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Project Summary

Destruction of VOCs by a Catalytic Paint Drying (IR) Device

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Volatile Organic Compounds (VOCs) are emitted from a number of different types of sources, one of which is paint drying and curing ovens. A device that catalytically oxidizes fuel to generate infrared (IR) radiation recently has been introduced by SUNKISS Thermoreactors, Inc., as a new technology for paint drying and curing. During its operation, the device also oxidizes some of the paint solvents that are evaporated in the oven, thus reducing overall emissions of VOCs into the atmosphere.

A system was constructed at the University of Central Florida (UCF) to experimentally test the SUNKISS device, to quantify its VOC destruction capabilities. The system consists of flow control and measuring devices, analytical equipment, and a 1m³ chamber in which the SUNKISS device was mounted. Three paint solvents—hexane, methyl ethyl ketone (MEK), and toluene—were dispersed in air streams that flowed through the chamber at various rates. The solvent destruction efficiency of the device was shown to be a strong function of the air residence time in the chamber, but was independent of VOC concentration. Hexane and MEK behaved similarly, while toluene was more reactive. Observed VOC destruction efficiencies ranged from less than 20 to over 50%. Some slight degree of fuel non-combustion was observed, as was a very small amount of CO generation.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Volatile Organic Compounds (VOCs) are emitted from a number of different types of sources, one of which is paint drying and curing ovens. In conventional ovens, items are dried by hot air or by electric infrared (IR) lamps. The solvents that evaporate are discharged to the atmosphere with the dryer effluent air unless that air is routed through a Final Control Device (FCD), such as an incinerator. Solvent concentrations in the oven exhaust air are typically 100-1000 ppm.

The amounts and types of VOC emitted from any process depend greatly on the type of paint, the type of process, and the configuration and rate of air flow through the paint booth, flash dryer, and oven. Many VOCs are photochemically reactive and can contribute to high oxidant levels in the ambient air. As a result, many large paint drying and curing operations have been required to reduce emissions of VOC to the atmosphere.

Recently, a novel type of paint drying device was introduced commercially. It oxidizes fuel gas on a catalyst and emits IR radiation in wavelengths adsorbed by paint pigments. A number of such devices are placed in the oven and oriented toward the painted parts to dry and cure the paint. According to tests by the manufacturer, the SUNKISS units achieve significant energy savings com-

pared to conventional hot air or IR (electric) lamp ovens. Recent installations of the SUNKISS system include several automotive, bus, and truck painting facilities in the U.S. and Canada.

Another benefit of the device is that some of the solvent vapors in the oven are oxidized on the catalytic surface during the drying process. Because of this concurrent VOC destruction, total mass emission rates of VOC from the oven can be reduced substantially. The degree of VOC destruction was of interest to the U.S. EPA and the American Electroplaters' Society because of the potential benefits of the device to the environment and to industry.

The main objective of the study conducted at UCF was to quantify the VOC destruction efficiency of the SUNKISS device under controlled laboratory conditions. Secondary objectives were (1) to test the effect on the VOC destruction efficiency of a painted object placed in the oven, and (2) to test the effectiveness of recent engineering modifications (i.e., a higher pressure fuel jet and thicker catalyst pad) on the VOC destruction efficiency.

Experimental Equipment and Procedures

System Description

The experimental apparatus, constructed specially for this project, is shown schematically in Figure 1. Basically, the equipment consists of air flow measurement and control devices, a solvent saturator system, a reaction chamber, and sampling and analytical apparatus. House air, filtered through glass wool, silica gel, and activated carbon, flowed through at least two rotameters in parallel. A measured rate of air, bubbled through liquid solvent in a double saturator system, produced a saturated stream of solvent vapor in air at 0°C. That stream, diluted by another measured flow of pure air to create a stream of air at a desired concentration and desired total flow rate, was fed into the reaction chamber.

The reaction chamber is a welded steel box enclosing about $1m^3$ of space. The SUNKISS device was mounted on the side opposite the air inlet, and an exhaust stack was mounted on the top on the inlet end of the chamber. The SUNKISS unit has an internal 60 cfm (1,700 l/min) fan that provided some mixing of the air in the chamber, and was augmented by a 200 cfm (5,700 l/min) fan mounted coaxially with the air flow inlet. The SUNKISS fan blew chamber air across the front face of the catalyst pad; some of the VOC was absorbed and oxidized on the surface of the catalyst.

