages can be set to trip the turbine automatically.

Problems with speed control can be attributed to the turbine governor, voltage regulator or mechanical problems in the control system. Most units now incorporate mechanical or electrical over-speed limit controls.

REFERENCES

1. Frederick M. Steingress and Harold J. Frost, Stationary Engineering, American Technical Publishers, Inc., Homewood, IL, 1991, pp. 227-275.

2. Kenneth Wark, Jr., Thermodynamics, Fifth Edition, McGraw Hill Book Company, New York, 1988, p. 739.

3. Basic Electricity, Field Manual, FM 55-506-1, Department of The Army, Washington, DC, April 1977, pp. 299-304.

4. Joe Kaiser, Electrical Power, Motors, Controls, Generators, Transformers, Goodheart-Willcox Company, Inc., South Holland, Illinois, 1991, pp. 166-186.

5. George Woodward, "Plant Operations," MWC Operator Training Overview Course Manual, Edited by John Eppich, ASME Professional Development Program, West Palm Beach, FL, February 24-26, 1992, Lesson V.K, pp. 1-17.

29. RISK MANAGEMENT I: PREVENTIVE MAINTENANCE

Slide 29-1

```
┌─────────────────────────────────────────────────┐
│         RISK MANAGEMENT PRINCIPLES               │
│                                                   │
│     1.  Achieve a Fair Return                     │
│     2.  Minimize Potential for Losses             │
└─────────────────────────────────────────────────┘
```

Risk management is a relatively new management term which focuses on the financial consequences of various operational activities.[1] It includes balancing the financial return from unit operations with the total operating expenses. In general, management plans are designed to achieve an optimum production which provides a fair return to the public, owners, and/or investors and also minimizes the potential for financial losses.

This learning unit considers the general aspects of preventive maintenance as a part of a risk management program. The safety aspects of risk management will be addressed in Learning Unit Number 30.

Slide 29-2

```
┌─────────────────────────────────────────────────┐
│        ASPECTS OF RISK MANAGEMENT                 │
│                                                   │
│     1.  Insurance Against                         │
│             Production & Casualty Losses          │
│     2.  Evaluation of Current Conditions          │
│     3.  Evaluation of Probability                 │
│     4.  Consideration of Economics                │
│     5.  Consideration of Intangibles              │
└─────────────────────────────────────────────────┘
```

Risk management can be thought of as an effective insurance program. In some industries, insurance policies are available to provide protection against revenue losses associated with unit outages, as well as casualty and liability losses. In general, losses will occur if equipment is not properly operated and maintained.

The achievement of balanced risk management is not easy, as it requires an evaluation of the probability of events occurring and a consideration of the value or cost of their consequences.[1] Judgments, of course, are aided by taking into account an analysis of the conditions on-site, the operating experiences at other similar facilities, and the general experiences of the industry.

A broader view of risk management includes the considerations of the

A broader view of risk management includes consideration of the intangible aspects of good public and personnel relations, as well as the various economic aspects of production and loss. Since operators are generally considered to be an important part of management, they have responsibilities to be open to staff concerns about values and costs, as well as suggestions for system improvement.

Slide 29-3

```
            POTENTIAL ECONOMIC LOSSES

     1.    Cost of Preventive Maintenance
     2.    Personal Injury
     3.    Equipment Repair/Replacement
     4.    Lost Revenue - Tipping Fees
     5.    Lost Revenue - Energy Sales
     6.    Extra Landfill Costs
     7.    Extra Transportation Costs
     8.    Fines - Regulatory Violations
     9.    Contractual Noncompliance Losses
```

General economic considerations include balancing applicable costs with the revenue associated with unit operations. Operating costs can be determined from financial records, as can the capital costs associated with equipment.

The economic aspects of risk management include: the costs of the preventive maintenance program; consideration of losses associated with injury and repair; lost revenue associated with equipment outages; and fines for regulatory violations.

Slide 29-4

```
            OPERATOR RESPONSIBILITIES

     1.    Safety
     2.    Production (System Operations)
     3.    Preventive Maintenance
     4.    Corrective Maintenance
     5.    Record Keeping & Communications
```

Operators participate in risk management through their decision-making on issues of safety, operation, corrective maintenance and preventive maintenance. Operators have the responsibility for assuring that the equipment is both properly operated and maintained.

A combustion unit must be properly operated and maintained so that it can perform reliably, efficiently and safely over its expected life. Consequently, there are considerable economic risks associated with an improper maintenance program.

Preventive maintenance (PM) consists of planned maintenance actions performed to prevent equipment breakdown. Corrective maintenance consists of the repairing of equipment that has failed or malfunctioned.[2]

Operators also have responsibilities for record keeping and communications. Operators help address these issues in the development of policies and standard operating procedures. For instance, many modern facilities now utilize computerized maintenance systems which aid supervisory personnel in their tasks of overseeing and planning the maintenance effort, evaluating its effectiveness, and controlling its costs.[2]

Slide 29-5

```
GOALS OF PREVENTIVE MAINTENANCE

1.    Minimize Total Operating Costs
2.    Enhance Equipment Life
3.    Assure Equipment Reliability
4.    Restore Unit Performance
5.    Minimize Down-Time
```

A preventive management concern is to minimize the total costs while preserving the plant's capital investment. Excessive maintenance can represent a significant cost. Priorities must be set in an attempt to balance the economic consequences associated with either acting now or deferring maintenance.

"A stitch in time saves nine" is still a valid expression. As maintenance is deferred, operational problems will generally worsen and unit down-time will be increased. The financial consequences include both the direct losses associated with making the repairs, and lost production and potential costs associated with safety hazards.

