An Introduction to Sulfur and Nitrogen Oxides Control in Air Pollution

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(Figures, tables and formulas in this publication may at times be a little difficult to read, but they are the best available. **DO NOT PURCHASE THIS PUBLICATION IF THIS LIMITATION IS UNACCEPTABLE TO YOU.**)

1. FORMATION OF SULFUR OXIDES (SOX)

1.1 DEFINITION OF SULFUR OXIDE. All fossil fuels contain sulfur compounds, usually less than 8 percent of the fuel content by weight. During combustion, fuel-bound sulfur is converted to sulfur oxides in much the same way as carbon is oxidized to CO2. Sulfur dioxide (SO2) and sulfur trioxide (SO3) are the predominant sulfur oxides formed. See equations 10-l and 10-2.

$$S + 0_2 \quad \text{----->} \quad S\,O_2 \qquad \text{(eq. 10-l)}$$

$$2\,s\,0_2 + 0_2 \quad \text{----->} \quad 2\,S\,O_3 \qquad \text{(eq. 10-2)}$$

1.2 STACK-GAS CONCENTRATIONS. In efficient fuel combustion processes, approximately 95 percent of the fuel-bound sulfur is oxidized to sulfur dioxide with 1 to 2% being cover-ted to sulfur trioxide.

1.3 FACTORS AFFECTING THE FORMATION OF SOX.

- SO3 formation increases as flame temperature increases. Above 3,150 degrees Fahrenheit, SO3 formation no longer increases.
- SO3 formation increases as the excess air rate is increased.
- SO3 formation decreases with coarser atomization.

2. AVAILABLE METHODS FOR REDUCING SOX EMISSIONS

2.1 FUEL SUBSTITUTION. Burning low sulfur fuel is the most direct means of preventing a SOx emissions problem. However, low sulfur fuel reserves are decreasing and are not available in many areas. Because of this, fuel cleaning technology has receive much attention. There are presently more than 500 coal cleaning plants in this country. At present, more than 20% of the coal consumed yearly by the utility industry is cleaned. Forty to ninety percent of the sulfur in coal can be removed by physical cleaning, depending upon the type of sulfur deposits in the coal. As fuel cleaning technology progresses and the costs of cleaning decrease, fuel cleaning will become a long term solution available for reducing sulfur oxide emissions.

2.2 CONSIDERATIONS OF FUEL SUBSTITUTION. Fuel substitution may involve choosing a higher quality fuel grade; or it may mean changing to an alternate fuel type. Fuel substitution may require any of the following considerations:

- Alternations in fuel storage, handling, preparation, and combustion equipment.
- When changing fuel type, such as oil to coal, a new system must be installed.
- When choosing a higher quality fuel, as in changing from residual to distillate fuel oil, modest modifications, such as changing burner tips, and oil feed pumps, are required.

2.3 CHANGES IN FUEL PROPERTIES. Consideration of possible differences in fuel properties is important. Some examples are:

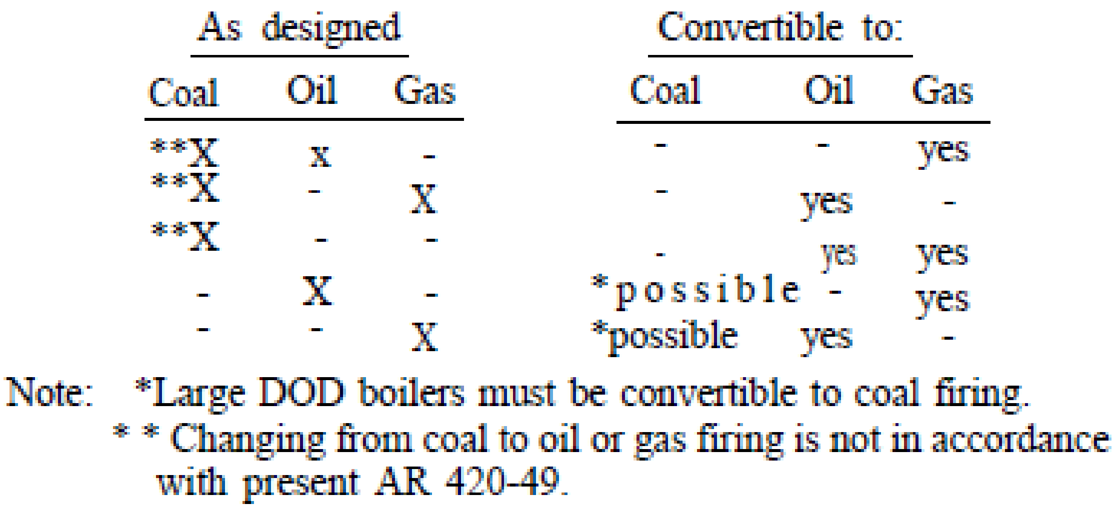
- Higher ash content increases particulate emissions.
- Lower coal sulfur content decreases ash fusion temperature and enhances boiler tube slagging.
- Lower coal sulfur content increases fly-ash resistivity and adversely affects electrostatic precipitator performance.
- Low sulfur coal types may have higher sodium content which enhances fouling of boiler convection tube surfaces.

- The combination of physical coal cleaning and partial flue gas desulfurization enables many generating stations to meet SO2 standards at less expense than using flue gas desulfurization alone.

2.4 MODIFICATION OF FUEL. Some possibilities are:

- Fuels of varying sulfur content may be mixed to adjust the level of sulfur in the fuel to a low enough level to reduce SO2 emissions to an acceptable level.
- Fuels resulting from these processes will become available in the not too distant future. Gasification of coal removes essentially all of the sulfur and liquefaction of coal results in a reduction of more than 85% of the sulfur.

2.5 APPLICABILITY OF BOILER CONVERSION FROM ONE FUEL TYPE TO ANOTHER. Table 10-l indicates that most boilers can be converted to other type of firing but that policies of the agencies must also be a consideration.



As designed			Convertible to:		
Coal	Oil	Gas	Coal	Oil	Gas
**X	x	-	-	-	yes
**X	-	X	-	yes	-
**X	-	-	-	yes	yes
-	X	-	*possible	-	yes
-	-	X	*possible	yes	-

Note: *Large DOD boilers must be convertible to coal firing.
* * Changing from coal to oil or gas firing is not in accordance with present AR 420-49.

Table 10-1

Convertibility of steam boilers

2.6 APPROACH TO FUEL SUBSTITUTION. An approach to fuel substitution should proceed in the following manner:

- Determine the availability of low sulfur fuels.

- For each, determine which would have sulfur emissions allowable under appropriate regulations.
- Determine the effect of each on particulate emissions, boiler capacity and gas temperatures, boiler fouling and slagging, and existing particulate control devices.
- Identify the required equipment modifications, including transport, storage, handling, preparation, combustion, and control equipment.
- For the required heat output calculate the appropriate fuel feed rate.
- Determine fuel costs.
- Determine the cost of boiler and equipment modification in terms of capital investment and operation.
- Annualize fuel costs, capital charges, and operating and maintenance costs.
- With the original fuel as a baseline, compare emissions and costs for alternate fuels.

2.7 MODIFICATION TO BOILER OPERATIONS AND MAINTENANCE.

- A method of reducing sulfur oxides emissions is to improve the boiler use of the available heat. If the useful energy release from the boiler per unit of energy input to the boiler can be increased, the total fuel consumption and emissions will also be reduced.
- An improvement in the boiler release of useful energy per unit of energy input can be achieved by increasing boiler steam pressure and temperature. Doubling the steam drum pressure can increase the useful heat release per unit of energy input by seven percent. Increasing the steam temperature from 900 to 1000 degrees Fahrenheit can result in an improvement in the heat release per unit of energy input of about 3.5 percent.
- Another way to maximize the boiler's output per unit of energy input is to increase the attention given to maintenance of the correct fuel to air ratio. Proper automatic controls can perform this function with a high degree of accuracy.
- If additional emphasis can be put on maintenance tasks which directly effect the boilers ability to release more energy per unit of energy input they should be

considered a modification of boiler operations. Items which fall into this category are:

- -Washing turbine blades
- -adjusting for maximum throttle pressure
- -adjusting turbine control valves to insure proper lift
- -adjusting preheater seals and feedwater heaters
- -insuring cleanliness of heat transfer surfaces, such as condensers, superheaters, reheaters, and air heaters.

2.8 LIMESTONE INJECTION. One of the earliest techniques used to reduce sulfur oxide emission was the use of limestone as a fuel additive. This technique involves limestone injection into the boiler with the coal or into the high temperature zone of the furnace. The limestone is calcined by the heat and reacts with the SO2 in the boiler to form calcium sulfate. The unreacted limestone, and the fly ash are then collected in an electrostatic precipitator, fabric bag filter, or other particulate control device. There are a number of problems associated with this approach:

- The sulfur oxide removal efficiency of the additive approach is in the range of 50 to 70% in field applications. However, it is considered feasible that when combined with coal cleaning, it is possible to achieve an overall SO2 reduction of 80 percent.
- The limestone used in the process cannot be recovered.
- The addition of limestone increases particulate loadings. In the precipitator this adversely affects collection efficiency.
- The effects of an increased ash load on slagging and fouling as well as on particulate collection equipment present a group of problems which must be carefully considered.
- The high particulate loadings and potential boiler tube fouling in high heat release boilers tend to cause additional expense and technical problems associated with handling large particulate loadings in the collection equipment.
- There have been many claims over the years regarding the applicability of fuel additives to the reduction of sulfur oxide emissions. The United States

Environmental Protection Agency has tested the effect of additives on residual and distillate oil-tired furnaces. They conclude that the additives have little or no effect.

2.9 FLUE GAS DESULFURIZATION (FGD). There are a variety of processes which have demonstrated the ability to remove sulfur oxides from exhaust gases. Although this technology has been demonstrated for some time, its reduction to sound engineering practice and widespread acceptance has been slow. This is particularly true from the standpoint of high system reliability. The most promising systems and their performance characteristics are shown in table 10-2.