Several sample lines and thermocouples were at strategic locations in the chamber. Samples were withdrawn by a vacuum pump through a gas sampling valve mounted on an ANTEK 2400 chromatograph equipped with a flame ionization detector. Samples were also routed to a Thermoelectron Model 48 CO analyzer.

Flow Measurement and Control

Air flow was measured and controlled, using manually controlled rotameters, each calibrated carefully with either an accurate wet test meter or an accurate dry gas meter. UCF house air first was passed through a filter package consisting of a layer of glass wool, followed by granular activated carbon, silica gel, and glass wool. The air was then split into four possible streams, the flow rate of each of which could be individually measured and adjusted. Piping permitted the main air flow rate to bypass the solvent saturator system, while one, two, or three of the other streams were routed through the saturator. Thus, almost any combination of total air flow rate (2-8 cfm; 57-227 l/min) and solvent-in-air concentration from 200 to 2000 ppm could be created and maintained during the operation.

Solvent Saturator System

The solvent saturator system produced a reproducible and reasonably
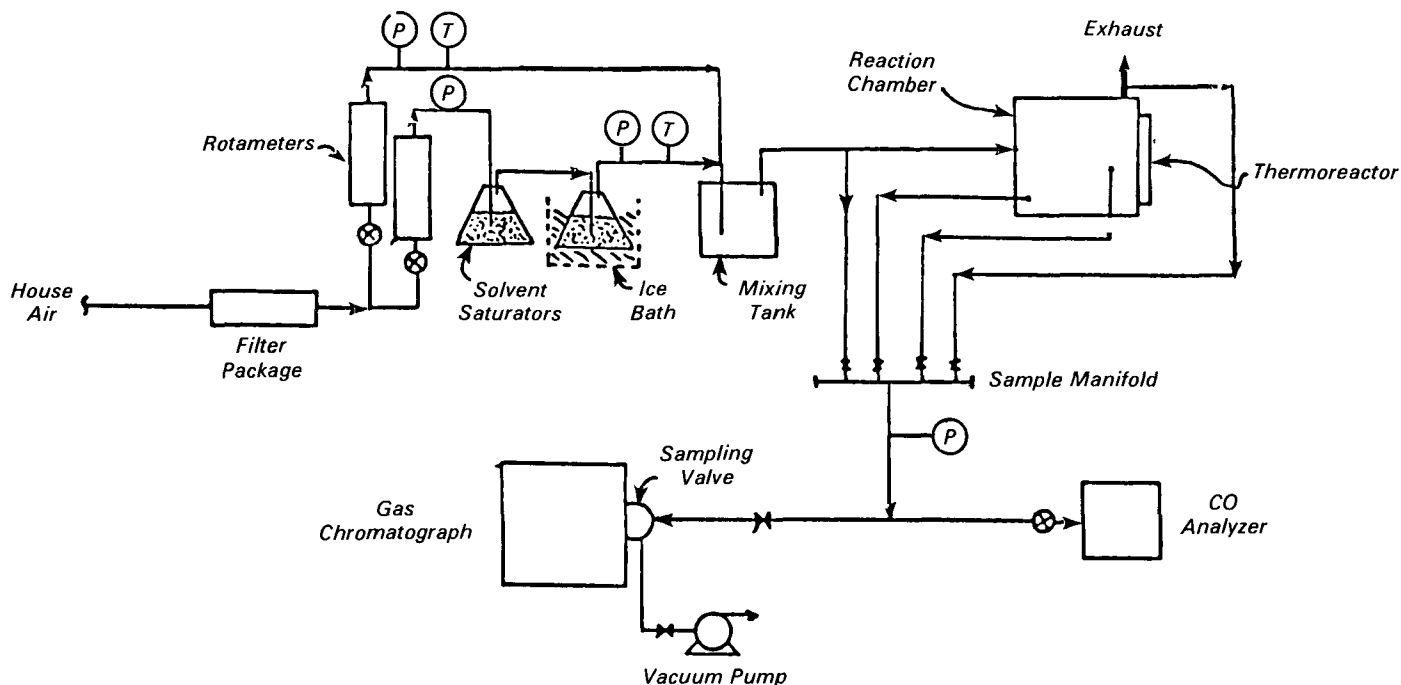

Figure 1. Schematic flow diagram of system.