Preventive maintenance is performed to assure that the unit can operate safely, efficiently, and reliably[3]. The general goals are particularly important in MWC units because of the increased complexity associated with adequately controlling the combustion of a fuel with such variable properties.

The old maintenance expression, "If it ain't broke, don't fix it," has generally evolved into "Fix it just before it breaks.[2]" To some extent, the performance of all equipment tends to deteriorate with operating time. Therefore, a preventive maintenance program is designed to assure that productive equipment life is preserved. Obviously, good operating practices must include many routine activities, such as maintaining proper boiler water conditions to avoid tube failures and boiler problems and maintaining the lubricating conditions for rotational equipment like compressors, fans, and turbines.

Preventive maintenance is also designed to restore performance efficiencies. Routine operations, such as soot blowing, are important operations which restore system efficiency.

Predictive maintenance is the part of preventive maintenance which tries to identify potential problems. Routine inspection of equipment and instrument readings, as well as a review of the performance and maintenance records, can lead to the identification of equipment problems. Predictive maintenance also includes the use of special instruments for vibrational analysis, lube oil sample analysis, ultrasonic testing, infrared imaging and meggering (e.g., measuring electrical resistance of insulation) of electric motors and wiring.[2]

Whether specific maintenance can be performed while the unit is in service or during an outage will be determined by the severity of the conditions and the design of the equipment. The scheduling of major (annual) outages requires planning, setting priorities, and arranging for special inspectors and appropriate maintenance personnel, supplies, replacement parts and repair equipment.

Slide 29-6

```
FEATURES OF A MAINTENANCE PROGRAM

1.   Review Vendor Recommendations
2.   Identification of Problems
3.   Evaluation of Options
4.   Communication & Planning
5.   Implementation
```

A maintenance program generally begins with the review of the equipment design features and an implementation of the manufacturers' recommended maintenance procedures. Special attention should be given to the specified lubrication requirements and limits operating conditions (temperatures, pressures, loads, etc.).

An important aspect of unit operations is to identify problems and solve them before they become unmanageable. Problem evaluation begins with an analysis of the current status and an attempt to identify problems and evaluate the causes.

Repairing the symptom of a problem may be easier than solving the real problem. For instance, a bad bearing can be replaced as a short-term solution. However, determining and eliminating the cause of the failure, such as correcting an imbalanced rotor or preventing a corrosion condition, can lead to a long-term solution to the problem.

Communication with other individuals is also an important aspect of operators' duties. Discussions and group meetings with auxiliary operators, maintenance staff, vendor representatives, engineers and/or designers may be required for planning a proper solution to a special maintenance problem.

Cooperative discussions may be in order before deciding whether to take the equipment off-line for repair or to delay the maintenance until the next scheduled outage. Knowledge of both the equipment design features and maintenance records will be important in the decision. Nevertheless, operators are called upon to make timely judgments about taking a unit out of service because of various equipment upsets and safety considerations.

The implementation of maintenance must be scheduled with the operator. A proper lock-out/tag-out program should be used for equipment that poses an electrocution or mechanical injury hazard. Lock-out often refers to the use of padlocks to lock circuit breakers in the "off" position. It also refers to the use of mechanical means to secure equipment (e.g., prevent rotation) for personnel safety. Tags are used to identify who is in charge of the maintenance activity.

Slide 29-7

```
┌─────────────────────────────────────────────┐
│         IN-SERVICE MAINTENANCE               │
│                                              │
│   1.  Follow Recommended Procedures          │
│   2.  Know Special Design Features           │
│   3.  Know Operational Relationships         │
└─────────────────────────────────────────────┘
```

In-service preventive maintenance includes the routine operations which are designed to maintain the equipment according to recommended procedures.[4] The equipment's special design and operational features will have to be known, including its relationship to other elements of the unit and the possibility of switching to alternate equipment.

Examples of in-service maintenance may include repairing cranes and leaking valve seals and replacing thermocouples, CEMS instruments, and control sensors.

Slide 29-8

```
┌─────────────────────────────────────────────┐
│        OUTAGE MAINTENANCE          .         │
│                                              │
│   1.  Make & Update an Outage Plan           │
│   2.  Arrange for Materials/Services         │
│   3.  Make Detailed Inspections              │
│   4.  Revise Plans as Necessary              │
│   5.  Follow Proper Procedures               │
│   6.  Inspect Upon Conclusion                │
└─────────────────────────────────────────────┘
```

The annual boiler outage is a standard inspection requirement associated with operating a pressurized boiler. The inspection and repair must be performed in accordance with applicable requirements. In general, the ASME Boiler Code relates to pressure vessel requirements and the National Boiler Inspection Code (NBIC) covers problems of inspections and repairs to boilers and auxiliary equipment that are not otherwise covered by the ASME Code[3]. In particular, the NBIC Code relates to authorized inspectors and to the proper welding procedures and welder qualifications.

REFERENCES

1.   James L. Riggs and Thomas M. West, Essentials of Engineering Economics, Second Edition, McGraw Hill Book Company, New York, 1986, pp. 438-464.

2.   Mike Shatynski, "Plant Maintenance," MWC Operator Training Overview Course Manual, Edited by John Eppich, ASME Professional Development Program, West Palm Beach, FL, February 24-26, 1992, Lesson IV.L, pp. 1-15.

3.   Steam, Its Generation and Use, 39th Edition, Babcock and Wilcox, New York, 1978, pp. 36-1 to 36-20.

4.   Joseph G. Singer, Combustion, Fossil Power Systems, 3rd Edition, Combustion Engineering, Inc., Windsor, CT, 1981, pp. 22-1 to 22-23.