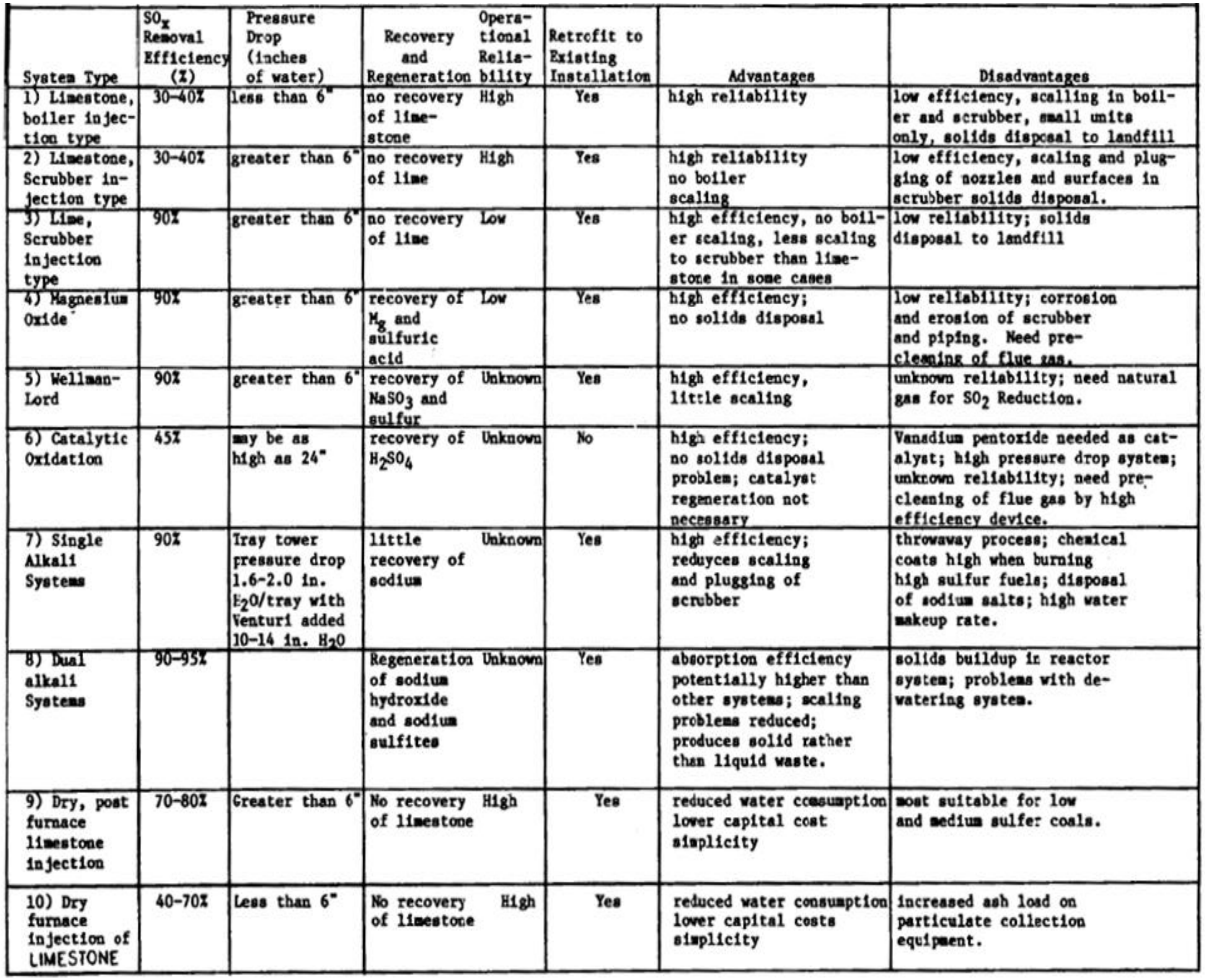
2.10 BOILER INJECTION OF LIMESTONE WITH WET SCRUBBER. In this system limestone is injected into the boiler and is calcined to lime. The lime reacts with the SO2 present in the combustion gases to form calcium sulfate and calcium sulfite. As the gas passes through a wet scrubber, the limestone, lime, and reacted lime are washed with water to form sulfite. As the gas passes through a wet scrubber, the limestone, lime, and reacted lime are washed with water to form a slurry. The resulting effluent is sent to a settling pond and the sediment is disposed by landfilling. Removal efficiencies are below 50% but can be reliably maintained. Scaling of boiler tube surfaces is a major problem.

2.11 SCRUBBER INJECTION OF LIMESTONE. In this FGD system limestone is injected into a scrubber with water to form a slurry (5 to 15% solids by weight). The limestone is ground into fines so that 85% passes through a 200- mesh screen. CaCO3 absorbs SO2 in the scrubber and in a reaction tank where additional time is allowed to complete the reaction. Makeup is added to the reusable slurry as necessary and the mixture is recirculated to the scrubber. The dischargeable slurry is taken to a thickener where the solids are precipitated and the water is recirculated to the scrubber. Limestone scrubbing is a throwaway process and sludge disposal may be a problem. At SO2 removal efficiencies of about 30%, performance data indicate that limestone scrubbers have a 90% operational reliability. Plugging of the demister, and corrosion and erosion of stack gas reheat tubes have been major problems in limestone scrubbers. Figure 10-1 shows a simplified process flow-sheet for a typical limestone scrubbing installation.

2.12 SCRUBBER INJECTION OF LIME. This FGD process is similar to the limestone scrubber process, except that lime (Ca(OH)2) is used as the absorbent. Lime is a more effective reactant than limestone so that less of it is required for the same SO2 removal efficiency. The decision to use one system over the other is not clear-cut and usually is decided by availability.

2.13 POST FURNACE LIMESTONE INJECTION WITH SPRAY DRYING. In this system, a limestone slurry is injected into a spray dryer which receives flue gas directly from the boiler. The limestone in the slurry reacts with the SO2 present in the combustion gases to form calcium sulfate and calcium sulfite. The heat content of the combustion gases drives off the moisture resulting in dry particulates exiting the spray dryer and their subsequent capture in a particulate collector following the spray dryer. The particulates captured in the collector are discharged as a dry material and the cleaned flue gases pass through the filter to the stack (fig lo-la).

2.14 DRY, POST FURNACE LIMESTONE INJECTION. Ground dry limestone is injected directly into the flue gas duct prior to a fabric filter. The limestone reacts in the hot medium with the SO2 contained in the combustion gases and is deposited on the filter bags as sodium sulfate and sodium sulfite. The dry particulate matter is then discharged to disposal and the cleaned flue gases pass through the filter medium to the stack (fig lo-lb).



System Type	SO_x Removal Efficiency (%)	Pressure Drop (inches of water)	Recovery and Regeneration	Operational Reliability	Retrofit to Existing Installation	Advantages	Disadvantages
1) Limestone, boiler injection type	30-40%	less than 6"	no recovery of limestone	High	Yes	high reliability	low efficiency, scalling in boiler and scrubber, small units only, solids dispcsal to landfill
2) Limestone, Scrubber injection type	30-40%	greater than 6"	no recovery of lime	High	Yes	high reliability no boiler scaling	low efficiency, scaling and plugging of nozzles and surfaces in scrubber solids disposal.
3) Lime, Scrubber injection type	90%	greater than 6"	no recovery of lime	Low	Yes	high efficiency, no boiler scaling, less scaling to scrubber than limestone in some cases	low reliability; solids disposal to landfill
4) Magnesium Oxide	90%	greater than 6"	recovery of M_g and sulfuric acid	Low	Yes	high efficiency; no solids disposal	low reliability; corrosion and erosion of scrubber and piping. Need precleaning of flue gas.
5) Wellman-Lord	90%	greater than 6"	recovery of $NaSO_3$ and sulfur	Unknown	Yes	high efficiency, little scaling	unknown reliability; need natural gas for SO_2 Reduction.
6) Catalytic Oxidation	45%	may be as high as 24"	recovery of H_2SO_4	Unknown	No	high efficiency; no solids disposal problem; catalyst regeneration not necessary	Vanadium pentoxide needed as catalyst; high pressure drop system; unknown reliability; need precleaning of flue gas by high efficiency device.
7) Single Alkali Systems	90%	Tray tower pressure drop 1.6-2.0 in. H_2O/tray with Venturi added 10-14 in. H_2O	little recovery of sodium	Unknown	Yes	high efficiency; reduyces scaling and plugging of scrubber	throwaway process; chemical coats high when burning high sulfur fuels; disposal of sodium salts; high water makeup rate.
8) Dual alkali Systems	90-95%		Regeneration of sodium hydroxide and sodium sulfites	Unknown	Yes	absorption efficiency potentially higher than other systems; scaling problems reduced; produces solid rather than liquid waste.	solids buildup in reactor system; problems with dewatering system.
9) Dry, post furnace limestone injection	70-80%	Greater than 6"	No recovery of limestone	High	Yes	reduced water consumption lower capital cost simplicity	most suitable for low and medium sulfer coals.
10) Dry furnace injection of LIMESTONE	40-70%	Less than 6"	No recovery of limestone	High	Yes	reduced water consumption lower capital costs simplicity	increased ash load on particulate collection equipment.

Table 10-2

Performance characteristics of flue-gas desulfurization

2.15 DRY FURNACE INJECTION OF LIMESTONE. In this system, dry ground limestone is injected into the boiler where it is calcined and reacts with the SO2 formed during combustion of the fuel. The flue gases containing the sodium sulfate, sodium sulfite, unreacted limestone, and fly ash all exit the boiler together and are captured on a particulate collector. The cleaned flue gases pass through the filter medium and out through the stack (fig 10-1c).

2.16 MAGNESIUM OXIDE (MGO) SCRUBBER. This is a regenerative system with recovery of the reactant and sulfuric acid. As can be seen in figure 10-2 the flue gas must be precleaned of particulate before it is sent to the scrubber. An ESP or venturi scrubber can be used to remove the particulate. The flue gas then goes to the MgO scrubber where the principal reaction takes place between the MgO and SO2 to form hydrated magnesium sulfite. Unreacted slurry is recirculated to the scrubber where it combines with makeup MgO and water and liquor from the slurry dewatering system. The reacted slurry is sent through the dewatering system where it is dried and then passed through a recovery process, the main step of which is calcination. High reliability of this system has not yet been obtained. SO2 removal efficiencies can be high, but scaling and corrosion are major problems.

2.17 WELLMAN LORD PROCESS. Sodium sulfite is the scrubbing solution. It captures the SO2 to produce sodium bisulfite, which is later heated to evolve SO2 and regenerate the sulfite scrubbing material. The SO2 rich product stream can be compressed or liquified and oxidized to sulfuric acid, or reduced to sulfur. Scaling and plugging are minimal problems because the sodium compounds are highly soluble in water. A Wellman- Lord unit has demonstrated an SO2 removal efficiency of greater than 90 percent and an availability of over 85 percent. The harsh acid environment of the system has caused some mechanical problems (See figure 10-3).

2.18 CATALYTIC OXIDATION. The catalytic oxidation process uses a high temperature (850 degrees Fahrenheit) and a catalyst (vanadium pentoxide) to convert SO2 to SO3. The heated flue gas then passes through a gas heat exchanger for heat recovery and vapor condensation. Water vapor condenses in the heat exchanger and combines with SO3 to form sulfuric acid. The acid mist is then separated from the gas in an absorbing tower. The flue gas must be precleaned by a highly efficient particulate removal device such as an electrostatic precipitator preceding the cat-ox system to avoid poisoning the catalyst. The major drawback of this system is that it cannot be economically retro-fitted to existing installations (fig 10-4).