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accurately known concentration of VOC in air. A wide range of concentrations could be produced by blending a stream of solvent-free air with an independently controlled stream of completely saturated air.

Primary air was passed through a dual saturator system consisting of two 1000 ml Erlenmeyer flasks, Teflon tube bubblers, and a copper cooling coil. Saturation of 40-50% was obtained in the first stage which operated at 25°C. The air then was passed through copper coils submerged in a 10°C water bath and then into a second saturator, surrounded by a 0°C water/ice bath. In the second stage, 100% saturation was achieved due to additional vapor/liquid contact, and probable condensation of VOC picked up in the first saturator. Dilution air was metered through a second calibrated rotameter, bypassing the saturator system, and was blended with the saturated stream to achieve desired concentrations. A mixing tank ensured complete mixing prior to the combined stream's flowing to the reaction chamber.

Reaction Chamber

The chamber was designed to enclose about $1m^3$ of space. The chamber was built from 11-gauge steel welded at all seams. Thus, it was structurally sound, leakproof, able to withstand all possible operating temperatures, and did not have any potential for self-emission of fumes (as plywood or composites might). The SUNKISS unit was mounted at the end of the chamber, opposite the air entrance.

The inlet gas (the premixed stream of air with a low concentration of VOC) entered through a diffuser-type entrance near the bottom of the chamber and directly across from the SUNKISS unit. Both the total inlet gas flow rate (2-8 cfm; 57-227 l/min) and the inlet VOC concentration (from about 200 to 2000 ppm) could be independently controlled. Inlet and outlet gases were monitored for concentration and temperature (sample ports built into the chamber enabled samples to be taken from within the chamber).

Test Procedure

A typical experimental run is described below. All instruments (i.e., gas chromatograph, Co analyzer, chart recorder) were allowed sufficient time for warmup and stabilization. The appropriate solvent was poured into the aturators, and all fittings were checked for leaks. The GC column temperature was adjusted (based on experience in this study) to provide the most consistent and accurate results for each solvent used.

The individual stream flow rates to achieve desired solvent concentrations and total inlet air flow rates were adjusted via inline rotameters. To ensure representative results, steady state conditions had to be maintained in the test chamber. The chamber average residence time, t_R (chamber volume/air flow rate), varied for the different flow rates. At each different flow rate, sample testing was delayed a period of $4 \times t_R$.

Each time a sample was analyzed for VOC, three or four samples at 1 minute intervals were analyzed, and the average of the peak heights on the chart recorder was allowed to represent the true VOC concentration. Chamber inlet and outlet samples were taken. The mean of the outlet solvent peaks was compared to the mean of the inlet tank peaks, and both were recorded. CO was also measured. Propane peaks were also observed and recorded. VOC destruction efficiencies were calculated based on inlet air molar flow rate × VOC inlet concentration vs. estimated outlet gas molar flow rate (including propane combustion products plus any entrained air) × outlet VOC concentration.

The above procedure was repeated at least three times for each specific test (each air flow rate and concentration), and a final destruction efficiency was calculated as the average of all the replications.

Results and Discussion

Initial Operating Tests

The SUNKISS unit was initially tested with the SUNKISS unit on with only fresh air (no VOC) entering the chamber. A VOC response was observed on the GC, which implied that some uncombusted propane fuel might be escaping into the chamber. Introduction of some hexane into the inlet air and observation of two separate peaks on the GC confirmed that propane gas was indeed entering the chamber. Disappearance of one peak when the propane fuel valve was shut further proved that one peak was propane. Recognition of the problem of propane non-combustion led to more detailed testing during the solvent destruction efficiency tests. In later tests, the percent propane combustion was calculated to be 98-99.8%, depending on the total air flow rate. Also, modifications of the SUNKISS device during the latter part of this research partially alleviated this problem of propane non-combustion. Quantitative propane results will be presented later.