30. RISK MANAGEMENT II: SAFETY

Slide 30-1

```
GENERAL HEALTH AND SAFETY

1.  Recognition of Hazards
2.  Consequences of Exposures
3.  Standard Safety Procedures
4.  Personal Protection Equipment
```

As mentioned in the previous learning unit, safety of people and equipment are prime considerations[1] in risk management. Management has the responsibility for training employees about the health and safety aspects of their jobs. Management also has the responsibility for enforcing safe practices.

All staff members should be able to recognize potential hazards and know the consequences of such exposures. They should also know the recommended safety procedures and be able to use safety equipment.

Operators should be aware of the significant safety risks associated with operating staff who perform their duties while having certain symptoms of illness.

Slide 30-2

```
MAJOR HAZARDS OF OPERATIONAL SYSTEMS

1.  Water Side Explosions
        Due to Loss of Water
2.  Gas Side Explosions
        Due to Explosive Mixtures
```

The MWC combustion system operates at high temperatures so that losses of water to the boiler and/or water-cooled heat exchangers can cause steam pressures to build up, leading to serious explosions.[1] The ASME boiler code requires designs to include pressure relief valves on the boiler system to prevent such explosions.[2] Specific code provisions include the number, type, installation and testing features of such safety valves.[3] Water-cooled heat exchangers may also have such protection.

Explosions can also result from the buildup of combustible gases, such as when ignition is lost by an auxiliary burner.[1] Modern combustion control systems are designed to prevent such hazards by tripping the fuel flow until an adequate purge condition has been obtained.

```
┌─────────────────────────────────────────────────────┐
│        OTHER MWC SYSTEM SAFETY HAZARDS                │
│                                                       │
│     1.  Exposure to MSW                               │
│     2.  Pit Fires & Explosions                        │
│     3.  Combustion & Boiler Systems                   │
│     4.  Removal of Blockages                          │
│     5.  Observation Hatches/Hopper Doors              │
│     6.  Operations in Confined Spaces                 │
└─────────────────────────────────────────────────────┘
```

All operating personnel must be aware that MWC units have potential safety hazards associated with exposure to MSW. When MSW is received, it contains components which can cause falls, cuts and diseases. Therefore, personnel should avoid personal contact with MSW.

Serious burns can occur if individuals contact steam pipes, valves and other hot metal objects. The improper opening of high pressure steam vents and/or the rupture of steam pipes can cause severe scalding.

MSW often contains items which could cause pit fires and/or explosions in the combustion unit. Although flammable liquids and explosives should never be fed into the unit[4], these problems can be limited by system design features and care during charging.

Generally, observation hatches into the furnace should be opened only after taking precautions against exposure to furnace pressure pulsations. Materials can blow through an observation hatch as a result of sootblowing, tube failure or aerosol can explosions on the fuel bed.[5] Therefore, individuals should not stand directly in front of open furnace ports or doors. Design provisions for safety include delivering aspirating air to the observation hatch and providing a protective transparent cover.[6] Open-ended pipes should not be used for removing slag from walls, as the hollow pipes can become very hot and can direct hot gases onto the handler.[5]

Operators should also be aware of the potential for eye damage associated with intense thermal radiation. Tinted goggles or other eye protection should be used.[5]

Hot, solid materials can flow out of open hopper doors and cause serious burns and injuries. Hot ash can remain hot for a long time due to its insulating properties.[6] Therefore, one should never step on fly ash.

In addition, it is potentially hazardous to enter confined spaces such as the equipment cavities of the furnace, steam drum, and baghouse or ESP. Hazards here

arise from poor ventilation, space being cramped, limited lighting and exposure to accumulated pollutants and/or dust.

Confined spaces should be entered only after they have been properly cooled and ventilated. Appropriate doors and valves should be locked or tagged. Explosion proof lights and properly grounded electrical extension cords should be used.[5]

Slide 30-4

```
+----------------------------------------+
|                                        |
|      Standard Safety Considerations    |
|                                        |
|      Electrical Shock                  |
|      Exposure to Corrosives            |
|      Noise & Vibration                 |
|      Exposure to Rotary Equipment      |
|      Awkward Access                    |
|      Movement of Heavy Objects         |
|      Welding and Metal Forming         |
|      Fire Hazards                      |
|                                        |
+----------------------------------------+
```

Standard industrial safety considerations include those associated with electrical shocks, noise, vibrating equipment, exposure to hot metal surfaces, exposure to rotating equipment, awkward access to equipment, movement of heavy objects, welding, exposure to corrosives and fire hazards.

For example, the electrical and steam service to rotary equipment should be "locked out" and "tagged out" before servicing. In addition, it may be appropriate to have the shaft blocked to prevent rotation, which could otherwise cause injuries such as mashed, cut, or severed fingers.

Operators should make use of material safety data sheets which describe the standard safety information about industrial chemicals. Important data sheets for MWC operators would include those for chemicals used in water treatment and scrubber systems, solvents, refractories, and paints. These data sheets provide information about the need for special handling and personal protective equipment (e.g., respirators). They also include health information, such as the toxic or carcinogenic features of exposures on humans and animals.

Fire safety is another major concern, particularly as pit fires can be very serious. Provisions are generally made in the charging device to limit the penetration of flames from the combustion chamber into the charge hopper. These can include the use of flame scanners which actuate water sprays[6] and water-cooled doors to reduce temperatures to below that required for ignition.