2.19 SINGLE ALKALI SODIUM CARBONATE SCRUBBING. In order to eliminate the plugging and scaling problems associated with direct calcium scrubbing, this FGD system was developed. As shown in figure 10-5, the process is a once through process involving scrubbing with a solution of sodium carbonate or sodium hydroxide to produce a solution of dissolved sodium sulfur salts. The solution is then oxidized to produce a neutral solution of sodium sulfate. Because it is a throwaway process, the cost of chemicals make it an unattractive SOx removal process when burning high sulfur fuels (greater than 1 percent).

2.20 DUAL ALKALI SODIUM SCRUBBING.

2.20.1 THE DUAL ALKALI SOx removal system is a regenerative process designed for disposal of wastes in a solid/slurry form. As shown in figure 10-6, the process consists of three basic steps; gas scrubbing, a reactor system, and solids dewatering. The scrubbing system utilizes a sodium hydroxide and sodium sulfite solution. Upon absorption of SO2 in the scrubber, a solution of sodium bisulfite and sodium sulfite is produced. The scrubber effluent containing the dissolved sodium salts is reacted outside the scrubber with lime or limestone to produce a precipitate of calcium salts containing calcium sulfate. The precipitate slurry from the reactor system is dewatered and the solids are deposed of in a landfill. The liquid fraction containing soluble salts is recirculated to the absorber. Double alkali systems can achieve efficiencies of 90 - 95% and close to 100% reagent utilization.

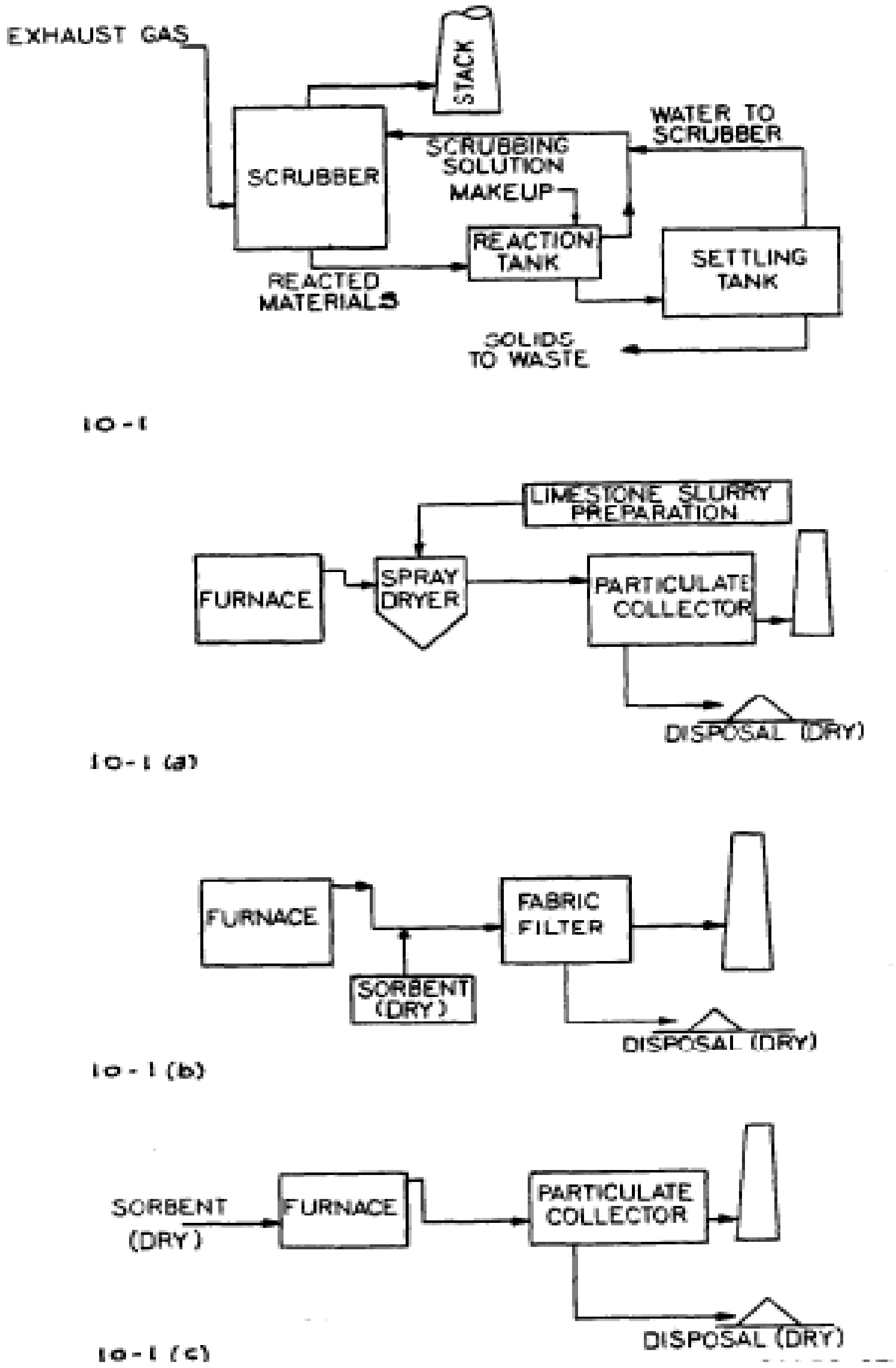


Figure 10-1

Lime (limestone) injection system schematic

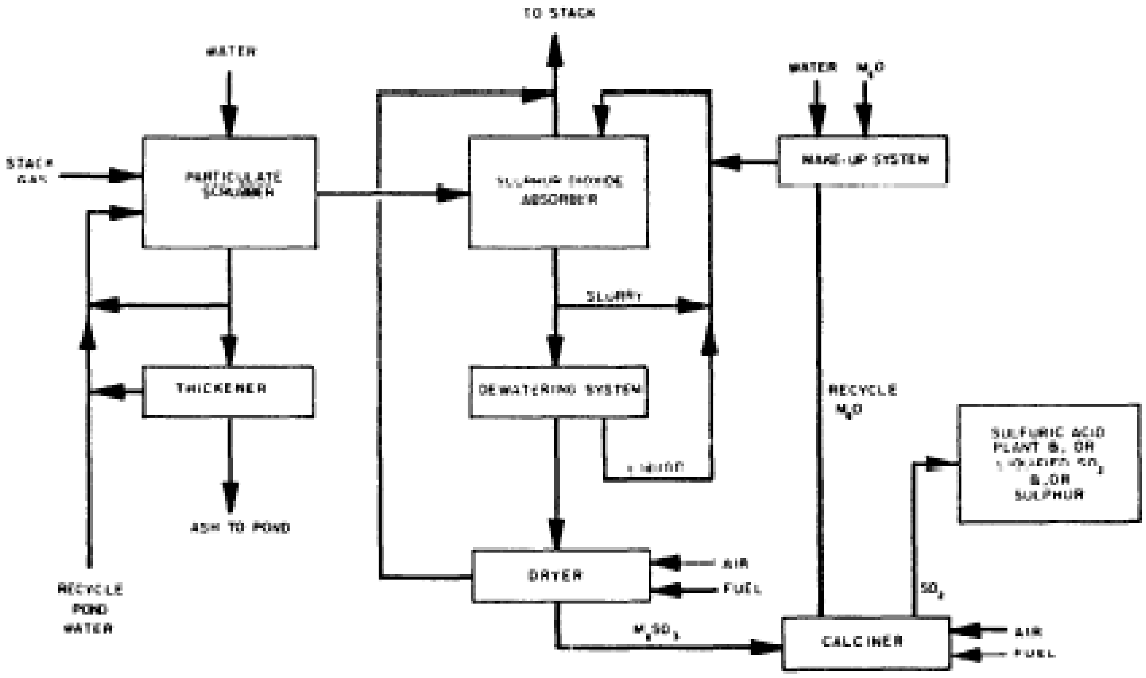


Figure 10-2

Magnesia slurry SO2 recovery process

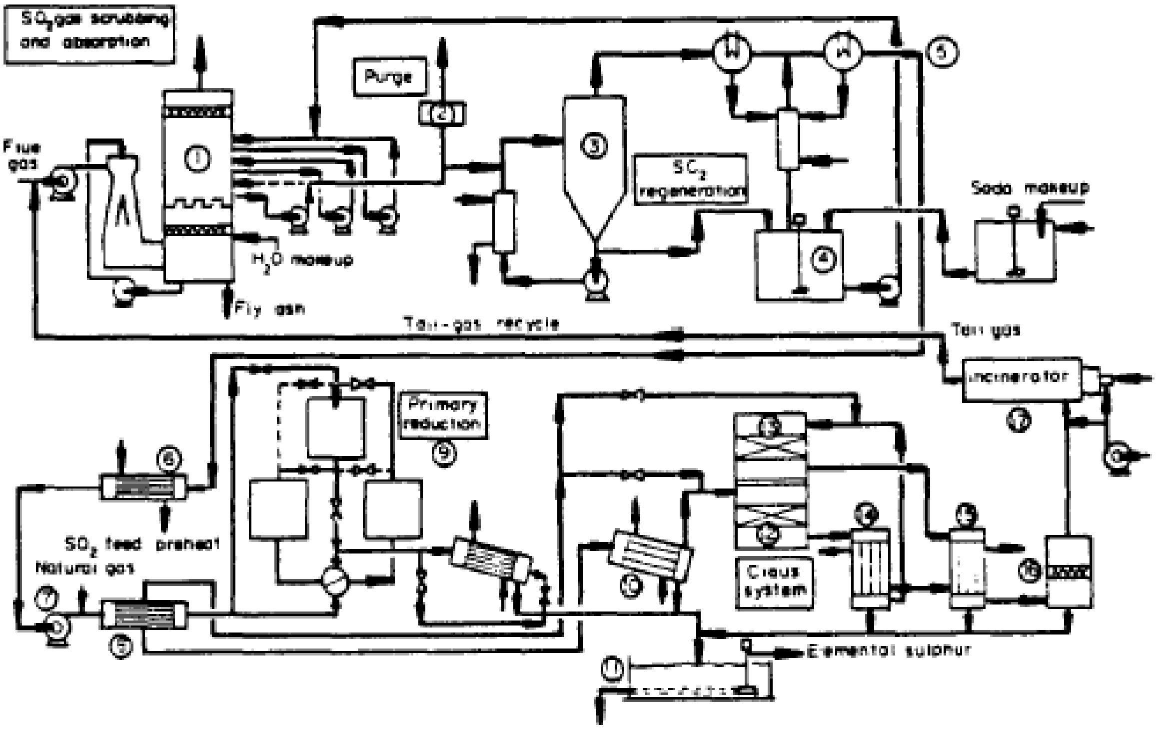
2.20.2 THIS SYSTEM IS DESIGNED to overcome the inherent difficulties of direct slurry scrubbing. All precipitation occurs outside the scrubber under controlled reactor conditions. The principal advantages of the dual alkali system are:

- Scaling problems associated with direct calcium-based scrubbing processes are significantly reduced.
- A less expensive calcium base can be used.
- Due to high solubility and concentration of active chemicals, lower liquid volumes can be used thereby lowering equipment costs.
- Slurries are eliminated from the absorption loop, thereby reducing plugging and erosion problems.
- A sludge waste, rather than a liquid waste, is produced for disposal.
- High SO2 removal efficiency (90% or more).

