PPP 0475
P-03452
29479
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THE USE OF OXYGEN IN HAZARDOUS WASTE INCINERATION -- A STATE-OF-THE-ART REVIEW

Min-Da Ho and and Maynard G. Ding
Linde Division, Union Carbide Industrial Gases Inc.
Tarrytown, New York 10591

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Revised June 1989

ABSTRACT

The use of advanced oxygen combustion technologies in hazardous waste incineration has emerged in the last two years as one of the most significant breakthroughs among all the competing treatment technologies. Unlike most others, oxygen combustion technologies can be easily retrofitted onto various existing incinerators. The capacity of existing incinerators can typically be increased by a factor of two or three, and destruction and removal efficiencies (DRE's) can potentially be improved with such a retrofit.

For many years, industrial furnaces have used oxygen enrichment of the combustion air and oxygen-fuel burners, but with conventional technologies a high oxygen level generally poses problems. The flame temperature is high, leading to high NOx formation and local overheating. Different technical approaches to overcome these problems and their respective effectiveness will be reviewed. Previously, commercial oxygen enrichment in incinerators was limited to a rather modest level (less than 26% O2). This paper will review some of the recent commercial applications of much higher oxygen enrichment levels in hazardous waste incinerators.

The general characteristics of any oxygen enriched flame, the benefits that can be anticipated, and the associated economic ramifications are explored in this paper. Also reported are the results of recent EPA evaluations of two unique oxygen combustion technologies: The Pyretron™ burner by American Combustion, Inc. and the LINDE® Oxygen Combustion System by the Linde Division of Union Carbide Industrial Gases, Inc.

INTRODUCTION

In response to the Federal Resource Conservation and Recovery Act (RCRA) amendments of 1984 and Superfund Reauthorization and Amendments (SARA) of 1986, incineration is generally considered to be the most permanent solution of hazardous chemical waste treatment. RCRA includes a statement of national policy which emphasizes that "reliance on land disposal of hazardous waste should be minimized or eliminated...land disposal should be used as a last resort and should be replaced in most cases by advanced treatment, recycling, incineration and other hazardous waste control technologies." Incineration is a proven technology for treating a wide range of materials including liquid, solid, and semi-solid wastes such as PCBs, solvents, organic residues, halogenated hydrocarbons, pesticides, herbicides, and laboratory waste.(1,2) In addition, the continued discovery of abandoned hazardous waste sites as a result of Superfund investigations has placed increasing pressure on the U.S. Environmental Protection Agency (EPA) to find alternate solutions for treating and disposing of toxic and hazardous wastes. The decreasing availability of landfill sites and the increasing public opposition to toxic and hazardous waste transport have added to the pressure.

EPA's regulations for incineration of hazardous wastes require that the system must achieve a Destruction and Removal Efficiency (DRE) of at least 99.99 percent of the Principal Organic Hazardous Constituents (POHCs) present in the waste and at least 99.9999 percent for dioxin and PCB contaminated wastes. High excess air levels are generally used to ensure that the incinerators meet these high performance standards.

The use of oxygen or oxygen-enriched air in place of air for incineration can improve the overall performance and efficiency of chemical waste incinerators, and reduce the overall cost of the system. As oxygen replaces part or all of the air for incineration, the nitrogen portion is reduced in both the oxidant and the flue gas. Hence, the volume of the oxidant and the flue gas are reduced per unit of waste processed. In addition, the concentration of oxygen in the fuel-oxidant mixture is increased.

EFFECTS OF OXYGEN ENRICHMENT ON GENERAL COMBUSTION CHARACTERISTICS

Oxygen enrichment (21-100%) of air reduces the amount of nitrogen present as a diluent in the reaction of fuel and oxygen. The rate of combustion reaction usually increases significantly with oxygen enrichment due to the higher partial pressures of both oxygen and fuel and the resulting higher equilibrium temperature. This higher reaction rate is one of the main reasons for the following changes in the combustion characteristics(3):

- higher flame speed
- lower ignition temperature
- wider flammability range
- higher blow-off velocity gradients
- higher adiabatic flame temperature

For incineration applications it is necessary to evaluate how these changes affect flame stability, flame temperatures and safety of the process.

Flame Stability

In general, a higher flame speed will improve flame stability and create a more intense and shorter flame. It is, however, difficult to quantitatively predict the actual effects on industrial burner flames which are post mixed and turbulent.

The lower flammability limit (lean limit) of a fuel and air mixture is little influenced by oxygen enrichment of the air. This is expected since excess oxygen in the lean limit is considered to act as a heat sink similar to nitrogen(4). The higher flammability limit (rich limit), on the other hand, is extended substantially with oxygen enrichment, as shown in Table 1. For example, the higher flammability limit of methane is increased from 14% to 61% by going from air to pure oxygen. For all the fuels cited, the ratio of the limits expands greatly.

For burner applications, wider flammability limits generally correlate with greater flame stability. The change in the upper limit allows the combustion of the fuel or waste to begin even in a highly fuel-rich mixture.

Stability of a premixed flame can be measured in terms of the critical velocity gradients at blow-off limits. "Blow-off" is the condition of a burner flame where the flow velocities of the gases forming the combustible mixture exceed the burning velocity everywhere in the flow field. In such conditions, the combustion wave is driven back from the burner and loses its stable "anchor" in relation to the burner face. As much as 100-1000 fold increases in blowoff velocity gradients were measured when pure oxygen was used instead of air (7). The dramatic increases in the blow-off velocity gradients with oxygen enrichment are considered to improve flame stability for wide turn down ranges of firing rate. A higher blow-off limit is also advantageous in designing high velocity burners with good flame stability.