Slide 30-5

```
┌─────────────────────────────────────────────────┐
│      PERSONAL PROTECTION EQUIPMENT               │
│                                                  │
│      1.   Ear Protection                         │
│      2.   Heavy Gloves                           │
│      3.   Hard Hat                               │
│      4.   Respirator                             │
│      5.   Goggles                                │
│      6. · Safety Shoes                           │
│      7.   Proper Clothing                        │
└─────────────────────────────────────────────────┘
```

Standard industrial safety procedures relate to the use of personal protective equipment, such as that listed above.[5,6]

In addition to the above listed personal safety protection equipment, persons should wear proper clothing so that there are no loose fitting parts which could become tangled in rotating equipment. Natural fiber work clothes should also be worn because some synthetic fibers can melt when exposed to hot equipment.[6]

Also, care should be exercised when walking to avoid bumps, slips and falls. Improper ladders and unsecured scaffolds should not be used. Care should be used to assure that objects are placed securely to avoid damage due to falling.[6]

Special care should be taken to avoid chemical burns resulting from skin contact with strong alkalis or acids.

Slide 30-6

```
┌─────────────────────────────────────────────────┐
│      SYMPTOMS OF ILLNESS                         │
│                                                  │
│      1.   Headaches                              │
│      2.   Lightheadedness                        │
│      3.   Dizziness                              │
│      4.   Nausea                                 │
│      5.   Loss of Coordination                   │
│      6.   Difficulty in Breathing                │
│      7.   Chest Pains                            │
│      8.   Exhaustion                             │
└─────────────────────────────────────────────────┘
```

The above symptoms of illness may result from heat stress, inhalation problems and/or a variety of non-occupational related conditions.[6] An impaired worker is a threat to the overall safety of the unit as well as to fellow personnel.

REFERENCES

1. <u>Steam, Its Generation and Use</u>, 39th Edition, Babcock and Wilcox, New York, 1978, pp. 34-8.

2. Frederick M. Steingress and Harold J. Frost, <u>Stationary Engineering</u>, American Technical Publishers, Inc., Homewood, IL, 1991, pp. 71-82.

3. E. B. Woodruff, H. B. Lammers and Thomas F. Lammers, <u>Steam Plant Operations</u>, Fifth Edition, McGraw-Hill Book Company, New York, 1984, pp. 223-230.

4. Louis Theodore, <u>Air Pollution Control and Waste Incineration for Hospitals and Other Medical Facilities</u>, Van Nostrand Reinhold, New York, 1990, pp. 364-367.

5. Joseph G. Singer, <u>Combustion, Fossil Power Systems</u>, 4th Edition, Combustion Engineering, Inc., Windsor, CT, 1991, pp. 21-1 to 21-34.

6. John Richards, <u>Municipal Waste Incinerator Air Pollution Control Inspector Course</u>, Prepared by Entropy Environmentalists, Submitted to U. S. Environmental Protection Agency, June 1991.

APPENDIX: GLOSSARY, ACRONYMS, AND SYMBOLS[1]

Absorption
: The passage of one substance into or through another, e.g., an operation in which soluble gases are dissolved into a liquid.

Acid Deposition
: Acid Rain: A complex chemical and atmospheric phenomena that occurs when emissions of sulfur and nitrogen compounds and other substances are transformed by chemical processes in the atmosphere and then deposited on earth in wet or dry forms. The dry forms are acidic gases or particulates.

AC
: Alternating Current (Electricity)

Activated Charcoal
: A highly adsorbent form of carbon used to remove odors and toxic substances from liquid or gaseous emissions.

Adsorption
: Adhesion of molecules of gas, liquid, or dissolved solids to a surface, such as occurs with the use of activated carbon.

Agglomeration
: The process by which particulates grow larger by collisions or contact with other particulates.

Air Pollutant
: Any substance in air which could, if in high enough concentration, harm humans, other animals, vegetation, or material. Generally, they fall into two different groups (1) those emitted directly by identifiable sources and (2) those produced in the atmosphere by interaction between two or more primary pollutants or normal atmospheric constituents.

APCD
: Air Pollution Control Device: Equipment incorporated into the exhaust gas stream of an incinerator to reduce emissions to the atomosphere of solid or gaseous pollutants. Such add-on devices include scrubbers (wet & dry) and fabric filters.

---

[1] The source for many of the items is the: "Glossary of Environmental Terms and Acronym List," Publication Number 19K-1002, USEPA, Office of Communications and Public Affairs, Washington, DC 20460, December 1989.

APTI	Air Pollution Training Institute, USEPA
Air Quality Criteria	The levels of pollution and lengths of exposure above which adverse health and welfare effects may occur.
Air Quality Standards	The maximum levels of pollutants prescribed by regulations that may not be exceeded during a specified time (National Ambient Air Quality Standards).
ASME	American Society of Mechanical Engineers
ASTM	American Society of Testing and Materials
Atmosphere, atm	A standard unit of pressure representing the pressure exerted by a 29.92-inch column of mercury at sea level.
Attainment Area	An area considered to have air quality as good as or better than the national ambient air quality standards. The area may satisfy attainment for one or more pollutants and a nonattainment area for others.
AWMA	Air and Waste Management Association
BACT	Best Available Control Technology: An emission limitation based on the maximum degree of emission reduction which (considering energy, environmental, and economic impacts, and other costs) is achievable through application of production processes and available methods, systems and techniques.
Baghouse Filter	Large fabric filter bag, usually made of glass fibers, used to control the emission of particulates.
BDT	Best Demonstrated Technology
Biologicals	Preparations made from organisms or from the products of their metabolism, intended for use in diagnosing, immunizing or treating humans or animals, or in research pertaining thereto.
Bottle Bill	Legislation which requires a returnable deposit on beer and soft drink containers and provides for retail

stores or other redemption centers.