2.21 ABSORPTION OF SO2.

2.21.1 ACTIVATED CARBON HAS BEEN USED as an absorbent for flue-gas desulfurization. Activated carbon affects a catalytic oxidation of SO2 to SO3, the latter having a critical temperature of 425 degrees Fahrenheit. This allows absorption to take place at operating temperatures. The carbon is subsequently regenerated in a separate reactor to yield a waste which is used in the production of high grade sulfuric acid, and the regenerated absorbent. There are serious problems involved in the regeneration of the absorbent, including carbon losses due to attrition, chemical decomposition, serious corrosion problems, and danger of combustion of the reactivated carbon.

2.21.2 ZEOLITES are a class of highly structured aluminum silicate compounds. Because of the regular pore size of zeolites, molecules of less than a certain critical size may be incorporated into the structure, while those greater are excluded. It is often possible to specify a certain zeolite for the separation of a particular material. Zeolites possesses properties of attrition resistance, temperature stability, inertness to regeneration techniques, and uniform pore size which make them ideal absorbents. However, they lack the ability to catalyze the oxidation of SO2 to SO3 and thus cannot desulfurize flue-gases at normal operating temperatures. Promising research is under way on the development of a zeolite material that will absorb SO2 at flue-gas temperatures by oxidation of SO3 and subsequently store it as a sulphate in the pores of the zeolite.



1) ABSORBER

2) SURGE TANK

3) REGENERATION SECTION

4) DISSOLVING TANK

5) CONCENTRATED SO DISCHARGE

6) PREHEATER

7) NATURAL GAS ADDITION

8) HEATER

9) CATALYTIC REDUCTION SECTION

10) COOLER

11) SULPHUR HOLDING PIT

12,13) CLAUS CONVERTER

14, 15) CONDENSORS

16) COALESCER

17) INCINERATOR

Figure 10-3

Wellman-Lord SO2 reduction system

2.22 COST OF FLUE-GAS DESULFURIZATION. The actual capital and operating costs for any specific installation are a function of a number of factors quite specific to the plant and include:

- -Plant size, age, configuration, and locations,

- -Sulfur content of the fuel and emission control requirements,
- -Local construction costs, plant labor costs, and cost for chemicals, water, waste disposal, etc.,
- -Type of FGD system and required equipment,
- -Whether simultaneous particulate emission reduction is required.

3. PROCEDURE TO MINIMIZE SOX EMISSION

3.1 EFFICIENCY REQUIREMENT. The SOx removal efficiency necessary for any given installation is dependent upon the strictest regulation governing that installation. Given a certain required efficiency, a choice can be made among the different reduction techniques. This section shows how a rational basis can be utilized to determine the best method.

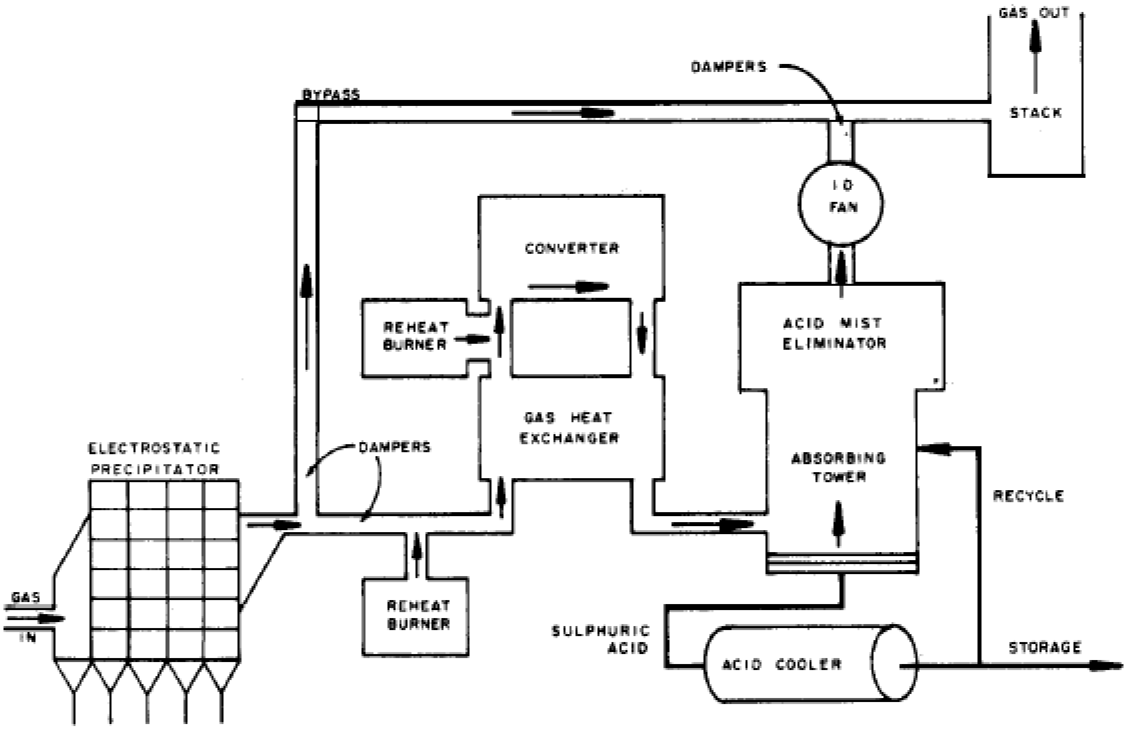


Figure 10-4

Catalytic oxidation system

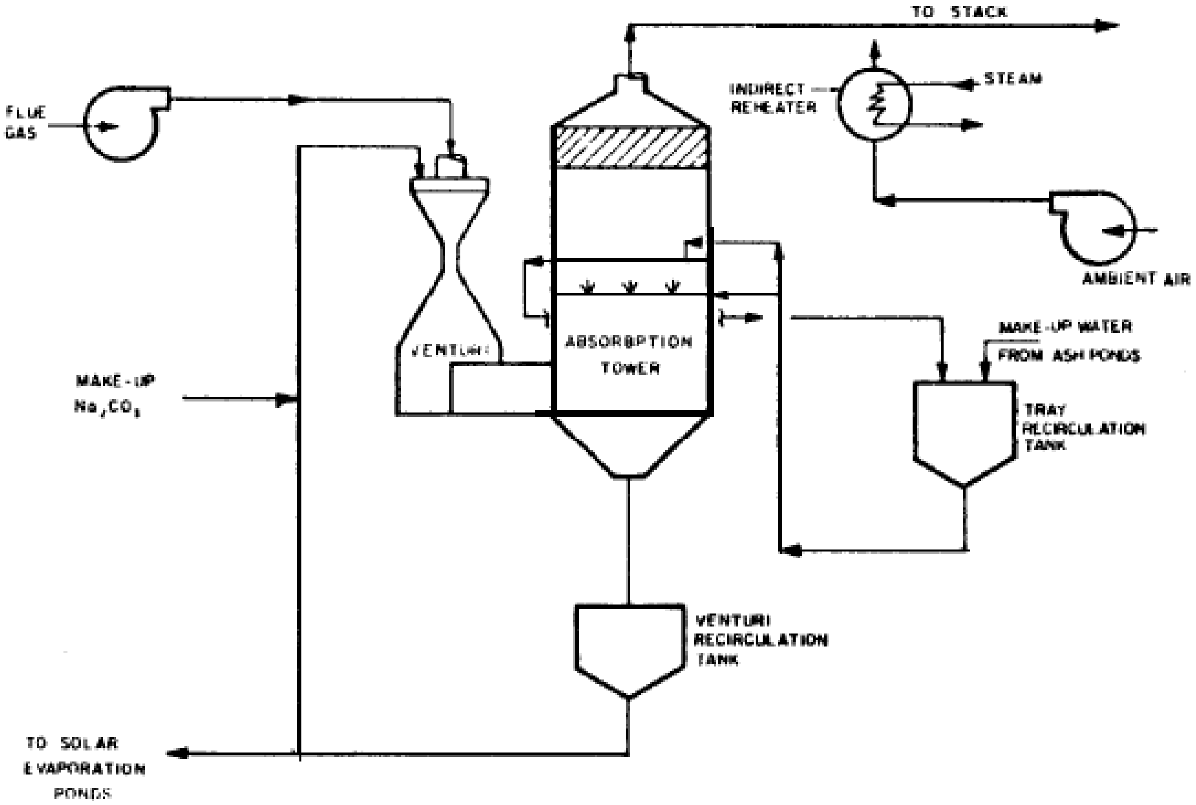


Figure 10-5

Single alkali sodium carbonate scrubber

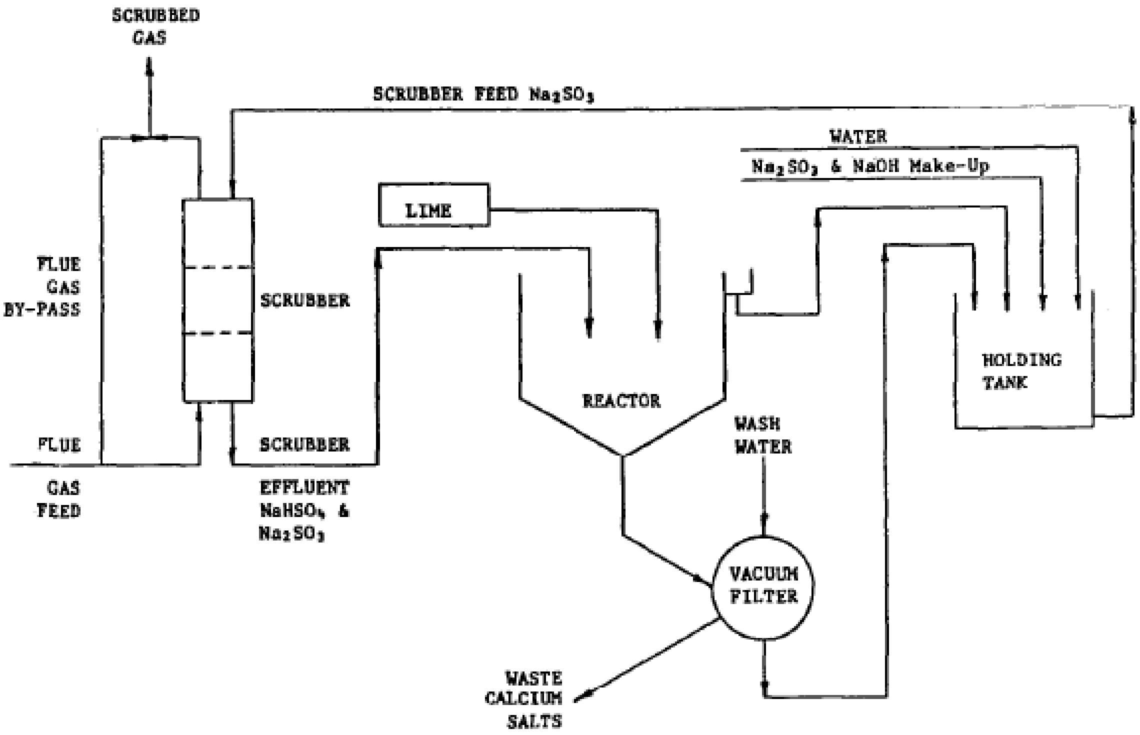


Figure 10-6

Dual alkali system

3.2 BOILER MODIFICATION. This technique is useful in reducing SOX emissions by 0 to 6% depending upon the boiler. For industrial boilers operating above 20% excess-air the use of proper control equipment or low excess-air combustion will usually reduce emissions by 4 to 5%. If the operating engineer is not familiar with boiler optimization methods, consultants should be utilized.