Adiabatic Flame Temperature

The adiabatic flame temperatures increase significantly with oxygen enrichment due to the reduction of nitrogen which acts as a diluent in combustion. The flame temperature increases by as much as 100°F for a 1% increase in oxygen concentration for low enrichment levels. The rate of increase in the flame temperature decreases gradually with the enrichment level and tapers off at high enrichment levels.

There are two main reasons for this phenomenon: (1) the amount of nitrogen eliminated with each unit percent oxygen enrichment diminishes with increasing enrichment level, and (2) endothermic dissociation of CO_2 and H_2O becomes increasingly significant at high temperatures. Table 2 lists adiabatic flame temperatures of selected fuels with air and oxygen at stoichiometric ratios.

Adiabatic flame temperature is the maximum flame temperature attainable under an ideal condition. The actual temperature of an industrial burner flame is significantly lower than the adiabatic flame temperature due to radiative heat loss and turbulent mixing with surrounding colder furnace gases.

It is important to recognize that the adiabatic flame temperature simply provides an upper limit in the attainable flame temperature and that higher flame temperature is not essential in increasing heat transfer in a furnace with oxygen enrichment. Special burners and oxygen enrichment techniques have been developed and applied in industries to increase heat transfer in a furnace without creating higher flame temperatures that might cause a local overheating problem(13-15). Further discussion on furnace heat transfer and flame temperature is given later in this paper.

Oxygen Safety

An important safety consideration resulting from higher reactivities and lower ignition temperatures in an oxygen enriched atmosphere is the material compatibility for oxygen service. Many materials which do not ignite in air can ignite in oxygen enriched atmospheres. Extensive studies have been conducted to evaluate metals, sealing materials and lubricants for oxygen service (8), and practical guidelines have been reported for piping (9,10), compressors, and pumps (11).

From the viewpoint of combustion safety, the potential to create a flammable mixture in a furnace prior to startup would increase if both the fuel and oxygen enriched air leak simultaneously. Thus, the prevention of accidental accumulation of oxygen enriched air in the furnace becomes an important design consideration for an oxygen-enriched combustion system.

ADVANTAGES OF USING OXYGEN

The main advantages of using oxygen for incineration can be summarized: (1) the fuel consumption, if supplemental fuel is required, is lowered primarily due to the reduced sensible heat loss to the flue gases; (2) the throughput of the incinerator, which is normally limited by the air blower capacity, the gas residence time and the size of the flue gas cleaning system when using air, can be significantly increased; (3) the DRE can potentially be improved due to the higher oxygen concentration in the fuel-oxidant mixture and longer residence time; (4) pollution control of the reduced flue gas is less costly and more effective; and (5) control of "puffs", as indicated by CO excursions, is achievable.

Fuel Savings with Oxygen

For the incineration of low BTU wastes such as aqueous waste and contaminated soil, very significant amounts of auxiliary fuel are consumed. In such a case, flue loss is usually the biggest single source of heat loss for a high temperature incinerator. In a typical waste incinerator fired with natural gas and cold air, about 50-70% of the higher heating value of the fuel is lost as sensible heat in the flue gas.

By replacing combustion air with oxygen, the corresponding reduction of nitrogen in the flue gas lowers the sensible heat loss dramatically. In Figure 1 the fuel required to provide 1 MM BTU of available heat to a furnace is plotted as a function of flue gas temperature for ambient air, enriched air, and oxygen. The "available heat" can be defined as the gross quantity of heat released within a combustion chamber minus the combustion flue gas loss. For this example, the fuel is methane and the oxygen concentration in the flue gas is 6 percent by volume. As the flue gas temperature increases, the fuel requirement to provide a given amount of energy above that temperature level increases, and the difference between air and oxygen as oxidants becomes greater. For example, as the temperature level increases from 1800°F to 2400°F, the fuel requirement to obtain 1 MM BTU of available energy increases from 2.2 to 6.1 MM BTU for air, and from 1.2 to 1.4 for oxygen. As a result, the fuel savings using oxygen increases substantially as the operating temperature of the furnace increases. Shown in Fig. 2 are the specific fuel savings by using oxygen enrichment in terms of MM BTU fuel savings per ton of oxygen, as a function of flue gas temperature and excess oxygen level.

Note that when the concentration of excess oxygen in the flue gas is increased for both the air and oxygen combustion systems to the same level, fuel efficiency of the air system deteriorates much faster than that for the oxygen system. Consequently, fuel savings by switching from air to oxygen becomes greater when the concentration of excess oxygen in the flue gas is higher. In addition, when the system throughput is increased with oxygen enrichment, further fuel savings can be realized.

Throughput Increases

Oxygen enrichment has been successfully used for throughput increases in a broad range of industrial furnaces(3,16-19). Production increases of 10-20% are typically possible with a few percent increase in oxygen concentration for most furnaces.

The extent of throughput improvements possible for a particular incinerator depends on the nature of the incinerator limitations. Some of the typical limitations are listed in Table 3. The most common limitations are those related to the capacity limitations of fuel and air supply systems and the flue handling system including the air pollution control devices. Oxygen enrichment is very effective in overcoming these limitations due to the reduction of the volume of oxidant and flue gas for the same fuel input and higher available heat to the furnace. Such benefits are especially significant for a low BTU waste which requires auxiliary fuel input. Shown in Figure 3, as an example, is the relative flue gas volume as a function of oxygen enrichment to obtain the same available heat.