Bottom Ash	Incombustible material remaining after combustion has been completed.
Btu	British Thermal Unit
Burn Cycle	An operating period (e.g., 24 hours) which includes at least one of each of the following MWI system operations, unit preheat, initiation of waste charging, waste destruction, burn-down (if applicable), unit shut-down, and ash removal.
Burn Rate	Total quantity of waste burned, usually expresses in lb/hr.
By-product	Material, other than the principal product, that is generated as a consequence of an industrial process.
C	Celsius (Degrees)
CAA	Clean Air Act
CAAA	Clean Air Act Amendments
Cadmium (Cd)	A heavy metal element that accumulates in the environment.
Cap	A layer of clay or other highly impermeable material installed over the top of a closed landfill to prevent entry of rainwater and minimize production of leachate.
Carbon Dioxide, CO_2	A colorless, odorless, non-poisonous gas which is produced by carbon combustion.
Carbon Monoxide, CO	A colorless, odorless, poisonous gas which is produced by incomplete combustion of carbon.
Carcinogen	Any substance that can cause or contribute to the production of cancer.
Catalyst	A device that enhances the rate of a specified chemical reaction.

CDD	Chlorinated Dibenzo-p-dioxin (All of the isomers of the tetra-, penta-, hexachloro, dibenzo-p-dioxins)
CDF	Chlorinated Dibenzofuran (All of the isomers of the tetra-, penta-, hexachloro, dibenzo-p-dioxins)
CEM	Continuous Emission Monitor
CEMS	Continuous Emission Monitoring System
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
CFM	Cubic Feet per Minute (ft^3/min)
CFR	Code of Federal Regulations
Charge Rate	Quantity of waste material loaded into a combustion unit, usually expressed in lb/hr.
Chlorinated Hydrocarbon	A group of chemicals composed of chlorine, hydrogen, and carbon elements. They include the persistent, broad-spectrum insecticides that linger in the environment and accumulate in the food chain.
CO	Carbon Monoxide
CO_2	Carbon Dioxide
Combustion	Rapid oxidation or burning which is accompanied by the release of energy in the form of heat and light.
Combustion Product	Substances produced during the burning or oxidation of a material.
Compost	A mixture of garbage and degradable trash with soil in which certain bacteria in the soil break down the garbage and trash into an organic soil conditioner or fertilizer.
Controlled Air	Combustion units which control the air flow rate to attain the desired rate of combustion.
Contaminant	Any physical, chemical, biological, or radiological substance or matter that has an adverse affect on air,

Appendix-4

water, or soil.

Coolant	A liquid or gas used to remove the heat generated by power production, industrial, and/or mechanical processes.
Cooling Tower	A structure designed to remove heat from water.
Corrosion	The dissolving and wearing away of metal caused by chemical reactions, such as between water and the pipes in which water is contained, chemicals touching metal surfaces, or contact between two metals.
Criteria Pollutants	Primary emitted pollutants identified by the USEPA under the Clean Air Act for which ambient air quality standards have been set to protect human health and welfare.
DAS	Data Acquisition System
DB	Dry Bulb (Dry Bulb Temperature)
DC	Direct Current (Electricity)
Decibel (dB)	A unit of sound measurement. The loudness of sound doubles for every increase of ten decibels.
Desulfurization	Removal of sulfur from fossil fuels to reduce pollution.
DI	Dry Injection
Dioxin	Any of a family of potentially toxic compounds known chemically as dibenzo-p-dioxins.
DS	Dry Scrubber
dscf	Dry Standard Cubic Feet
dscm	Dry Standard Cubic Meter
E	Electrical Potential, Voltage
EER	Energy and Environmental Research Corporation
Effluent	Wastewater--treated or untreated--that flows out of a

	treatment plant, sewer, or industrial system.
EDF	Environmental Defense Fund
Emission	Pollution discharged into the atmosphere from smokestacks and other vents.
Emission Standard	The maximum amount of air polluting discharge legally allowed from a single source.
Endothermic	Chemical reactions that absorb energy from the surroundings.
EP	Extraction Procedure
EPA	U. S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ESP	Electrostatic Precipitator: An air pollution control device that removes particulates from a gas stream by imparting a electrical charge to the particulates which causes them to be deposited and adhere to metal plates in the unit.
Excess-Air	Combustion units operationg with fuel/air mixtures having greater than stoichiometric quantities of air.
Excess Air	The additional air supplied above the stoichiometric quantities required for complete combustions, often expressed as a percentage of the stoichiometric air (e.g., Air supplied at 50% excess air corresponds to 1.5 times the quantity of stoichiometric air).
Exothermic	Chemical reactions where chemical energy is transferred as heat to the surroundings.
F	Fahrenheit (Degrees)
Fabric Filter	A cloth device that catches dust particles.
FBC	Fluidized Bed Combustion
FCE	Final Control Element

FC	Flow Controller
FD	Forced Draft
FE	Fugitive Emissions
FF	Fabric Filter
FGD	Flue Gas Desulfurization: A technology which uses a sorbent, usually lime or limestone, to remove sulfur dioxide from the gases produced by burning fuels.
FID	Flame Ionization Detector
Fixed Carbon	The combustible, non-volatile portion of the fuel's composition.
Flue Gas	A mixture of products of combustion and air constituting the exhaust of a combustion process.
Fly Ash	Non-combustible residual particles removed from the combustion chamber by flue gas.
FR	Federal Register
FT	Flow Transducer
ft^3	Cubic Feet
Fuel Bed	The layer of waste material (fuel) undergoing the combustion process on a hearth or grate.
Fugitive Emissions	Emissions not caught by a capture system.
FY	Fiscal Year
g	Gram
GC	Gas Chromatograph
GC/MS	Gas Chromatograph/Mass Spectrograph
GCP	Good Combustion Practice
Generator	(1) A facility that emits pollutants into the air or

releases hazardous waste into water or soil.
(2) A facility that produces electricity.