3.3 FUEL SUBSTITUTION. This method can be used for almost any percent reduction necessary. Availability and cost of the fuel are the major factors to be considered. Fuels can be blended to produce the desired sulfur input. Care must be taken, however, so that the ash produced by the blending does not adversely affect the boiler by lowering the ash fusion temperature or causing increased fouling in the convection banks.

3.4 FLUE-GAS DESULFURIZATION. Various systems are available for flue-gas desulfurization. Some of these systems have demonstrated long term reliability of operation with high SOx removal efficiency. Lime/limestone injection and scrubbing systems have been most frequently used. It must be recognized that each boiler control situation must be accommodated in the overall system design if the most appropriate system is to be installed. The selection and design of such a control system should include the following considerations:

- Local SO2 and particulate emission requirements, both present and future,
- Local liquid and solid waste disposal regulations,
- Local market demand for recovered sulfur,
- Plant design limitations and site characteristics,
- Local cost and availability of chemicals, utilities, fuels, etc.,
- Added energy costs due to process pumps, reheaters, booster fans, etc.

4. SAMPLE PROBLEMS. The following problems have been provided to illustrate how to determine the maximum fuel sulfur content allowable to limit SOx emission to any particular level.

4.1 APPROXIMATELY 90 TO 97 PERCENT OF FUEL sulfur is oxidized to sulfur dioxide (SO2) during combustion. This means that for every lb of sulfur in the fuel, approximately 2 lbs of sulfur oxides will appear in the stack gases. (The atomic weight of oxygen is l/2 that of sulfur.) Since most of the sulfur oxides are in the form of SO2, emissions regulations are defined in these units. To estimate maximum probable SO2 emissions, the following equation applies:

$$\frac{\text{lbs SO}_2}{\text{MMBtu}} = \frac{2 \times \text{\% Sulfur by Weight in Fuel}}{\text{Fuel Heating Value (Btu/lb)}} \times 10^4 \qquad \text{(eq. 10-1)}$$

4.2 ASSUME A FUEL-OIL BURNING boiler must limit emissions to .35 lbs/MMBtu. What is the maximum allowable sulfur content if No. 6 Residual fuel-oil is to be used?

4.2.1 FROM TABLE 10-3, TYPICAL ANALYSIS OF FUEL-OIL TYPES, an average heating value of 18,300 Btu/ lb for No. 6 residual fuel has been assumed. Maximum allowable sulfur content is determined as:

$$.35\ \frac{\text{lbs SO}_2}{\text{MMBtu}}$$

$$\times\ \frac{2 \times \text{\% Sulfur by Weight in Fuel}}{18{,}300\ \text{Btu}} \times 10^4$$

$$\text{\% Sulfur} = \frac{(.35)\ (18{,}300)}{2 \times 10^4} = .32\%$$

4.2.2 TABLE 10-3 SHOWS THAT No. 5 and No. 6 fuel oils have fuel sulfur contents in excess of .32%. If No. 4 fuel oil is chosen, a fuel with less than .32% sulfur may be available.

4.3 ASSUME A FUEL-OIL BURNING BOILER must limit SOx emission to .65 lbs/MMBtu. If No. 6 residual fuel oil is to be used, can SOx emission limits be met?

4.3.1 FROM TABLE 10-3, THE MINIMUM sulfur content in No. 6 fuel oil is .7%. If .7% sulfur fuel can be purchased, the heating value of the fuel must be:

$$\text{a)}\quad .65\ \frac{\text{lb SO}_2}{\text{MMBtu}} = \frac{2 \text{ x } .7\% \text{ Sulfur}}{\text{H. Value}} \text{ x } 10^4$$

$$\text{b) Heating Value} = 21{,}538 \text{ Btu/lb}$$

4.3.2 SINCE THE HEATING VALUE OF No. 6 fuel oil is generally between 17,410 and 18,990 Btu/lb, SOx emission limits cannot be met using this fuel. If we assume a No. 6 fuel-oil with one percent sulfur and a heating value of 18,600 Btu/lb is used the percent SOx removal efficiency that will be required is determined as:

$$\text{a)}\quad \frac{\text{lbs SO}_2\text{emissions.}}{\text{MMBtu}} \text{ x } \frac{2 \text{ x } 1\% \text{ Sulfur}}{= 18{,}600 \text{ Btu/lb}} \text{ x } 10^4 = 1.08$$

$$\text{b)}\quad \frac{1.08\ -\ .65}{1.08} = 40\% \text{ removal of SO}_2\text{required}$$

4.4 ASSUME A BOILER INSTALLATION burns No. 4 fuel-oil with a heating value of 19,000 Btu/lb. What is the maximum fuel sulfur content allowable to limit SOx emissions to .8 lbs/MMBtu?

$$(1)\quad \frac{.80\ (\text{lbs}\ SO_2)}{\text{Mil Btu}} = \frac{2 \text{ x } \%\ \text{Fuel Sulfur}}{19{,}000\ \text{Btu/lb}} \text{ x } 10^4$$

$$(2)\ \%\ \text{Fuel Sulfur} = \frac{.80\ (19{,}000)}{2 \text{ x } 10^4}$$

$$= .76\%$$

4.5 ASSUME A COAL BURNING BOILER MUST limit SOx emissions to 1 lb/MMBtu. If sub-bituminous coal with a heating value of 12,000 to 12,500 Btu/lb (see table 10-4) is to be used what is the maximum allowable fuel sulfur content?

$$(1)\quad \frac{(1.0\ \text{lbs}\ SO_2}{\text{MMBtu}} = \frac{2 \text{ x } \%\ \text{Fuel Sulfur}}{12{,}000\ \text{Btu/lb}} \text{ x } 10{,}000$$

$$(2)\ \%\ \text{Fuel Sulfur} = \frac{1.0\ (12{,}000)}{2 \text{ x } 10{,}000}$$

$$= .60\%$$

4.6 SINCE COAL OF THIS LOW SULFUR content is not available, what SOx removal efficiency would be required burning 1% sulfur coal?

$$(1)\quad \text{Estimated}\quad SO_2\,\text{emissions} = \frac{\text{lbs}}{\text{MMBtu}}\ \frac{2 \text{ x } 1\%}{12{,}000} \text{ x } 10^4$$

$$= \frac{1.67\ \text{lbs}\ SO_2}{\text{Mil Btu}}$$

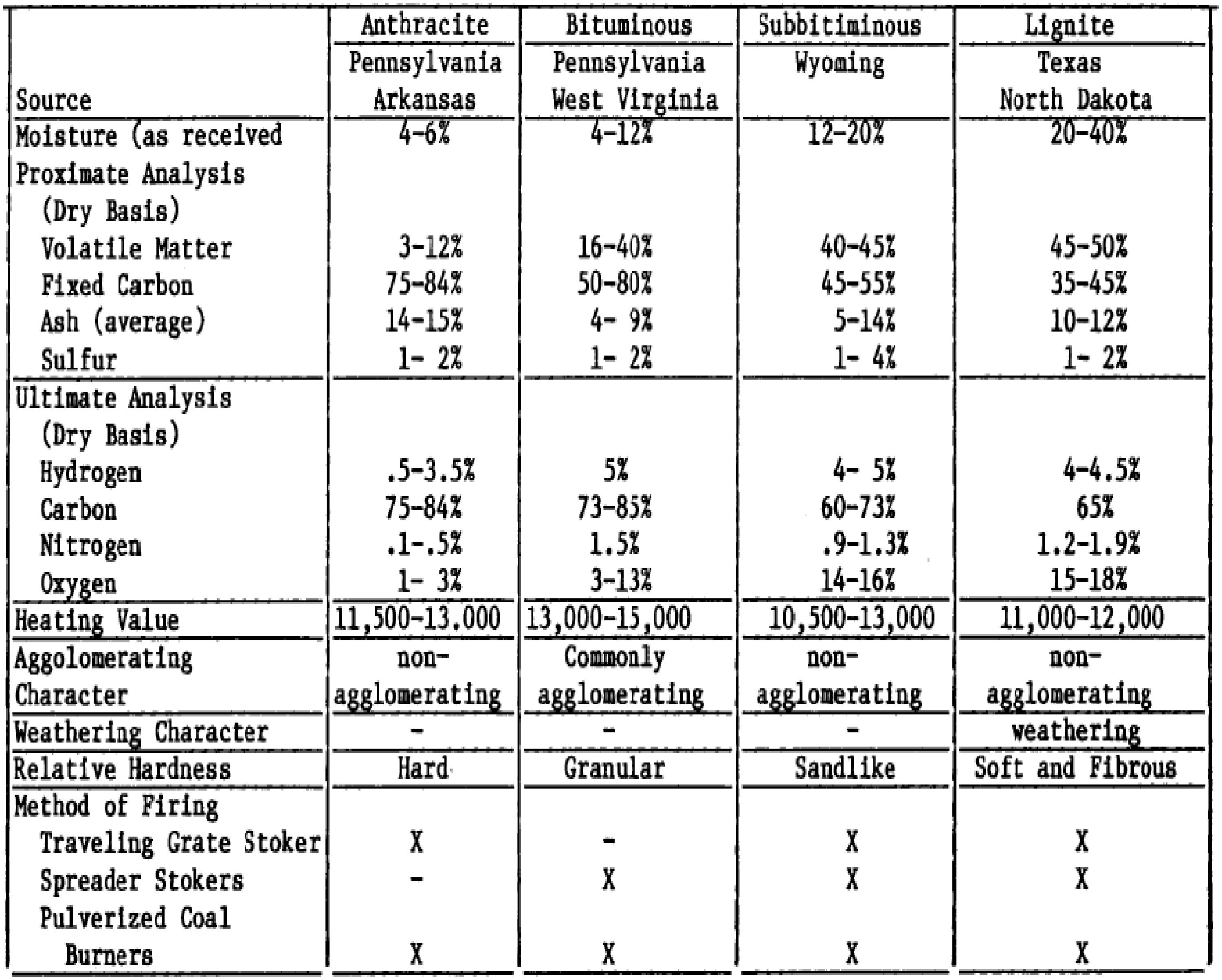
$$(2)\ \%\ \text{Removal Efficiency} = \frac{1.66\text{-}1.0}{1.66}$$