In the incineration of medium BTU waste (2000-8000 BTU/lb) with oxygen enrichment, by reducing and in some cases eliminating the use of auxiliary fuel, the thermal capacity of an incinerator can be dedicated to the combustion of hazardous waste instead of auxiliary fuel. Throughput increase in this manner can often be achieved. Even for incineration of high BTU waste where auxiliary fuel is not required, a specific flue gas volume reduction can be achieved with oxygen enrichment in conjunction with the use of waste water injection.

The dust carryover problem, a common process limitation, is related to particle size, characteristics of the particulate matter, and the aerodynamic patterns within the kiln. Although the improvement by using oxygen can not be accurately predicted, the lower kiln superficial gas velocity should be beneficial in reducing the dust carryover. For example, dust carryover problems in cement, lime and hazardous waste rotary kilns have been effectively alleviated by the lower flue gas volumes resulting from oxygen enrichment(17,19,20).

In many cases the capacity of an incinerator is limited by the mechanical design of the system. Mechanical modifications must be made in order to overcome such limitations before oxygen enrichment can be useful.

For the incineration of low-BTU wastes, such as contaminated soil, the heat transfer rate to the heat load may be a rate-limiting factor. High temperature oxygen/oxygen-enriched flames have been successfully applied to certain glass melters and kilns to increase heat transfer to strategic areas in the vessels. In most waste incinerators such as a rotary kiln, however, a high temperature flame can cause overheating of the refractory walls and possible slagging problems. On the other hand, an extremely high temperature flame is not essential to achieve a higher overall heat transfer rate. Gas radiation from hot combustion products to the surrounding refractory walls and re-radiation to the heat load is the primary mode of heat transfer in most high temperature furnaces. The intensity of gas radiation is not only a function of gas temperature and concentrations of CO_2, H_2O, and soot, but also is strongly influenced by the volume of the radiating gas. The volume of a flame is usually a small fraction of the entire furnace. Thus, in a radiation dominant furnace with temperature limitations, the preferred condition for productivity improvement is to increase the average gas temperature of the heat transfer zone by enhancing the temperature uniformity, rather than by a localized increase in flame temperature. The above principle should be applied intelligently to maximize the benefit of oxygen-enriched combustion.

Performance Improvements

It is sometimes argued that the high flame temperature achievable with oxygen enrichment is conducive to higher DREs due to improved oxidation kinetics. However, studies have shown that with a temperature above 2000°F, the combustion reaction is limited by the rate of mass transfer processes of oxygen and toxic molecules (i.e. atomization, evaporation and mixing), rather than the kinetic rates, the contribution of extremely high temperatures being quite limited. Therefore, a flame with high momentum and moderate temperature may be most suitable for incinerator applications. EPA studies have also shown that well-run conventional air-based incineration systems achieved very high DREs at temperatures between 1800°F to 2200°F(1,21).

On the other hand, EPA studies and pilot scale tests also show that the performance of incinerators could deteriorate significantly during some upset conditions (or so called "failure modes")(22,23). Oxygen enrichment can alleviate many of the failure modes. One of the important failure modes is the occurrence of flameout. This failure mode can clearly benefit from oxygen enrichment which improves flame stability. Poor atomization, low combustion temperature and slow evaporation of liquid waste have been cited as important failure modes (24). Although atomization of waste depends mostly on the burner system design, oxygen enrichment has been shown to improve evaporation of liquid waste by raising the intensity of the flame and therefore improving the burnout efficiency of waste (25).

Transient Emissions Control

Another important failure mode is transient emissions (puffs) from incinerators. When high-BTU wastes are fed into rotary kiln incinerators in an intermittent mode, the transient combustion behaviors of these materials create unsteady releases of combustible gases which may momentarily exceed the oxygen supply to the incinerator. These temporary oxygen-deficient conditions can cause the release of products of incomplete combustion (PICs) which are often called "puffs". These "puff" phenomena have raised public concerns recently and have been the subject of research projects sponsored by the EPA (26,27).

It has been suggested that the higher partial pressure of oxygen in the combustion chambers available with oxygen enrichment, can alleviate the temporary oxygen-deficient conditions. This approach, the subject of a recent EPA study reporting mixed results, is discussed later in this paper (28). In addition, it should also be noted that too high an oxygen level is not only inefficient, but may also cause high NOx emission level (28). Therefore, oxygen enrichment, per se, may not be an ideal solution to the transient puff problem.

On the other hand, advanced process control techniques utilizing advanced process sensors and dynamic oxygen injection can reduce puff occurrences significantly (20). Properly designed computer-control algorithms can automatically adjust the amount of oxygen according to unforeseen changes in the heating value of the waste.

Such benefits are more difficult to achieve with conventional air systems. The main reason for this difficulty is that the critical process variables of temperature, residence time and oxygen feed are inter-dependent when combustion air is used. For example, an increase in the excess oxygen level in the combustion chamber would carry enough associated nitrogen to lower the temperature and the residence time of combustion gases and possibly cause the loss of kiln vacuum.

If oxygen is used in place of air for excess oxygen level control, and auxiliary fuel and/or dynamic water spray is used to control incinerator temperature variations, the above process variables can be controlled independently without adversely affecting the others.

TECHNICAL CONSIDERATIONS IN THE USE OF OXYGEN IN INCINERATION

For many years industrial furnaces have used oxygen enrichment of the combustion air and oxygen-fuel burners, but with conventional technologies a high enrichment level may pose problems. The flame temperature is typically high, leading to potentially high NOx formation and local overheating.