Effect of Solvent Concentration

Several tests were conducted at 170 l/min (6 cfm) air flow, but at different inlet concentrations of hexane in air. Basically, chamber inlet and outlet (and some interior point) concentrations were measured to determine the percentage destruction efficiency of the SUNKISS unit. Because the total molar flow rate out of the chamber was not equal to the inflow rate of solvent laden air (the fuel gas plus entrained ambient air also entered the chamber), the VOC destruction efficiency was calculated as:

$$E = \frac{n_oC_o - n_eC_e}{n_oC_o} = 1 - \frac{n_eC_e}{n_oC_o} \qquad (1)$$

where

n_o = inlet molar flow rate of stream of air with VOC

C_o = inlet concentration

n_e = total molar flow rate of exhaust gases

C_e = exit concentration

Equation (1) properly accounts for the dilution effect; i.e., that VOC concentrations in the outlet stream will be somewhat lower than in the inlet due solely to dilution by the addition of other gases.

It was determined from data supplied by the manufacturer that the propane injection rate was about 0.087 gmole/min. Furthermore, based on data from the manufacturer, the ambient air entrained by the inlet jet of the fuel (the primary air) was calculated to be about 0.133 gmole/min. Complete propane combustion produces 7 moles of gases for 6 consumed. Thus, the total molar flow of gases exiting the chamber was equal to the sum of the moles of solvent laden air flowing in, plus 7/6 times the propane flow, plus the entrained ambient air flow. In other words, the molar flow rate out was equal to moles of solvent laden air in, plus 0.23 gmoles/min. Molar expansion due to oxidation of the VOC was ignored.

Several individual solvent destruction tests were carried out using hexane in air. All replications of individual tests were quite reproducible. Certain con-
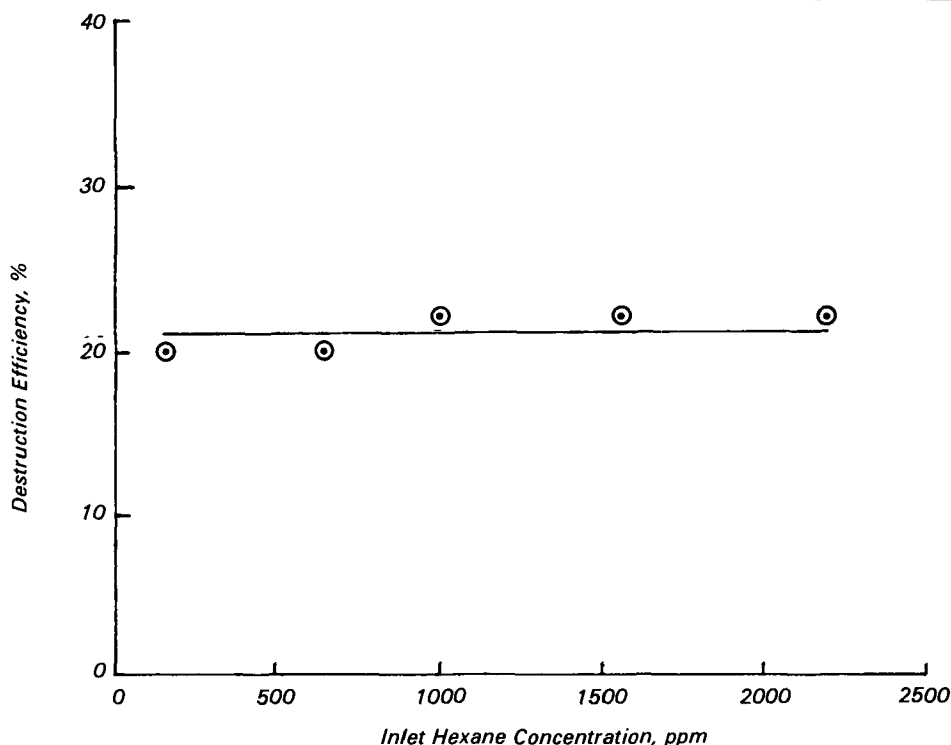
Figure 2. Hexane destruction efficiency vs. inlet hexane concentration.

centrations of hexane-in-air and certain air flow rates into the chamber were replicated as many as five or six times. The destruction efficiency for each test never varied more than 2 percentage points from the mean. The results are shown in Figure 2.

Effect of Chamber Residence Time

After it was shown that destruction efficiency was essentially independent of inlet hexane concentration, the effect of inlet air flow rate was investigated. For a fixed volume chamber, the volumetric air flow rate into the chamber is related to the inverse of the average residence time. The average residence time in a CSTR is actually best calculated by the volume of the chamber, divided by the exhaust (as opposed to the inlet) gas rate. In these experiments, the exhaust gas volumetric flow rate was higher than the measured air inflow rate due to the fuel and primary air inflow, and due to the volume expansion of the gas in the chamber caused by increased temperature. The ideal gas law was used to calculate the outlet exhaust volumetric flow.