GLC   Gas Liquid Chromatograph

Greenhouse Effect   The warming of the Earth's atmosphere caused by a build-up of carbon dioxide and other trace gases. This build-up allows light from the sun's rays to heat the Earth without a counterbalancing loss of heat.

GW   Ground Water

GWM   Ground Water Monitoring

H_2O Water

Halogen   Any of a group of five chemically-related nonmetallic elements that includes bromine, fluorine, chlorine, iodine, and astatine.

Hammermill   A high-speed machine that uses hammers and cutters to crush, grind, chip or shred solid wastes.

HAP   Hazardous Air Pollutant

HAZMAT   Hazardous Material

HC   Hydrocarbon

HCl   Hydrogen Chloride

HDPE   High Density Polyethylene

Hearth   Refractory or cast iron surface with orifices allowing underfire air to enter the fuel bed

Heat Release   The total energy released from combustion, can be expressed in either Btu/lb or Btu/hr.

Heating Value   The total energy released from combustion, usually expressed in either Btu/lb.

Heavy Metals   Metallic elements with high atomic weights, e.g., mercury, chromium, cadmium, arsenic, and lead. They can damage living things at low concentrations

and tend to accumulate in the food chain.

HHV	Higher Heating Value
HON	Hazardous Organic (NESHAP)
HP	Horsepower
hr	Hour
HVAC	Heating, Ventilating, and Air Conditioning (System)
HW	Hazardous Waste
HWI	Hazardous Waste Incinerator
I	Current (Electrical)
IAP	Indoor Air Pollution
ID	Inside Diameter
ID	Induced Draft
IIA	Incinerator Institute of America
I/M	Inspection/Maintenance
in. wc	Inches of water column, a differential pressure indicated by the height of a water column, often measured by a manometer.
Incineration	A treatment technology involving destruction of waste by controlled burning at high temperatures, to remove the water and reduce the remaining residues to a non-burnable residue which can be properly disposed.
Incinerator	A furnace designed for burning of certain types of solid, liquid, or gaseous materials.
Infectious Agent	Any microorganism that is capable of producing infection or disease and may adversely impact human health.
Ion Exchange Treatment	A common water softening method that removes some

organic and other materials by adding calcium oxide or calcium hydroxide to increase the pH to a level where the metals will precipitate out.

IPM	Inhalable Particulate Matter
IR	Infrared
kg	Kilogram
kW	Kilowatt
KWH	Kilowatt Hour
LAER	Lowest Achievable Emission Rate
Landfill	(1) Sanitary landfills are land disposal sites for non-hazardous solid wastes. The waste is spread in layers and compacted. A cover material is added each day. (2) Chemical landfills are disposal sites for hazardous wastes. They are selected and designed to minimize the release of hazardous substances into the environment.
lb	Pound
LC	Liquid Chromatography
LC	Logic Controller (Level Controller)
LCRS	Leachate Collection and Removal System
LD	Land Disposal
LDCRS	Leachate Detection, Collection, and Removal System
Leachate	A liquid that results from water collecting contaminants as it trickles through wastes, particularly, from waste disposed in landfill. Leaching may result in hazardous substances entering surface water, ground water, or soil.
Lead (Pb)	A heavy metal that can be hazardous to health if large enough amounts are breathed or swallowed.

LEL	Lower Explosive Limit
LFL	Lower Flammability Limit
LHV	Lower Heating Value
LIMB	Limestone-Injection, Multi-Stage Burner
Limestone Scrubbing	Process in which sulfur gases in flue gas are passed through a limestone and water solution to remove sulfur before the gases reach the atmosphere.
Liner	A relatively impermeable barrier designed to prevent leachate form leaking from a landfill. Liner materials include plastic and dense clay.
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
LT	Level Transducer
m^3	cubic meter
MACT	Maximum Acheivable Control Technology
MD	Mail Drop
Medical Waste	Any waste, including solid, semi-solid, or liquid material, which is generated in the diagnosis, treatment, or immunization of human beings or animals, in research pertaining thereto, or in the production or testing of biologicals. This includes both regulated and non-regulated waste materials. The term does not include any hazardous waste or any household waste.
Mercury	A heavy metal that can accumulate in the environment and can be highly toxic if large enough amounts are breathed or swallowed.
Methane	A colorless, nonpoisonous flammable gas which can be created by anaerobic decomposition of organic compounds.

MIS	Management Information System
MMT	Million Metric Ton(s)
Moisture	The water content in the fuel composition (fuel moisture) or in flue gas (flue gas moisture), which is derived from fuel moisture, combustion reactions, and moisture in air.
Monitoring	Periodic or continuous surveillance of testing to determine the level of compliance with statutory requirements and/or pollutant levels.
Monofill	A special landfill which receives only a single waste material. Federal RCRA requirements require special siting considerations and design provisions for a cap, leachate containment, monitoring, and treatment system.
MP	Melting Point
MRF	Material Recovery Facility
MS	Mass Spectrometry
MSDS	Material Safety Data Sheet
MSW	Municipal Solid Waste
MT	Metric Ton(s) (1,000 Kilograms)
MW	Megawatt(s)
MW	Molecular Weight
MWC	Municipal Waste Combustor
MWI	Medical Waste Incinerator: All equipment related to the medical waste incineration process, including the feeder to the incinerator, the incinerator, the gas cleaning equipment, the residue management equipment, control and monitoring equipment, and any boiler or heat exchanger equipment that utilizes waste heat from the incinerator.