Various techniques exist for introducing oxygen into industrial furnaces. The selected technique depends on the desired results and the present limitations of the furnace. Oxygen enrichment can be achieved quite inexpensively through routine enrichment of the combustion air. However, general enrichment techniques are typically limited to a level of 5 percent (26 percent oxygen in the oxidant) due to increased flame temperatures.

Oxygen-enriched combustion can also be accomplished by strategically injecting the oxygen into the furnace using either lances or oxy-fuel burners. Undershot lancing of the existing air-fuel burners is a beneficial technique for significant production increase in most rotary kilns. The advantage of this method over general enrichment is that only the segment of the flame facing the solid bed (load) is enriched. The bulk of the main flame shields the refractories from the high flame temperature produced at the point of oxygen impingement.

Oxygen-fuel burners, which offer greater flexibility in heat distribution, are applicable for production increases as high as 100%. Conventional oxygen-fuel burners also tend to produce a high temperature flame and high NOx formation. They are used quite commonly in applications such as auxiliary burners in electrical arc furnaces for scrap melting, and recently in glass melting furnaces.

In order to overcome the disadvantages associated with conventional oxygen combustion technologies noted above, the patented LINDE® Aspirator Burner (or "A" Burner) was developed by the Linde Division of Union Carbide (31,32). The key feature of the "A" Burner is that the furnace gases are aspirated into the oxidant jets prior to mixing with the fuel, as explained in references 32 and 33. By maintaining sufficient distance between high velocity oxygen jets and the fuel flow, enough of the furnace gases can be aspirated into the oxygen jet prior to mixing with the fuel so that the resulting flame temperature can be reduced to a value equivalent to an air flame temperature. Gas mixing and recirculation within the furnace are accomplished by the mixing effect of the high velocity oxygen jets, which results in a uniform temperature distribution within the incinerator.

Nitrogen Oxides

The nitrogen oxides (NOx) emissions due to thermal fixation of ambient nitrogen are strongly dependent on the flame temperature. They depend not only on the particular burner design, but also on the furnace temperature, the post-flame oxygen partial pressure, and the nitrogen content of the furnace gases. A recent study sponsored by the Department of Energy (DOE)(35) obtained extensive NOx data on various oxygen-enriched combustion conditions. The burners tested represented both conventional air-fired designs and oxygen/fuel burners designed primarily for very high oxygen levels. The four burners tested were:

- Bloom® Engineering Hot Air Burner
- Maxon Kinemax® Burner
- Maxon/Corning Oxytherm® Burner
- LINDE "A" Burner

The Bloom Burner and the Maxon Kinemax Burner are conventional air-fired designs. These two burners were selected for this project as representative of a large number of current industrial furnace installations. These burners are not necessarily optimized for oxygen-enriched air firing or low emissions. They are typical examples of industrial burners with non-water cooled refractory burner tiles. The Oxytherm Burner was developed jointly by Maxon and Corning Glass for the application of oxygen/fuel combustion in glass furnaces. The burner is also a non-water cooled refractory design with a specially designed refractory exit which shapes the flame while withstanding high flame temperatures. The Oxytherm Burner tested was designed for operation with essentially pure oxygen, that is, 90-100 percent oxygen, as the oxidant. The design basis for the LINDE "A" Burner was discussed earlier.

Referring to Figure 4, this DOE study showed that for conventional air burners NOx emissions increased sharply (up to 2.2 lb NOx/MMBTU) as the level of oxygen enrichment was increased in the range of 35-50 percent oxygen. However, the LINDE "A" burner showed low NOx emissions for the entire range of 35-100 percent oxygen. The lowest NOx emissions were achieved at 100 percent oxygen (0.01 to 0.03 lb/MM BTU) due to the low partial pressure of nitrogen in the furnace. However, for incinerators under even a slight vacuum, close to 100% oxygen would be very difficult to achieve due to the inevitable air infiltration.

More recently, in the EPA Mobile Incinerator trial burn tests using the LINDE "A" Burner (20), NOx emissions were 0.07 to 0.18 lb/MMBTU. In a separate pilot test using the Pyretron(TM) Burner by American Combustion, Inc., EPA reported NOx levels that averaged between approximately 1.1 to 2.6 lb/MMBTU. More details are given in a later section on these results.

Flame Temperature and Furnace Temperature Distributions

In the DOE study, the different burners demonstrated distinct axial radiant heat flux distributions which changed by varying degrees as the level of oxygen enrichment was increased. Linde's "A" Burner demonstrated the ability to vary its flame patterns and thus heat flux distributions by employing interchangeable oxygen nozzles.

Due to the varying characteristics of waste feeds in hazardous waste incinerators, the control of temperature distribution is both challenging and important. Local hot spots can cause potential refractory damage, and more frequent clinker formation or slag buildup (slagging), which requires eventual shutdown of the furnaces for slag removal. These slags are masses of ash material which have deformed and fused together. This is a condition which occurs approximately between 1800°F and 2500°F; however, the presence of low melting point ash and metals in the waste feed may cause the formation of eutectic solutions with substantially lower melting temperatures. Suspended solid particles can also be melted in a hot flame and later redeposited onto the refractory wall.

The geometric configuration of an incinerator, e.g. a long and narrow rotary kiln, may also present a special challenge in heat distribution. Therefore, the ability of an oxygen-enriched burner system to control both its flame temperature and the furnace temperature distribution in a hazardous waste incinerator is critical in order to achieve the maximum benefits.

RECENT TECHNICAL AND COMMERCIAL DEVELOPMENT

While oxygen combustion is used more commonly in the metal industries, its use for full-scale hazardous waste incineration is now emerging.