$$= 40\%$$

Grade of Fuel Oil	No. 1	No. 2	No. 4	No. 5	No. 6
Weight, precent					
Sulfur	0.01-0.5	0.05-1.0	0.2-2.0	0.5-3.0	0.7-3.5
Hydrogen	12.3-14.5	11.8-13.9	(10.6-13.0)	(10.5-12.0)	(86.5-90.2)
Carbon	85.9-86.7	86.1-88.2	(86.5-89.2)	(86.5-89.2)	(86.5-90.2)
Nitrogen	Nil-0.1	Nil-0.1	-	-	-
Oxygen	-	-	-	-	-
Ash	-	-	0-0.1	0-0.1	0.01-0.5
Gravity					
Deg API	40-44	28-40	15-30	14-22	7-22
Specific	0.825-0.806	0.887-0.825	0.996-0.876	0.972-0.922	1.022-0.922
Lb per gal	6.87-6.71	7.39-6.87	8.04-7.30	8.10-7.68)	8.51-7.68
Pour point, F	0 to -50	0 to -40	-10 to +50	-10 to +80	+15 to +85
Viscosity					
Centistokes at 100°F	1.4-2.2	1.9-3.0	10.5-65	65-200	260-750
SUS at 100°F	-	32-38	60-300	-	-
SSF at 122°F	-	-	-	20-40	45-300
Water and Sediment, Vol%	-	0-0.1	tr-1.0	0.05-1.0	0.05-2.0
Heating Value Btu, per lb, gross	19,670-19,860	19,170-19,750	18,280-19,400	18,100-19,020	17,410-18,990

Table 10-3

Typical analysis of Fuel Oil Types



	Anthracite	Bituminous	Subbitiminous	Lignite
Source	Pennsylvania Arkansas	Pennsylvania West Virginia	Wyoming	Texas North Dakota
Moisture (as received	4-6%	4-12%	12-20%	20-40%
Proximate Analysis (Dry Basis)				
Volatile Matter	3-12%	16-40%	40-45%	45-50%
Fixed Carbon	75-84%	50-80%	45-55%	35-45%
Ash (average)	14-15%	4- 9%	5-14%	10-12%
Sulfur	1- 2%	1- 2%	1- 4%	1- 2%
Ultimate Analysis (Dry Basis)				
Hydrogen	.5-3.5%	5%	4- 5%	4-4.5%
Carbon	75-84%	73-85%	60-73%	65%
Nitrogen	.1-.5%	1.5%	.9-1.3%	1.2-1.9%
Oxygen	1- 3%	3-13%	14-16%	15-18%
Heating Value	11,500-13.000	13,000-15,000	10,500-13,000	11,000-12,000
Aggolomerating Character	non-agglomerating	Commonly agglomerating	non-agglomerating	non-agglomerating
Weathering Character	-	-	-	weathering
Relative Hardness	Hard	Granular	Sandlike	Soft and Fibrous
Method of Firing				
Traveling Grate Stoker	X	-	X	X
Spreader Stokers	-	X	X	X
Pulverized Coal Burners	X	X	X	X

Table 10-4

Typical analysis of coal types

5. NITROGEN OXIDES (NOx) CONTROL AND REDUCTION, TECHNIQUES

5.1 FORMATION OF NITROGEN OXIDES

5.1.1 NITROGEN OXIDES (NOx). All fossil fuel burning processes produce NOx. The principle oxides formed are nitric oxide (NO) which represents 90-95 percent (%) of the NOx formed and nitrogen dioxide (NOx) which represents most of the remaining nitrogen oxides.

5.1.2 NOx FORMATION Nitrogen oxides are formed primarily in the high temperature zone of a furnace where sufficient concentrations of nitrogen and oxygen are present. Fuel nitrogen and nitrogen contained in the combustion air both play a role in the formation of NOx. The largest percentage of NOx formed is a result of the high temperature fixation reaction of atmospheric nitrogen and oxygen in the primary combustion zone.

5.1.3 NOx CONCENTRATION. The concentration of NOx found in stack gas is dependent upon the time, temperature, and concentration history of the combustion gas as it moves through the furnace. NOx concentration will increase with temperature, the availability of oxygen, and the time the oxygen and nitrogen simultaneously are exposed to peak flame temperatures.

5.2 FACTORS AFFECTING NO_x EMISSIONS

5.2.1 FURNACE DESIGN AND FIRING TYPE. The size and design of boiler furnaces have a major effect on NOx emissions. As furnace size and heat release rates increase, NOx emissions increase. This results from a lower furnace surface-to-volume ratio which leads to a higher furnace temperature and less rapid terminal quenching of the combustion process. Boilers generate different amounts of NOx according to the type of firing. Units employing less rapid and intense burning from incomplete mixing of fuel and combustion gases generate lower levels of NOx emissions. Tangentially tied units generate the least NOx because they operate on low levels of excess air, and because bulk misting and burning of the fuel takes place in a large portion of the furnace. Since the entire furnace acts as a burner, precise proportioning of fuel/air at each of the individual fuel admission points is not required. A large amount of internal recirculation of bulk gas, coupled with slower mixing of fuel and air, provides a combustion system which is inherently low in NOx production for all fuel types.

5.2.2 BURNER DESIGN AND CONFIGURATION. Burners operating under highly turbulent and intense flame conditions produce more NOx. The more bulk mixing of fuel and air in the primary combustion zone, the more turbulence is created. Flame color is an index of flame turbulence. Yellow hazy flames have low turbulence, whereas, blue flames with good definition are considered highly turbulent.

5.2.3 BURNER NUMBER. The number of burners and their spacing are important in NOx emission. Interaction between closely spaced burners especially in the center of a multiple burner installation, increases flame temperature at these locations. The tighter spacing lowers the ability to radiate to cooling surfaces, and greater is the tendency toward increased NOx emissions.

5.2.4 EXCESS AIR. A level of excess air greatly exceeding the theoretical excess air requirement is the major cause of high NOx emissions in conventional boilers. Negotiable quantities of thermally formed NOx are generated in fluidized bed boilers.

5.2.5 COMBUSTION TEMPERATURE. NOx formation is dependent upon peak combustion temperature, with higher temperatures producing higher NOX emissions.

5.2.6 FIRING AND QUENCHING RATES. A high heat release rate (firing rate) is associated with higher peak temperatures and increased NOx emissions. A high rate of thermal quenching, (the efficient removal of the heat released in combustion) tends to lower peak temperatures and contribute to reduced NOx emissions.

5.2.7 MASS TRANSPORTATION AND MIXING. The concentration of nitrogen and oxygen in the combustion zone affects NOx formation. Any means of decreasing the concentration such as dilution by exhaust gases, slow diffusion of fuel and air, or alternate fuel-rich/fuel-lean burner operation will reduce NOx formation. These methods are also effective in reducing peak flame temperatures.

5.2.8 FUEL TYPE. Fuel type affects NOx formation both through the theoretical flame temperature reached, and through the rate of radiative heat transfer. For most combustion installations, coal-fired furnaces have the highest level of NOx emissions and gas-fired installations have the lowest levels of NOx emissions.

5.2.9 FUEL NITROGEN. The importance of chemically bound fuel nitrogen in NOx formation varies with the temperature level of the combustion processes. Fuel nitrogen is important at low temperature combustion, but its contribution is nearly negligible as higher flame temperatures are reached, because atmospheric nitrogen contributes more to NOx formation at higher temperatures.

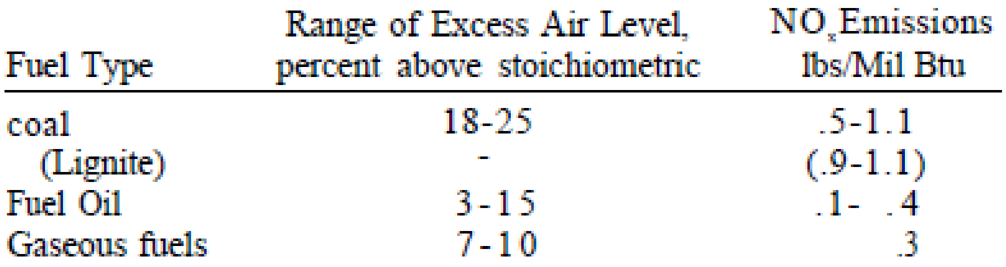
5.3 NOx REDUCTION TECHNIQUES

5.3.1 FUEL SELECTION. Reduction of NOx emissions may be accomplished by changing to a fuel which decreases the combustion excess air requirements, peak flame temperatures, and nitrogen content of the fuel. These changes decrease the concentration of oxygen and nitrogen in the flame envelope and the rate of the NOx formation reaction.

5.3.1.1 THE SPECIFIC BOILER MANUFACTURER should be consulted to determine if a fuel conversion can be performed without adverse effects. The general NOx reduction capability of initiating a change in fuel can be seen comparatively in table 11-l.

5.3.1.2 A CONSIDERATION WHEN contemplating a change in fuel type is that NOx emission regulations are usually based on fuel type. Switching to a cleaner fuel may result in the necessity of conforming to a more strict emission standard.

5.3.1.3 CHANGING FROM A higher to a lower NOx producing fuel is not usually an economical method of reducing NOx emissions because additional fuel costs and equipment capital costs will result.



Fuel Type	Range of Excess Air Level, percent above stoichiometric	NO_x Emissions lbs/Mil Btu
coal	18-25	.5-1.1
(Lignite)	-	(.9-1.1)
Fuel Oil	3-15	.1- .4
Gaseous fuels	7-10	.3

Table 11-1

General NOx emission and excess air requirements for fuel types

5.3.2 LOAD REDUCTION. Load reduction is an effective technique for reducing NOx emissions. Load reduction has the effect of decreasing the heat release rate and reducing furnace temperature. A lowering of furnace temperature decreases the rate of NOx formation.

5.3.2.1 NOX REDUCTION BY LOAD REDUCTION is illustrated in figure 11-l. As shown, a greater reduction in NO2 is attainable burning gas fuels because they contain only a small amount of fuel-bound nitrogen. Fuel-bound nitrogen conversion does not appear to be affected by furnace temperatures, which accounts for the lower NOx reductions obtained with coal and oil tiring. Some units such as tangentially fired boilers show as much as 25 percent decrease in NOx emissions with a 25 percent load reduction while burning pulverized coal.