Effect of Solvent Type

In addition to hexane, two other common paint solvents were tested: methyl ethyl ketone (MEK) and toluene. In essence, the MEK destruction efficiencies nearly duplicated those observed with hexane. The MEK data trended a slight bit lower than hexane and showed a slight bit more scatter, but the same essential behavior was evidenced. The results for toluene showed significantly more solvent destruction than with either hexane or MEK. All the destruction efficiencies are plotted vs. residence time in Figure 3.

Painted Object Tests

As part of a planned attempt to more closely simulate conditions in a real oven, a painted (black) metal plate was placed in the test chamber during the toluene tests. The plate measured approximately 40 by 65 cm, and was placed normal to the IR from the catalyst pad about 40 cm from the device. The plate simulated a painted part being cured. Destruction efficiencies were increased only about 2 percentage points over what had previously been observed for any given solvent at any given air flow rate.

Two similar steel plates (one was painted and the other was not) were placed in the oven. To each plate, a thermocouple was attached to measure surface temperature. At the start of the test, a steady stream of air was flowing through the oven, and the SUNKISS unit was turned on. The temperature of the painted plate's surface increased quickly to a significantly higher temperature than that of the unpainted plate. At steady state, the painted plate was about 40°C hotter than the unpainted plate, which essentially achieved the inside chamber air temperature.

Effect of SUNKISS Device Modifications

During the course of this research, the manufacturer modified the basic device to increase solvent destruction efficiency and to decrease residual (unburned) propane concentrations. The modifications were basically: (1) smaller fuel jets with an increased fuel supply pressure, and (2) a thicker catalyst pad with more catalyst surface area. Each modification was tested in the UCF experimental test system.

To install the new system, the old catalyst pad and the old fuel injection orifice were replaced with the new ones. The propane fuel pressure was increased from 11 in. H_2O to 2 psig (3 to 14 kPa). Hexane was used as the solvent, and several air flow rates were tested (all at an inlet hexane concentration of 1000 ppm). Three replications were made at each of six flow rates, and hexane destruction efficiencies were determined. Also, propane and CO concentrations were measured at each inlet air flow rate.

The results of the above tests showed a slight (but non-negligible) improvement in VOC destruction. In addition, propane non-combustion with the new system (new pad-new jets) was reduced considerably at all flow rates, compared with that observed with the old system. CO concentrations were lower at the high air flow rates, but higher at the low air flow rates.

In calculating the destruction efficiencies, the increase in dilution effect due to the new jets was accounted for. The new jets were designed to pass the same molar rate of fuel into the SUNKISS device, but at a higher velocity. The higher velocity entrains more ambient air in through the back of the catalyst pad and permits more complete combustion of propane. However,

the additional air adds to the total volumetric flow of gases through the chamber, thus diluting the concentrations of VOC, propane, and CO somewhat compared with the original system.

Estimates of the air entrainment rate of the newly modified system were obtained from SUNKISS, Inc. It had been estimated previously that, with a propane supply pressure of 11 in. H_2O (3 kPa) and with the old jets, about 0.113 cfm (about 0.13 gmoles/min) of ambient air was drawn into the chamber. With the new jets, at 2 psig (14 kPa), the ambient air entrainment rate was about 0.663 cfm or 0.78 gmoles/min. At the lower air flow rates into the chamber (2, 3, or 4 cfm: 57, 85, or 113 l/min), there is significant dilution due to the additional primary air brought in with the new system. (Note that the calculations of destruction efficiencies that follow depend

on the above estimates of air entrainment rates.) The outlet air flow rates from the chamber were not measured in this work.

After accounting for the additional air dilution due to the new jets, the VOC destruction efficiencies were calculated for the new jets—new pad system. Also, because chamber residence times at each inlet air flow rate were decreased due to the additional primary air flow, the residence times were also recalculated. The fairest comparison is to plot the efficiencies against gas residence time as shown in Figure 4. This plot shows that VOC destruction efficiencies did improve with the new system.

To fairly compare propane combustion under the new system vs. the old system, the molar flow rates of propane out of the chamber were calculated under each system. The rate of propane

into the SUNKISS device was assumed constant at 0.10 gmole/min. The percent of propane combusted was calculated for each system and compared for each inlet air flow rate.