ENSCO/Pyrotech tested the use of oxygen enrichment up to 50% O_2 in an early liquid injection mobile incinerator for the destruction of PCBs (36). This system used a water-cooled burner block to withstand the high flame temperature (over 4000°F). Extremely high NOx emissions (over 5000 ppm) and burner maintenance problems were cited as deterrents to the use of oxygen. In addition, ENSCO's original incentive for using oxygen was to achieve a high flame temperature, but they found that such temperatures were not necessary to achieve a 99.9999% destruction and removal efficiency (DRE) (37).

According to a recent review paper (6), ThermalKEM (formerly Stablex) in

Rock Hill, South Carolina, has been using oxygen enrichment on their (35 MM BTU/hr) Consumat dual chamber incinerator since 1986 by enriching the combustion air to the upper chamber (afterburner) to the 25-26% O_2 level. Reportedly, this technique was successful in eliminating high CO excursions caused by batch loading of solid wastes.

In Japan, a bench-scale oxygen burner was developed by Nippon Sanso K.K. to incinerate pure PCBs at about 5 lb/hr. Excellent destruction efficiency was reported (>99.9999%) with a temperature more than 2700°F (38).

In Europe, during 1985(39) Union Carbide Europe (UCE) in conjunction with Studiecentrum voor Kernenergie (SCK) in Mol, Belgium successfully replaced an air-oil burner with an oxygen-oil burner in a small high temperature slagging incinerator treating radioactive and hazardous waste, doubling the capacity. A scale-up unit of a similar design will be operational in 1989.

In addition, UCE has been assisting a customer in France since July 1987 in using oxygen enrichment at a large commercial rotary kiln incinerator. Originally the slow evaporation of water from the liquid wastes led to a long and lazy flame which extended the length of the combustion chamber. Oxygen enrichment of up to 24% is used to shorten the flame length significantly. It also helps to stabilize the burner operation despite product inconsistencies and variations. A 100% production increase of liquid waste with low to medium heat content (900 to 5000 Btu/lb) was effected from the use of oxygen enrichment (25).

Recently, the U.S. EPA has evaluated separately two modern oxygen combustion technologies using dissimilar approaches: the LINDE Oxygen Combustion System by the Linde Division of Union Carbide Industrial Gases Inc. and the Pyretron burner(30) by American Combustion Inc. (ACI). The Pyretron burner was tested earlier in a bench scale rotary kiln simulator at the EPA Research Triangle Park (RTP) Laboratory. It was later tested in a pilot scale rotary kiln incinerator at the EPA Combustion Research Facility (CRF) in Arkansas. Test results for both programs have been recently reported. The pertinent conclusions about oxygen combustion with the ACI burner from the RTP test were(28):

(1) It is hard to draw conclusions regarding the individual effects of oxygen enrichment on transient puffs due to the confounding effects of temperature, oxygen partial pressure, and total oxygen feed rates.

(2) Oxygen enrichment may cause unacceptable emissions of NOx. Concentrations as high as 1500 ppm (corrected at 7 percent oxygen) were reported for higher oxygen enrichment levels (up to 30%).

In the CRF test of the ACI burner conducted in late 1987(29), the waste stream selected for the test was a mixture of waste material from the Stringfellow Superfund site and decanter tank tar sludge (listed waste K087). The resulting waste stream had a heat content of approximately 8600 BTU/lb. The base test using air burners had a feed rate of 105 lb/hr. The maximum feed rate using Pyretron burners in both the kiln and the afterburner was 210 lb/hr. Water injection was used to control temperature in the kiln. In all tests DREs exceeded 99.99%. The effect of the Pyretron on transient emissions could not be directly ascertained. Transient emissions, as measured by CO spikes, were obtained during operation of both the air burner and the Pyretron burner. However, the pattern of these emissions showed too much variability to conclusively state whether the Pyretron reduced transient emissions. NOx data have recently been reported for these tests (45). NOx emission levels from this operation of the American Combustion burner system averaged 725 ppm to 1753 ppm at about 9% CO_2 and 15% O_2 (approximately 1.1 to 2.6 lb NOx/MMBTU).

A LINDE Oxygen Combustion System was installed in the EPA Mobile Incineration System (MIS) in June, 1987 to replace an air burner on the rotary kiln (20,40). The LINDE pure oxygen burner normally supplied over 60% of the overall oxygen in the kiln, the rest coming principally from the kiln air leakage. The capacity of the modified MIS was more than doubled with the use of oxygen. The original maximum throughput of dioxin contaminated soil was about 2000 lb/hr. The system capacity was easily increased to 4000 lb/hr as confirmed by certified verification tests. Based on these test results, a RCRA Part B permit was extended and modified for the EPA MIS. Also, trial burn tests of the unit with PCBs and other RCRA listed POHCs in solid and liquid matrixes showed DREs surpassing EPA standards at solid waste feed rates of about 4000 lb/hr.

According to the trial burn results(41), NOx emission levels from the Linde oxygen system averaged between 54.6 and 138.3 ppm at about 15% CO_2 and 7% O_2 (0.07 to 0.18 lb NOx/MMBTU) which compare favorably with the data from the previous air system levels obtained in the 1985 trial burn(42) (between 126-166 ppm at about 11% CO_2 and 7% O_2 or 0.19 to 0.235 lb NOx/MMBTU). Also for the incineration of solid wastes with high heat content, kiln "puffs," as measured by CO spikes, were virtually eliminated with the help of Linde's proprietary oxygen feedforward-feedback system. It was found that the tendency of the rotary kiln to slag was not aggravated from the use of the LINDE Oxygen Combustion System when the flame pattern was adjusted correctly. This experience has shown that when the system is operated with a good understanding of the process and waste feed characteristics, the occurrence of slagging is minimal (43).