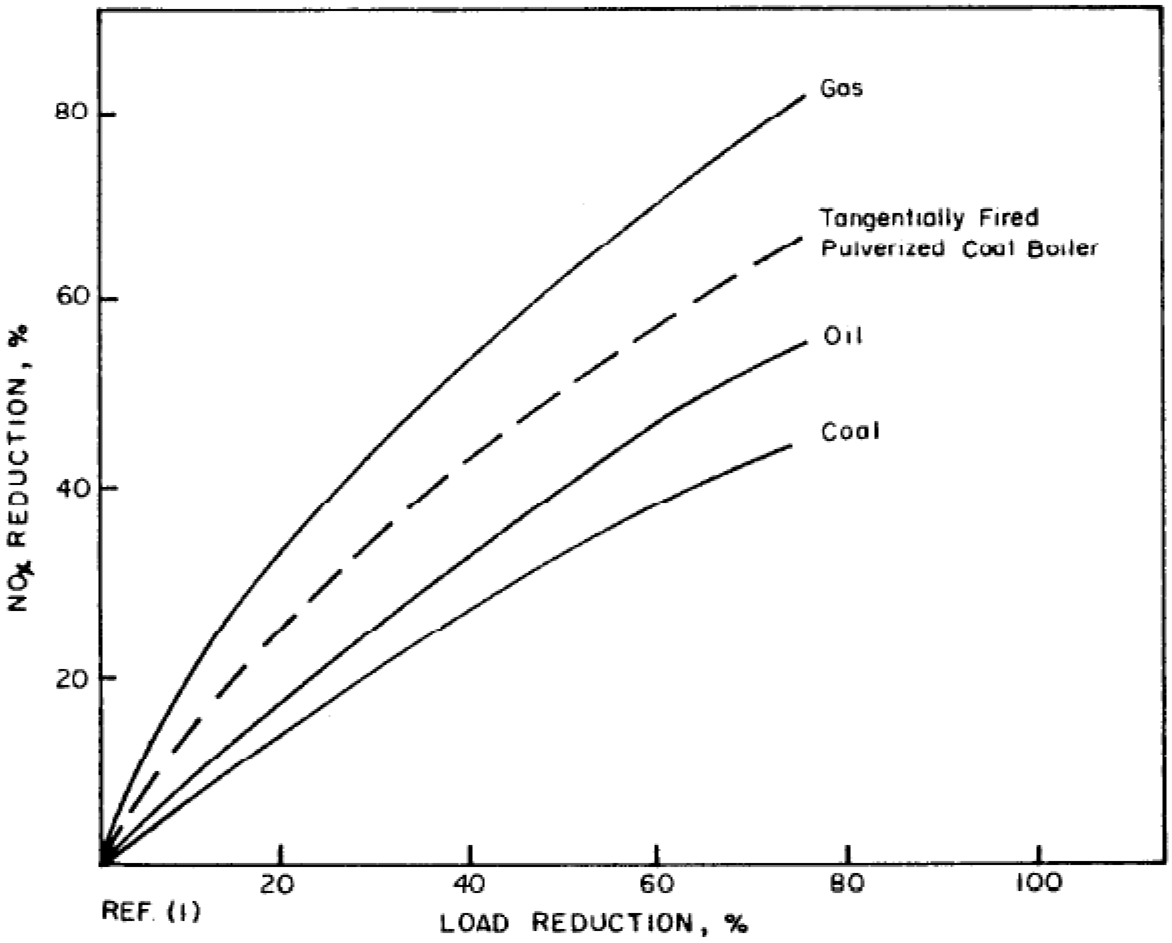


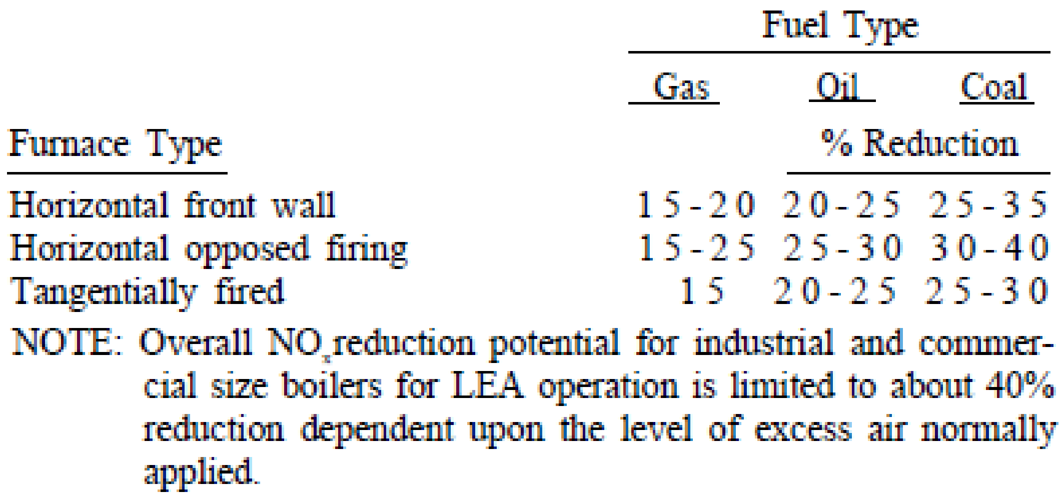
Figure 11-1

Possible NOx reductions vs load reductions

5.3.2.2 ALTHOUGH NO CAPITAL COSTS are involved in load reduction, it is sometimes undesirable to reduce load because it may reduce steam cycle efficiency.

5.3.3 LOW EXCESS AIR FIRING (LEA). In order to complete the combustion of a fuel, a certain amount of excess air is necessary beyond the stoichiometric requirements. The more efficient the burners are in misting, the smaller will be the excess air requirement. A minimum amount of excess air is needed in any system to limit the production of smoke or unburned combustibles; but larger amounts may be needed to maintain steam temperature to prevent refractory damage; to complete combustion when air supply between burners is unbalanced; and to compensate for instrument lag between operational changes. Practical minimums of excess air are 7 percent for natural gas, 3 to 15 percent for oil firing, and 18 to 25 percent for coal firing.

5.3.3.1 SINCE AN INCREASE IN the amount of oxygen and nitrogen in a combustion process will increase the formation and concentration of NOx, low excess air operation is the first and most important technique that should be utilized to reduce NOx emissions. A 50 percent reduction in excess air can usually reduce NOx emissions from 15 to 40 percent, depending upon the level of excess air normally applied. Average NOx reductions corresponding to a 50 percent reduction in excess air for each of the three fuels in different boiler types are shown in table 11-2. Reductions in NOx emissions up to 62 percent have been reported on a pulverized coal fired boiler when excess air is decreased from a level of 22 percent to a level of 5 percent.



	Fuel Type		
	Gas	Oil	Coal
Furnace Type	% Reduction		
Horizontal front wall	15-20	20-25	25-35
Horizontal opposed firing	15-25	25-30	30-40
Tangentially fired	15	20-25	25-30

NOTE: Overall NO$_x$ reduction potential for industrial and commercial size boilers for LEA operation is limited to about 40% reduction dependent upon the level of excess air normally applied.

Table 11-2

Possible NOx emission reductions attainable with a 50% reduction in excess air from normal levels (greater than 10% excess air)

5.3.3.2 THE SUCCESSFUL APPLICATION of LEA firing to any unit requires a combustion control system to regulate and monitor the exact proportioning of fuel and air.

For pulverized coal fired boilers, this may mean the additional expense of installing uniform distribution systems for the coal and air mixture.

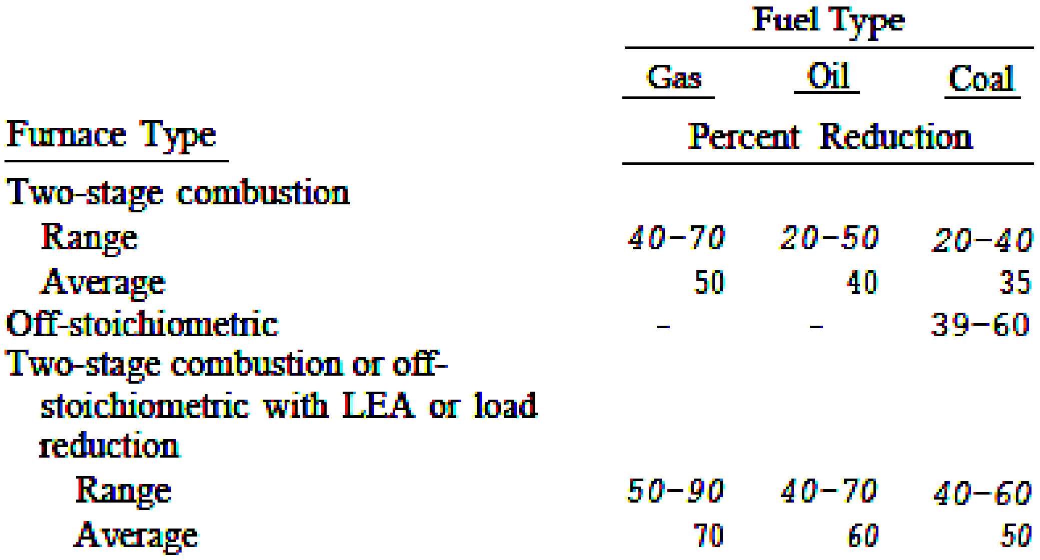
5.3.3.3 LOW EXCESS AIR FIRING IS a desirable method of reducing NOx emission because it can also improve boiler efficiency by reducing the amount of heat lost up the stack. Consequently, a reduction in fuel combustion will sometimes accompany LEA firing.

5.3.4 LOW EXCESS AIR FIRING WITH LOAD REDUCTION. NOx emissions may be reduced by implementing a load reduction while operating under low excess air conditions (table 11-2). This combined technique may be desirable in an installation where NOx emissions are extremely high because of poor air distribution and the resultant inefficient operation of combustible equipment. A load reduction may permit more accurate control of the combustion equipment and allow reduction of excess air requirements to a minimum value. NOx reduction achieved by simultaneous implementation of load reduction and LEA firing is slightly less than the combined estimated NOx reduction achieved by separate implementation.

5.3.5 TWO-STAGE COMBUSTION. The application of delayed fuel and air mixing in combustion boilers is referred to as two stage combustion. Two-stage combustion can be of two forms. Normally it entails operating burners fuel-rich (supplying only 90 to 95 percent of stoichiometric combustion air) at the burner throat, and admitting the additional air needed to complete combustion through ports (referred to as NO ports) located above and below the burner. There are no ports to direct streams of combustion air into the burner flame further out from the burner wall thus allowing a gradual burning of all fuel. Another form of two-stage combustion is off-stoichiometric firing. This technique involves firing some burners fuel-rich and others airrich (high percentage of excess air), or air only, and is usually applied to boilers having three or more burner levels. Off-stoichiometric firing is accomplished by staggering the air-rich and fuel-rich burners in each of the burner levels. Various burner configuration tests have shown that it is generally more effective to operate most of the elevated burners air-rich or air only. Off-stoichiometric firing in pulverized coal fired boilers usually consists of using the upper burners on air only while operating the lower levels of burners fuel-rich. This technique is called over-fire air operation.