To fairly compare CO production under each system, the CO generated was expressed as a percentage of all the carbon atoms combusted. That is, first the molar rate of hexane that was destroyed in the chamber was calculated. Then, that rate was multiplied by the number of carbon atoms per molecule of hexane (six). Next, the molar propane combustion rate was multiplied by the number of carbons in propane (three). The two numbers were summed to give a total carbon atom combustion rate. The molar flow rate of CO exiting the chamber was calculated and divided by the total carbon atom combustion rate to give the CO generation percentage. The propane and CO results are given in Table 1.

Conclusions and Recommendations

The solvent destruction capability of the SUNKISS thermoreactor has been tested under laboratory conditions. This catalytic device has been shown to be effective in oxidizing VOC in air in a completely mixed chamber with destruction efficiencies primarily dependent on air flow rates (residence times) in the chamber. Observed destruction efficiencies ranged from less than 20% to above 50%. The destruction efficiencies were essentially independent of VOC concentration, but were higher for toluene than for either hexane or MEK. These destruction efficiencies were significantly lower than those typical of a final control device (such as a vapor incinerator), but may be high enough to contribute significantly to an overall VOC control program.

Some slight degrees of fuel noncombustion and a very small amount of CO generation were observed, particularly at the lower total air flow rates. The IR generated by the device is absorbed by a painted surface resulting in higher surface temperatures than for unpainted steel, thus enhancing the drying and curing process. The newer SUNKISS system (thicker pad, smaller fuel jets, and higher fuel pressure) resulted in better VOC destruction efficiencies and in more complete propane combustion and is recommended over the older system. The SUNKISS system can dry and cure painted objects and
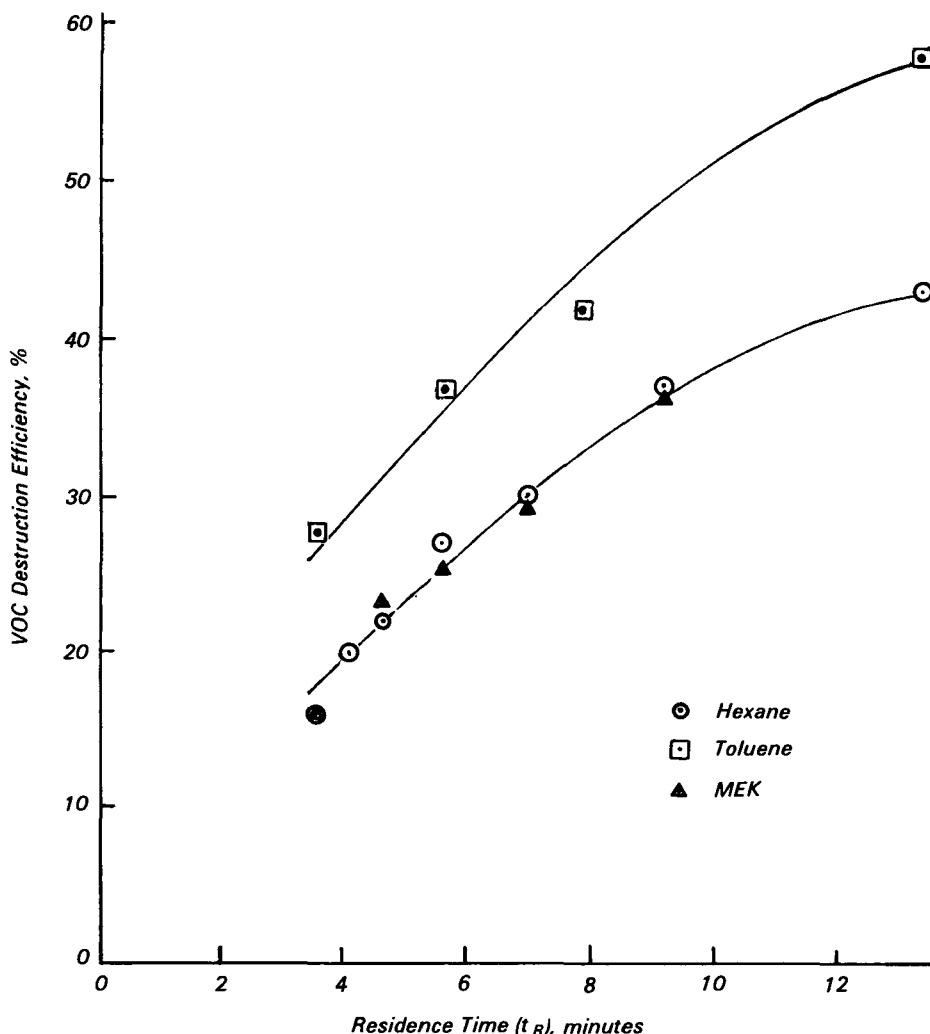