The EPA MIS, after its modifications, was used to decontaminate more than 5 million pounds of soil from several dioxin-contaminated sites in southwest Missouri. EPA has found that it is both more economical and more reliable to use the modified Mobile Incinerator equipped with the LINDE Oxygen Combustion System than the previous air system (43). Since the EPA Mobile Incinerator is to date the only incinerator in the U.S. with a RCRA permit to incinerate dioxin contaminated waste, EPA used the modified MIS to incinerate over 2 million pounds of brominated sludges contaminated with dioxin from sites in southwestern Missouri(43,44).

Recently, the LINDE Oxygen Combustion System has also been demonstrated successfully in a transportable incinerator with a system capacity many times greater than the EPA MIS. Results of this installation will be published at a later date. Also, the Army Corps of Engineers recently awarded a $52 million incineration contract for a major Superfund site to a contractor using the LINDE Technology.

ECONOMICS

With all the technical benefits, the success of oxygen combustion technologies also depends on the economic impact of using oxygen. The principal economic benefit from oxygen combustion is derived from the very significant throughput improvement. The large fixed portion of daily incinerator operating costs (typically $10,000 to $30,000 per day) is spread over a much larger quantity of waste processed. For example, for mobile/transportable incinerators a doubled throughput can reduce the allocated incineration cost of contaminated soil by typically $100 to $500 per ton of waste, while the cost of oxygen required is typically less than $50 per ton of waste incinerated.

In addition, whenever supplemental fuel is required for incineration, the fuel savings by using oxygen can offset the cost of oxygen and often show a net cost savings based on fuel savings alone. The economics of using oxygen to save fuel, of course, depend on the relative cost of fuel and oxygen. For example, at the EPA MIS a remarkable specific fuel savings of 50 million Btu per ton of oxygen used was demonstrated (20). Assuming a No. 2 fuel oil cost of $0.60 per gallon or $4.40 per million BTU, the break-even oxygen cost is $220 per ton of oxygen. The actual cost of oxygen ranges from about $50 per ton of oxygen produced by a large on-site facility to about $120 per ton for delivered liquid oxygen.

CONCLUSION

Recent technology innovations have demonstrated the significant advantages of using oxygen in the field of hazardous waste incineration. Common concerns associated with conventional oxygen combustion such as local overheating and high NOx emission are valid. Advancements in combustion technology to overcome those problems have been demonstrated in extended field operations.

While the general principles discussed in this paper would apply to most situations, the best method to employ oxygen varies with each individual incineration system as well as with the profiles of the waste feed. The application of sophisticated technological know-how is often required. The process economics also change from site to site and need to be analyzed on a case by case basis, although frequently the benefits of oxygen far exceed its cost if used intelligently. The increasing use of oxygen combustion in commercial incineration applications speaks well for its economic and technical attractiveness.

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Disclaimer

The work described in this paper was not funded by the U.S. Environmental Protection Agency. The contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

Table 1

COMPARISON OF FUEL FLAMMABILITY LIMITS IN AIR AND OXYGEN (5,6)

Fuel	Flammability Limits (vol% fuel) Lower Air	Lower O_2	Higher Air	Higher O_2
Hydrogen, H_2	4	4	74	94
Carbon monoxide, CO	12	16	75	94
Ammonia, NH3	15	15	28	79
Methane, CH4	5	5	4	61
Methylene Chloride	*	16	*	66
Vinyl chloride	4	4	22	70

* Not flammable in air

Table 2

APPROXIMATE FLAME TEMPERATURES OF SELECTED FUELS AT STOICHIOMETRIC RATIOS (12)

Fuel	Air K	Air °F	Oxygen K	Oxygen °F
Acetylene	2600	4220	3410	5680
Carbon monoxide	2400	3860	3220	5340
Heptane	2290	3660	3100	5120
Hydrogen	2400	3860	3080	5080
Methane	2210	3520	3030	4990

Table 3

EFFECTIVENESS OF OXYGEN ENRICHMENT FOR THROUGHPUT INCREASE

Limitations	Effectiveness of O_2/O_2-Enrichment
THERMAL CAPACITY	Effective
Air Blower	
Fuel Supply	
Burner	
Incinerator Draft	
Air Pollution Control System	
Combustion Gas Residence Time	
DUST CARRYOVER	Effective
MECHANICAL SOLID PROCESSING CAPACITY	No Effect
HEAT TRANSFER	Conditionally Effective