5.3.5.1 TWO-STAGE COMBUSTION IS EFFECTIVE in reducing NOx emissions because: it lowers the concentration of oxygen and nitrogen in the primary combustion zone by fuel-rich firing; it lowers the attainable peak flame temperature by allowing for gradual combustion of all the fuel; and it reduces the amount of time the fuel and air mixture is exposed to higher temperatures.

5.3.5.2 THE APPLICATION OF SOME FORM OF two stage combustion implemented with overall low excess air operation is presently the most effective method of reducing NOx emissions in utility boilers. Average NOx reductions for this combustion modification technique in utility boilers are listed in table 11-3. However, it should be noted that this technique is not usually adaptable to small industrial boilers where only one level of burners is provided.



	Fuel Type		
	Gas	Oil	Coal
Furnace Type	Percent Reduction		
Two-stage combustion			
Range	40-70	20-50	20-40
Average	50	40	35
Off-stoichiometric	-	-	39-60
Two-stage combustion or off-stoichiometric with LEA or load reduction			
Range	50-90	40-70	40-60
Average	70	60	50

Table 11-3

Possible NOx reductions, percent of normal emissions

5.3.6 REDUCED PREHEAT TEMPERATURE. NOx emissions are influenced by the effective peak temperature of the combustion process. Any modifications that lower peak temperature will lower NOx emissions. Lower air preheat temperature has been demonstrated to be a factor in controlling NOx emissions. However, reduced preheat temperature is not a practical approach to NOx reduction because air preheat can only be varied in a narrow range without upsetting the thermal balance of the boiler. Elimination of air preheat might be expected to increase particulate emissions when burning coal or oil. Preheated air is also a necessary part of the coal pulverizer operation on coal fired units. In view of he penalties of reduced boiler efficiency and other disadvantages, reduced preheat is not a preferred means of lowering NOx emissions.

5.3.7 FLUE-GAS RECIRCULATION. This technique is used to lower primary combustion temperature by recirculating part of the exhaust gases back into the boiler combustion air manifold. This dilution not only decreases peak combustion flame temperatures but also decreases the concentration of oxygen available for NOx formation. NOx reductions of 20 to 50 percent have been obtained on oil-fired utility boilers but as yet have not been demonstrated on coal-fired units. It is estimated that flue gas recirculation has a potential of decreasing NOx emissions by 40 percent in coal-fired units.

5.3.7.1 FLUE GAS RECIRCULATION has also produced a reduction on CO concentrations from normal operation because of increased fuel-air mixing accompanying the increased combustion air/ gas volume. Gas recirculation does not significantly reduce plant thermal efficiency but it can influence boiler operation. Radiation heat transfer is reduced in the furnace because of lower gas temperatures, and convective heat transfer is increased because of greater gas flow.

5.3.7.2 THE EXTENT OF THE applicability of this modification remains to be investigated. The quantity of gas necessary to achieve the desired effect in different installations is important and can influence the feasibility of the application. Implementing flue-gas recirculation means providing duct work and recycle fans for diverting a portion of the exhaust flue-gas back to the combustion air windbox. It also requires enlarging the windbox and adding control dampers and instrumentation to automatically vary flue-gas recirculation as required for operating conditions and loads.

5.3.8 STEAM OR WATER INJECTION. Steam and water injection has been used to decrease flame temperatures and reduce NOx emissions. Water injection is preferred over steam because of its greater ability to reduce temperature. In gas and coal fired units equipped with standby oil firing with steam atomization, the atomizer offers a simple means for injection. Other installations require special equipment and a study to determine the proper point and degree of atomization. The use of water or steam injection may entail some undesirable operating conditions, such as decreased efficiency and increased corrosion: A NOx reduction rate of up to 10 percent is possible before boiler efficiency is reduced to uneconomic levels. If the use of water injection requires installation of an injection pump and attendant piping, it is usually not a cost-effective means of reducing NOx emissions.

5.4 POST COMBUSTION SYSTEMS FOR NOx REDUCTION.

5.4.1 SELECTIVE CATALYTIC REDUCTION (SCR) of NOx is based on the preference of ammonia to react with NO, rather than with other flue-gas constitutents. Ammonia is injected so that it will mix with flue-gas between the economizer and the air heater. Reaction then occurs as this mix passes through a catalyst bed. Problems requiring resolution include impact of ammonia on downstream equipment, catalyst life, fluegas monitoring, ammonia availability, and spent-catalyst disposal.

5.4.2 SELECTIVE NONCATALYTIC REDUCTION (SNR) Ammonia is injected into the flue-gas duct where the temperature favors the reaction of ammonia with NOx in the flue gas. The narrow temperature band which favors the reaction and the difficulty of controlling the temperature are the main drawbacks of this method. c. Copper oxide is used as the acceptor for SO, removal, forming copper sulfate. Subsequently both the copper sulfate which was formed and the copper oxide catalyze the reduction of NO to nitrogen and water by reaction with ammonia. A regeneration step produces an SO, rich steam which can be used to manufacture by-products such as sulfuric acid.

5.5 STEP-BY-STEP NOX REDUCTION METHOD

5.5.1 APPLICABILITY. The application of NOx reduction techniques in stationary combustion boilers is not extensive. (However, NOx reduction techniques have been extensively applied on automobiles.) These techniques have been confined to large industrial and utility boilers where they can be more easily implemented where NOx emissions standards apply, and where equipment modifications are more economically justified. However, some form of NOx control is available for all fuel-burning boilers without sacrificing unit output or operating efficiency. Such controls may become more widespread as emission regulations are broadened to include all fuel-burning boilers.

5.5.2 IMPLEMENTATION. The ability to implement a particular combustion modification technique is dependent upon furnace design, size, and the degree of equipment operational control. In many cases, the cost of conversion to implement a modification such as flue-gas recirculation may not be economically justified. Therefore, the practical and economic aspects of boiler design and operational modifications must be ascertained before implementing a specific reduction technique.

5.5.2.1 TEMPERATURE REDUCTION THROUGH the use of two-stage combustion and flue-gas recirculation is most applicable to high heat release boilers with a multiplicity of burners such as utility and large industrial boilers.

5.5.2.2 LOW EXCESS AIR OPERATION (LEA) coupled with flue-gas recirculation offers the most viable solution in smaller industrial and commercial size boilers. These units are normally designed for lower heat rates (furnace temperature) and generally operate on high levels of excess air (30 to 60%).

5.5.3 COMPLIANCE. When it has been ascertained that NOx emissions must be reduced in order to comply with state and federal codes, a specific program should be designed to achieve the results desired. The program direction should include: -an estimate of the NOx reduction desired, -selection of the technique or combination thereof, which will achieve this reduction; -an economic evaluation of implementing each technique, including equipment costs, and changes in operational costs; -required design changes to equipment -the effects of each technique upon boiler performance and operational safety.

5.5.4 PROCEDURE. A technical program for implementing a NOx reduction program should proceed with the aid of equipment manufacturers and personnel who have had experience in implementing each of the NOx reduction techniques that may be required in the following manner:

5.5.4.1 NOx EMISSION TEST. A NOx emission test should be performed during normal boiler load times to ascertain actual on-site NOx generation. This test should include recording of normal boiler parameters such as: flame temperature; excess air; boiler loads; flue-gas temperatures; and firing rate. These parameters can be referred to as normal operating parameters during subsequent changes in operation.

5.5.4.2 REDUCTION CAPABILITIES. The desired reduction in NOx emissions, in order to comply with standards, should be estimated based on measured NOx emission data. Specific NOx reduction techniques can then be selected based on desired reductions and reduction capabilities outlined in preceding paragraph 11-3.

5.5.4.3 EQUIPMENT OPTIMIZATION. Any realistic program for NOx reduction should begin with an evaluation and overhaul of all combustion related equipment. A general improvement of boiler thermal efficiency and combustion efficiency will reduce the normal level of NOx emissions. Of major importance are:

- the cleanliness of all heat transfer surfaces (especially those exposed to radiative heat absorption),

- maintaining proper fuel preparation (sizing, temperature, viscosity),
- insuring control and proper operation of combustion equipment (burners nozzles, air registers, fans, preheaters, etc.),
- maintaining equal distribution of fuel and air to all burners.

5.5.4.4 LOW EXCESS AIR OPERATION. Low excess air operation is the most recommended modification for reducing NOx emission. Possible reductions are given in preceding table 11-2. However, a control system is needed to accurately monitor and correct air and fuel flow in response to steam demands. Of the control systems available, a system incorporating fuel and air metering with stack gas O2 correction will provide the most accurate control. A system of this nature will generally pay for itself in fuel savings over a 2 to 3-year period, and is economically justified on industrial boilers rated as low as 40,000 lb of steam/hr.

5.5.4.5 FLUE-GAS RECIRCULATION. Flue-gas recirculation is the second most effective NOx reduction technique for boilers where two stage combustion cannot be applied. Low excess air operation and flue-gas recirculation must be implemented simultaneously from a design point of view. LEA operation may require installation or retrofitting of air registers to maintain proper combustion air speed and mixing at reduced levels or air flow. Flue gas recirculation will require larger air registers to accommodate the increased volume of flow. Therefore, simultaneous application of LEA operation and flue-gas recirculation may minimize the need for redesign of burner air registers. Knowledge of furnace thermal design must accompany any application of flue-gas recirculation which effectively lowers furnace temperature and thus, radiative heat transfer. Convective heat transfer is also increased by increased gas flow due to the dilution of combustion air. It is advisable to consult boiler manufacturers as to the applicability of flue-gas recirculation to their furnaces.

5.5.5 SUMMARY. The potential and applicability of each NOx reduction technique is summarized in table 11-4.

Technique	Potential NO_x Reduction (%)	Advantages	Disadvantages
Load Reduction	See Figure 11-1	Easily implemented; no additional equipment required; reduced particulate and SO_x emissions.	Reduction in generating capacity; possible reduction in boiler thermal efficiency.
Low Excess Air Firing (LEA)	15 to 40 see Table 11-2	Increased boiler thermal efficiency; possible reduction in particulate emissions may be combined with a load reduction to obtain additional NO_x emission decrease; reduction in high temperature corrosion and ash deposition.	A combustion control system which closely monitors and controls fuel/air rations is required.
Two Stage Combustion			
Coal	30	-	Boiler windboxes must be designed for this application.
Oil	40	-	
Gas	50	-	Furnace corrosion and particulate emissions may increase.
Off-Stoichiometric Combustion			Control of alternate fuel rich/ and fuel lean burners may be a problem during transient load conditions.
Coal	45	-	
Reduced Combustion Air Preheat	10-50	-	Not applicable to coal or oil fired units; reduction in boiler thermal efficiency; increase in exit gas volume and temperature; reduction in boiler load.
Flue Gas Recirculation	20-50	Possible improvement in combustion efficiency and reduction in particulate emissions.	Boiler windbox must be modified to handle the additional gas volume; ductwork, fans and controls required.

Table 11-4

Comparison of NOx reduction techniques