MWTA	Medical Waste Tracking Act
N_2	Nitrogen
NAA	Nonattainment Area
NAAQS	National Ambient Air Quality Standards
Natural Gas	A natural fuel containing primarily methane and ethane that occurs in certain geologic formations.
NDIR	Nondispersive Infrared Analysis
NESCAUM	Northeast States for Coordinated Air Use Management
NESHAPS	National Emissions Standards for Hazardous Air Pollutants
New Source	Any stationary source which is built or modified after publication of final or proposed regulations that prescribe a standard of performance which is intended to apply to that type of emission source.
ng	Nanogram(s), 10^{-9} grams
ng/dscm	Nanogram(s) per Dry Standard Cubic Meter
NIOSH	National Institute of Occupational Safety and Health
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NOx	Nitrogen Oxides
NRDC	National Resources Defence Council
NSPS	New Source Performance Standards
NSWMA	National Solid Waste Management Association
NTIS	National Technical Information Service
OD	Outside Diameter

O&M	Operations and Maintenance
Opacity	The amount of light obscured by particulate pollution in a gas stream. Opacity is used as an indicator of emissions of particulates and organic products of incomplete combustion.
Organic	In chemistry, any compound containing carbon. Generally refers to compounds derived from living organisms.
OSHA	Occupational Safety and Health Act (Administration)
OSW	Office of Solid Waste, USEPA
Overfire Air	Air forced into the region above the fuel bed of an incinerator to provide the oxygen required for complete combustion.
Packed Tower	A pollution control device that forces dirty gases through a tower fitted with packing materials while liquid is sprayed over the packing. The liquid is selected to enhance the pollutants being either dissolved or chemically reacted.
PAH	Polycyclic Aromatic Hydrocarbon
PAN	Peroxyacetyl Nitrate
Particulate Matter	Fine liquid or solid particles such as dust, smoke, mist, or fumes.
Particulate Emission	Fine liquid or solid particles such as dust, smoke, mist, or fumes found in the flue gas emissions carried into the atmosphere.
Particulate Loading	The mass of particulate emissions, generally expressed in mass per unit volume of the air.
Pathogen	Those organisms (e.g., bacteria and viruses) which are capable of causing disease.
Pathogenic Waste	Waste materials that contain organisms capable of causing an infectious disease.
Pathological Waste	Waste materials that consisting of anatomical parts

	such as body parts and blood. Also waste materials relating to the study of the nature of disease.
PC	Personal Computer
PC	Pulverized Coal
PCB	Polychlorinated Biphenyls: A group of toxic, persistent chemicals which have been used in transformers and capacitors for insulating purposes. Further sales and new uses were banned in 1979.
PCDD	Polychlorinated Dibenzo-p-dioxins
PCDF	Polychlorinated Dibenzofurans
PEL	Personal Exposure Limit
Permit	An authorization, license, or equivalent control document issued by an approving agency to implement the requirements of an environmental regulation.
pH	A measure of acidity or alkalinity of a liquid or solid material.
PHC	Principal Hazardous Constituent
PIC	Products of Incomplete Combustion
PLC	Programmable Logic Controller
PM	Particulate Matter
PM	Preventive Maintenance
PM-10	Particulate Matter, Sized Less Than 10 Micrometers
PMR	Pollutant Mass Rate
POM	Polycyclic Organic Matter
ppb	Parts per Billion
PPE	Personal Protective Equipment

ppm	Parts per Million (generally on a volumetric basis)
ppmdv	Parts per Million on a Dry, Volumetric Basis
ppmv	Parts per Million on a Volumetric Basis
ppm-weight	A measure of mass concentration which is equivalent to both micrograms/gram and milligrams/kilogram.
ppt	Parts per Trillion
Precursor	A compound that "precedes" or leads to the formation of a particular compound of interest.
Proximate Analysis	The fuel's composition expressed fractionally as volatile matter, fixed carbon, moisture, and non-combustible (ash).
PSD	Prevention of Significant Deterioration
psi	Pounds per Square Inch (Pressure)
psia	Pounds per Square Inch Absolute (Pressure)
psig	Pounds per Square Inch Gage (Pressure)
PT	Pressure Transducer
PVC	Polyvinyl Chloride
Pyrolysis	Chemical decomposition of a organic materials under conditions of high temperature and limited oxygen.
QA	Quality Assurance
QA/QC	Quality Assurance/Quality Control: A system of procedures, checks, audits, and corrective actions to ensure that all EPA required sampling, monitoring and reporting activities are of the highest achievable quality.
QC	Quality Control
QMO Standard	ASME Standard QMO-1, Standard for the Qualification and Certification of Medical Waste

Incinerator Operators

QRO Standard	ASME Standard QMO-1-1989, Standard for the Qualification and Certification of Resource Recovery Facility Operators
Quench Tank	A water-filled tank used to cool incinerator ash residues.
R	Resistance (Electrical)
RACT	Reasonably Available Control Technology: The lowest emission limitation that a particular source is capable of meeting by application of control technology that is reasonably available, technically feasible, and economically feasible.
RCRA	Resource Conservation and Recovery Act
R&D	Research and Development
RDF	Refuse-Derived Fuel
Refuse Reclamation	Conversion of solid waste into useful products.
Resource Recovery	The process of obtaining matter or energy from materials formerly discarded.
Retention Time	Amount of time materials are maintained under high temperature combustion conditions (e.g., the time volatile matter is retained in secondary chamber or the time solids are retained in primary chamber).
Risk Assessment	The qualitative and quantitative evaluation performed in an effort to define the risk. Example risks include the potential for economic loss and the environmental risks to human health and/or the environment caused by the presence or potential presence or use of pollutants.
RPM	Revolutions per Minute
RTP	Research Triangle Park, NC
SARA	Superfund Amendments and Reauthorization Act of