Figure 1

FUEL REQUIREMENT TO PROVIDE 1 MM BTU OF AVAILABLE HEAT

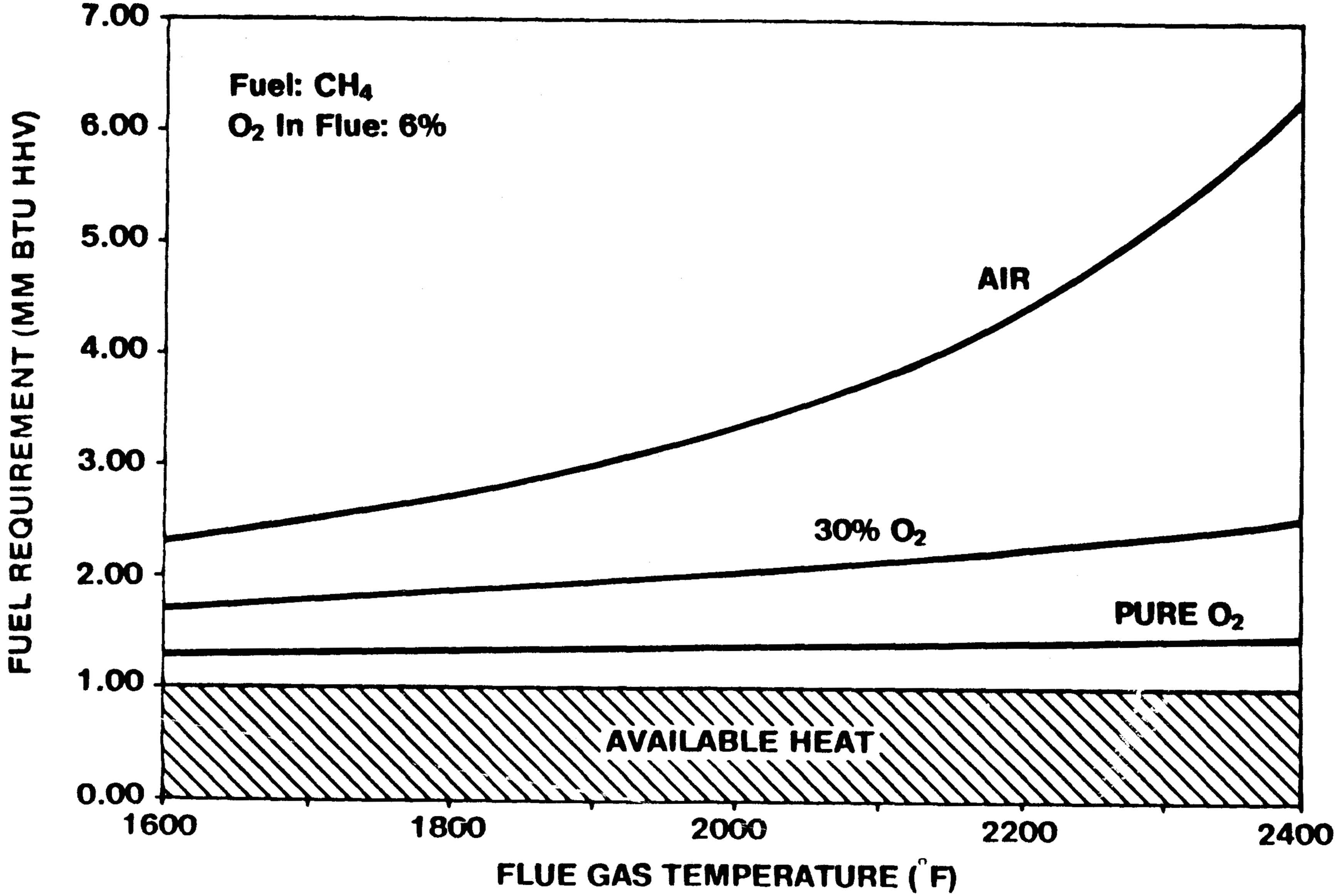

Figure 2

FUEL SAVING WITH OXYGEN - METHANE GAS

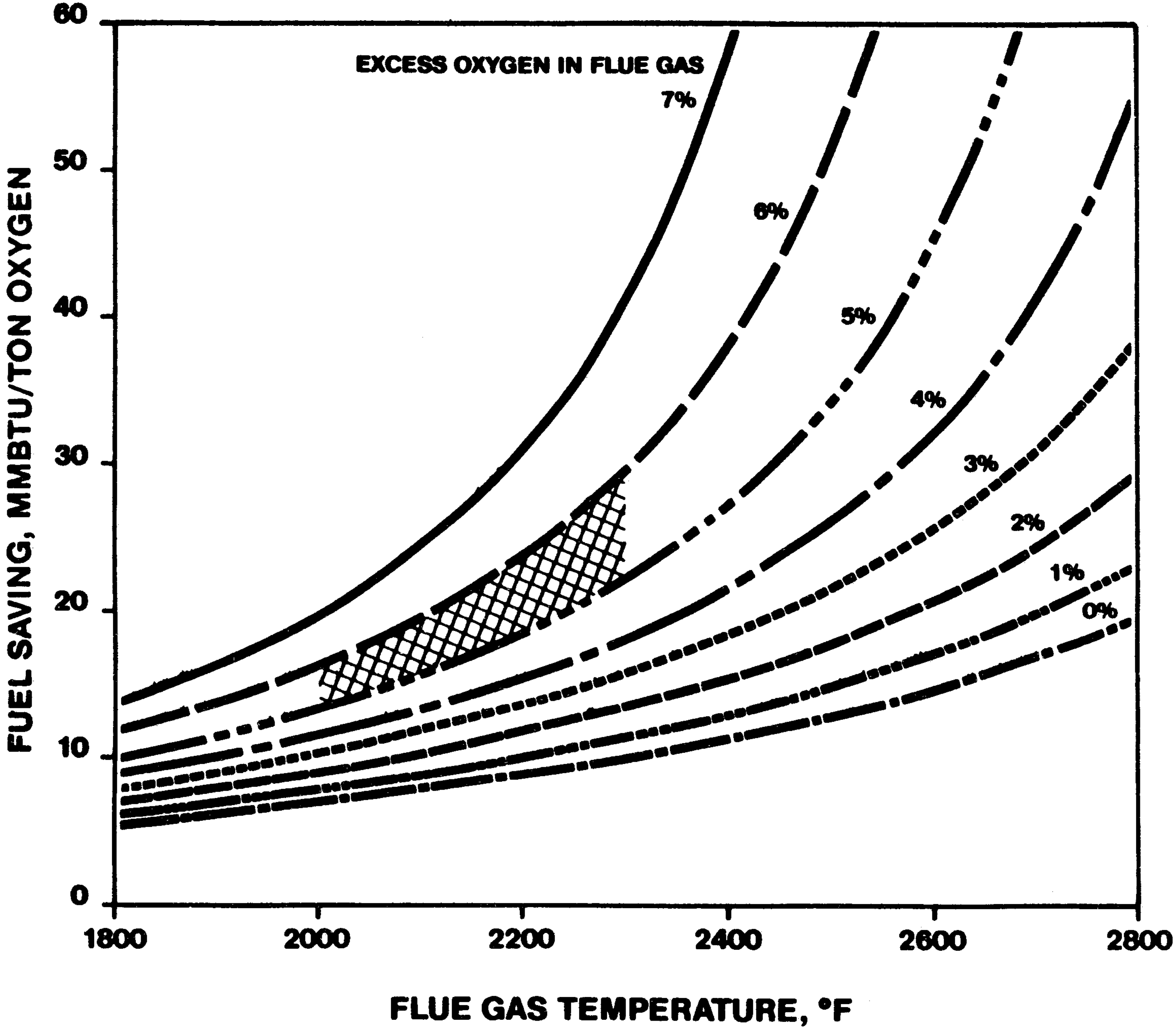

Figure 3