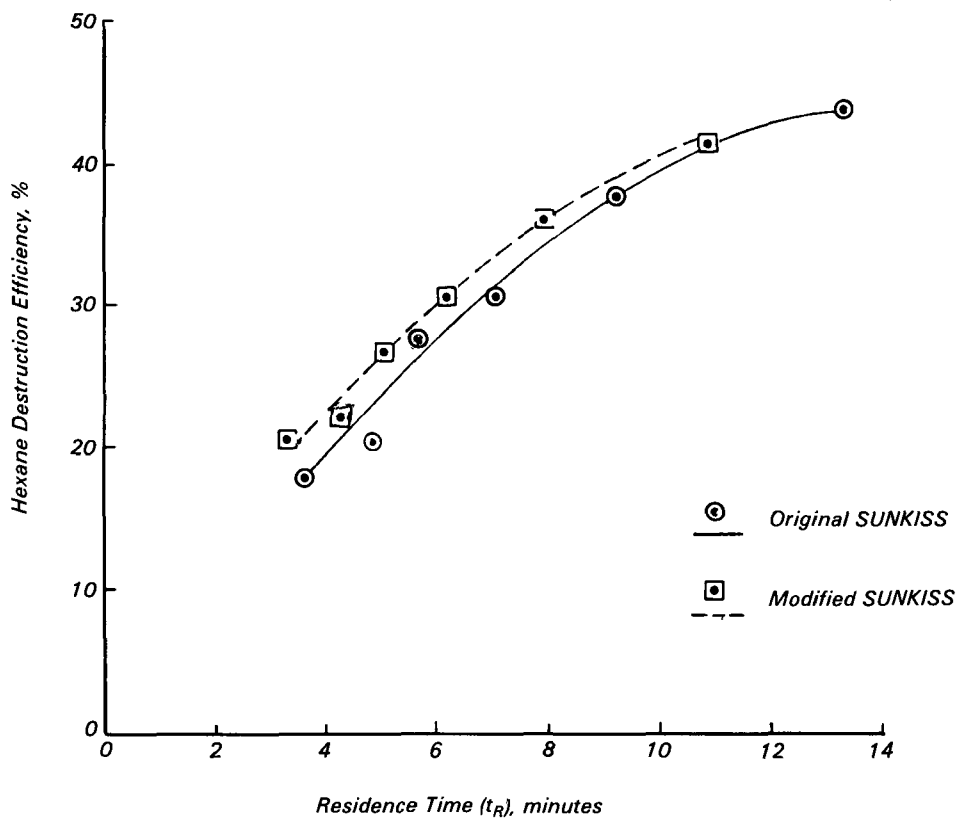**Figure 3.**   VOC destruction efficiency vs. gas residence time.

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Figure 4. Hexane destruction efficiency vs. gas residence time for original and modified SUNKISS systems.

Table 1. Propane Combustion and CO Generation: Modified vs. Original SUNKISS

Inlet Air Flow Rate cfm (l/min)	Original SUNKISS		Modified SUNKISS	
	Propane Combustion[a] %	CO Generation[b] %	Propane Combustion[a] %	CO Generation[b] %
2 (57)	97.8	0.03	99.4	0.07
3 (85)	98.4	0.06	99.6	0.05
4 (113)	98.8	0.08	99.7	0.06
5 (142)	99.2	0.07	99.7	0.06
6 (170)	99.4	0.07	99.8	0.05
8 (227)	99.6	0.07	99.8	0.05

[a]Based on molar flow rates of propane into and out of the chamber.
[b]Based on total moles of carbon atoms combusted.

help reduce VOC emissions to the atmosphere. It is worthy of consideration as part of any proposed operation that involves solvent evaporation inside enclosures.

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