1986

SCFM	Standard Cubic Feet per Minute
SCR	Selective Catalytic Reduction
Scrubber	An air pollution control device that uses a spray of water, liquid solutions, or dry materials in a process to remove pollutants from a flue gas.
SD	Standard Deviation
SDA	Spray Dryer Absorber
sec	Second
SI	System International (Units)
SIP	State Implementation Plan
Sludge	The semi-solid residue from any of a number of air or water treatment processes.
Slurry	A watery mixture of insoluble matter that results from some pollution control technique.
Smog	Air pollution associated with oxidants.
Smoke	Particles suspended in gases after incomplete combustion of materials.
SNCR	Selective Non-Catalytic Reduction
SO_2	Sulfur Dioxide: A heavy, pungent colorless gaseous air pollutant formed by oxidation of sulfur.
SOC	Synthetic Organic Chemicals
SOCMI	Synthetic Organic Chemicals Manufacturing Industry
Soot	Carbon dust formed by incomplete combustion.
SOP	Standard Operating Procedure
SP	Set Point

Stack	A chimney or smokestack; a vertical pipe that discharges used gases.
STALAPCO	State and Territorial Air Pollution Control Officials
Starved Air	The characteristic combustion condition where burning occurs with less than stoichiometric air.
Starved-Air	Incinerators which are designed for the primary chamber to operate under sub-stoichiometric conditions.
Stationary Source	A fixed, non-moving producer of pollution, mainly facilities using combustion processes.
Stoichiometric	The theoretical air required for complete combustion.
STP	Standard Temperature and Pressure
Stuff and Burn	A characterization applicable to units which are operated in a batch charging mode.
SWANA	Solid Waste Association of North America
SWDA	Solid Waste Disposal Act
TCDD	Dioxin (Tetrachlorodibenzo-p-dioxin)
TCDF	Furan (Tetrachlorodibenzofurans)
TCLP	Toxicity Characteristic Leachate Procedure
TDS	Total Dissolved Solids
THC	Total Hydrocarbons
TLV	Threshold Limit Value
Toxic	Materials which have the effect of a poison and as such present an unreasonable risk of injury to health or to the environment.
TPD	Tons per Day
TPY	Tons per Year

TSP	Total Suspended Particulates
TSS	Total Suspended Solids
UEL	Upper Explosive Limit
UFL	Upper Flammability Limit
Underfire Air	Combustion air which enters the fuel bed from orifices in the hearth or or openings in the grate.
UV	Ultraviolet rays: Radiation emitted from the sun that can be useful or potentially harmful. UV rays from some parts of the spectrum enhance plant life. Human exposure to UV rays can cause sun burns and skin cancer.
USEPA	U. S. Environmental Protection Agency
Vapor	The gaseous phase of substances that are liquid or solid at atmospheric temperature and pressure.
Vaporization	The change of a substance from a liquid to a gas.
VE	Visual Emissions
Virulence	The disease-evoking power of a microorganism in a given host.
VOC	Volatile Organic Compounds
Volatile Matter	The combustible portion of the fuel which is evolved as gaseous matter upon the application of heat.
VOST	Volatile Organic Sampling Train
VP	Vapor Pressure
Wastewater	The spent or used water (from a process) which contains dissolved or suspended matter.
WB	Wet Bulb (Wet Bulb Temperature)
WTE	Waste-to-Energy

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-453/B-93-020	2.	3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE Municipal Waste Combustor Operator Training Program Course Manual	5. REPORT DATE April 1993
	6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S) J. Taylor Beard, W. Steven Lanier, and Suh Y. Lee	8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS Energy & Environmental Research Corporation 18 Mason Lane Irvine, CA 92718	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO. 68-CO-0094

12. SPONSORING AGENCY NAME AND ADDRESS DAA for Office of Air Quality Planning and Standards Office of Air and Radiation U.S. Environmental Protection Agency Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED Final
	14. SPONSORING AGENCY CODE 200 /04

15. SUPPLEMENTARY NOTES

Michael G. Johnston, EPA/Office of Air Quality Planning and Standards

16. ABSTRACT

The Course Manual, along with the Instructor's Guide (EPA-453/B-93-021), constitute a model State training program to address the training needs of municipal waste combustor (MWC) operators. The training program focuses on the knowledge required by operators for understanding the basis for proper operation and maintenance of MWC's with particular emphasis on the aspects of combustion which are important for environmental control. The training program includes general introductory material relative to municipal solid waste (MSW) treatment and MSW as a fuel. The bulk of the program addresses the principles of good combustion. The potential sources of air pollution emissions and their control are discussed. Instrumentation, automatic control systems, control room operations and practices, and the troubleshooting of upsets are presented. Special system considerations are included: water treatment, electrical theory, and turbines and generators. Finally, risk management procedures such as preventive maintenance and safety considerations are addressed.

The training program fulfills the requirements of the Clean Air Act of 1990, as amended, for the development of a model State training program.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Municipal Waste Combustors Operator Training Incinerators	Air Pollution Control	13B

18. DISTRIBUTION STATEMENT Release Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 393
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (Rev. 4-77)   PREVIOUS EDITION IS OBSOLETE