FLUE GAS VOLUME REDUCTION WITH OXYGEN
FUEL: METHANE; FLUE GAS AT 2000 °F, 6% EXCESS O_2

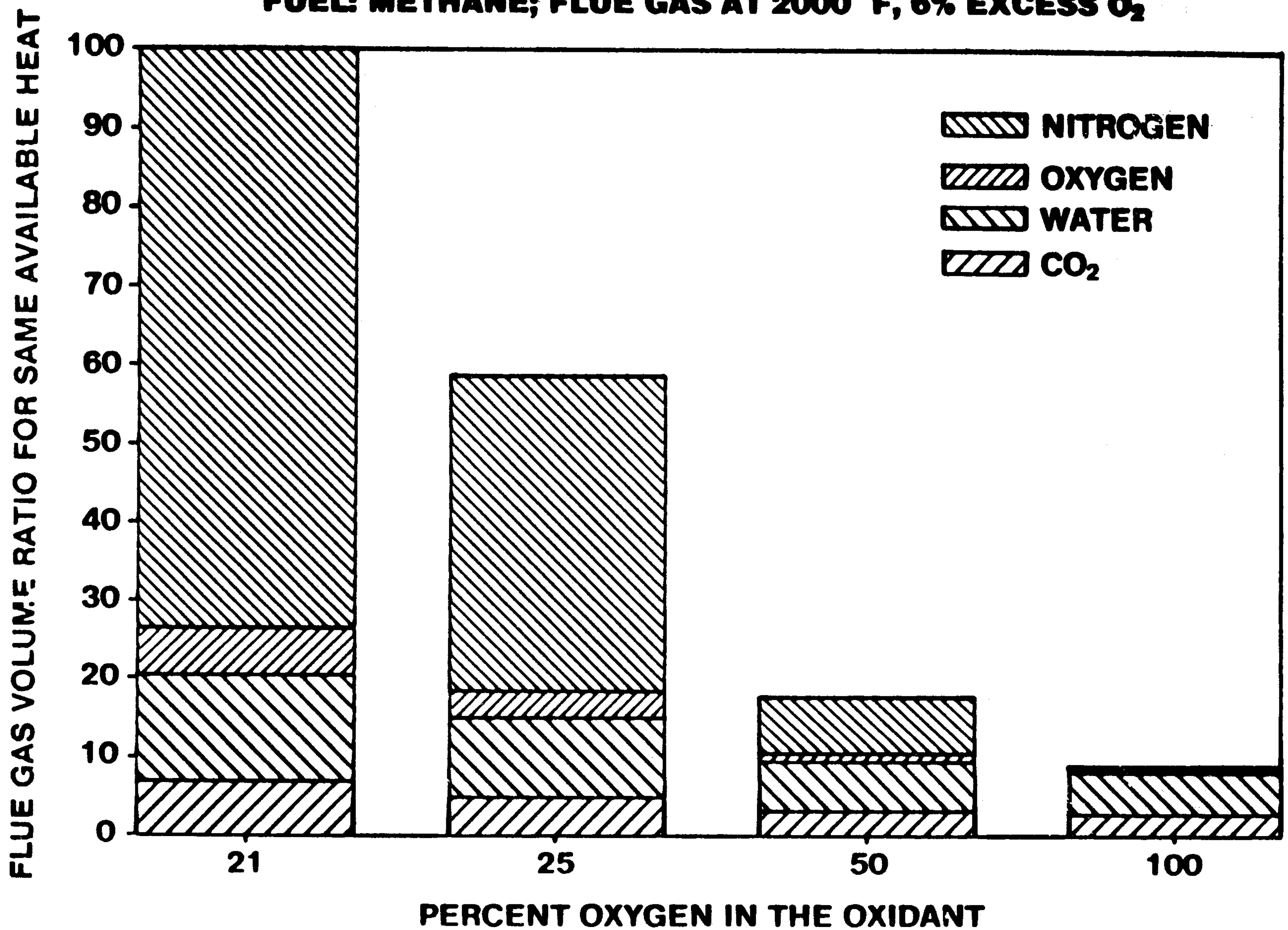

Figure 4

SUMMARY OF NOx EMISSIONS

FUEL: NATURAL GAS EXCESS O_2 = 2% (DRY)

SOURCE: DOE STUDY