

**The Role of Basic Design Data
in Preventing Explosions within Fired Equipment:
*A Case Study***

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ABSTRACT

The availability, collection, and proper application of accurate and complete Basic Design Data (BDD) are essential aspects of Loss Prevention practice. This paper presents a case study to illustrate the importance of properly collecting and applying accurate BDD when designing Fired Equipment. In the case study presented, an explosion occurred inside a newly installed Catalytic Thermal Oxidizer (CatOx) shortly after initial start-up. Root cause investigation revealed that the project team, in the design and specification of the CatOx control system, had misapplied the BDD. Consequently, this led to operation of the CatOx within the flammability envelope of the particular system, resulting in an explosion.

This paper provides a brief discussion of BDD and its application. The case study is presented in detail using flammability diagrams for the system to demonstrate where the CatOx was intended to operate versus where it actually operated during the incident. The discussion leads the reader through the incident lifecycle, from the conceptual design of the CatOx, through the Engineering and Commissioning phases, and into the Incident Investigation. Thus, emphasizing the impact of BDD on design and performance of Fired Equipment.

INTRODUCTION

Basic Design Data (BDD) refers to a broad range of information that is required for effective and safe designs in the Chemical Processing Industries (CPI) [1]. This information often includes chemical and physical material properties, materials of construction, reliability data, and information on operating history. However, the scope of BDD is not limited to traditional Loss Prevention rudiments, such as those previously listed. In certain cases it may be necessary to complement the scope of data with information from other disciplines (e.g., Occupational Health, Toxicology, Product Stewardship, etc.) to ensure the data is complete. For example, with the introduction of new and more stringent environmental regulations, facilities continue to be faced with the challenge of reducing emissions of Volatile Organic Compounds (VOC) to the atmosphere. A common solution to this challenge is to retrofit an existing operation with an end-of-pipe treatment system such as a Vent Collection and Destruction System (VCDS) [2]. From a Loss Prevention perspective, the success of such an installation becomes highly dependent on coordinating the collection of BDD with appropriate Environmental professionals.

The importance of having complete and accurate BDD when designing fired equipment cannot be underestimated. A review of past incidents from the CPI confirms this concept. There are a number of cases documented where fired equipment has been subject to explosions. The basic cause is the accumulation of a combustible mixture within the equipment, and the subsequent ignition of that mixture within the confined space(s) of the equipment [3]. The fact that an ignition source is nearly always present inside fired equipment in order to maintain controlled combustion increases the risk of having an explosion. Hence, the avoidance of ignition sources is not a credible basis of safety in VCDS design [2].

The remainder of this paper examines an actual incident in which an explosion occurred within a Catalytic Thermal Oxidizer (CatOx) shortly after initial Start-up of the system.

FACILITY BACKGROUND

The subject facility, located in the Commonwealth of Pennsylvania, has several operating units, each manufacturing various grades of Polystyrene type products. In general, the processes involve polymerization of Styrene monomer to produce Solid Polystyrene (SPS) in either bead or pellet form. Products going into the packaging and food service markets are further processed to become Expandable Polystyrene (EPS). EPS is essentially Polystyrene bead that has been impregnated with a blowing agent - namely Isopentane (2-Methylbutane) in the example presented here. The impregnation stage of the process is performed as a batch operation, in which SPS beads are suspended in water and impregnated with Isopentane. The batch vessels are inerted with nitrogen throughout the entire process to reduce the risk of fire and explosion.

In the 2002-2003 timeframe, a project was initiated to increase production of an EPS-type product by nearly 800% over the next three to four years. The expansions were planned to occur in several phases in an effort to maintain satisfactory production levels while minimizing outage time.

It was evident that Isopentane emissions would significantly increase as a result of this expansion. Isopentane, a VOC, was already present in the process at various locations, beginning with the impregnation vessels and ending with the packaging line. While the early stages of the project would not be adding new point sources of VOC emissions, the increase in throughput rates would, in fact, substantially increase Isopentane emissions from the facility. Thus, it was necessary to implement measures to collect and destroy these emissions for compliance with the facility's environmental permits.

The project team was charged with the task of determining a suitable technology for collecting and destroying the Isopentane emissions. Thermal oxidization presented itself as the logical choice by offering very high Destruction and Removal Efficiencies (DRE) along with the flexibility of several (potentially) different equipment designs. Thermal oxidization is the process of oxidizing flammable and combustible materials by raising their temperature above the auto-ignition temperature in the presence of oxygen, and maintaining that temperature for sufficient time to complete the oxidation reaction [4,8]. The resulting Products of Combustion (POC) from this process are simply CO₂ and H₂O.

Four primary types of thermal oxidizers are available to the designer: Direct-Flame Thermal Oxidizers; Recuperative Thermal Oxidizers; Regenerative Thermal Oxidizers; and Catalytic Thermal Oxidizers. Catalytic Thermal Oxidizers offer several unique advantages over the other varieties listed [4]. Most important to this project is their ability to operate in an environment that frequently cycles on and off, such as that of a batch operation. Furthermore, Catalytic Thermal Oxidizers are more tolerant of high VOC concentrations, and are attractive from a capital cost perspective.

COLLECTION OF BASIC DESIGN DATA

A number of methodologies have been published [2,4] that provide guidance for designing thermal oxidizers, and in general they begin with identifying and characterizing the waste gas streams. The project identified five waste gas streams that would be collected and piped to the Catalytic Thermal Oxidizer (CatOx). Figure 1 provides a listing of these streams, along with the flow rate and Isopentane concentration data provided to the project team for each stream.

Source	Type	Avg Flow (SCFM)	Max Flow (SCFM)	Avg Conc (% i-C5)	Max Conc (% i-C5)	Stream Balance
(2) Reactors Vent/Purge	Batch	55	68	6.7	8.0	Nitrogen
Conveyor Exhaust	Continuous	643	665	0.33	0.56	Air
Packaging Vent	Continuous	102	103	0.016	0.058	Air
Packaging Exhaust	Continuous	897	970	0.18	0.32	Air
Oxidizer Design Basis	Continuous	1,855	2,100	0.24	0.30	Air

Figure 1. Catalytic Thermal Oxidizer Waste Streams

The two streams collected from the reactor venting and purging operations are *Contaminated inert-gas streams*. In other words, these streams contain high concentrations of Isopentane (HVOC) in nitrogen. However, the other three streams are characterized as *Contaminated air streams*, as they contain low concentrations of Isopentane (LVOC) in air. Note the relative differences in the reported flow rates of the two types of waste streams. Although the Isopentane concentrations in the contaminated inert-gas streams are significantly higher, the reported flow rates for these streams are several orders of magnitude lower than the contaminated air streams.

Flammability data for Isopentane and the range of possible mixtures that could be formed were also assembled. Figure 2 lists the relevant flammability data for Isopentane.

Molecular Weight	72.2
Boiling Point	82 deg F / 28 deg C
Flash Point	-60 deg F / -51 deg C
Autoignition Temperature	800 deg F / 426 deg C
Lower Flammable Limit (LFL), v% fuel in air	1.4
Upper Flammable Limit (UFL), v% fuel in air	7.6
Minimum Oxygen Concentration (MOC), v% oxygen	12

Figure 2. Properties of Isopentane

Figure 3 [5,6] represents the flammability diagram for this system, and provides a very useful tool for examining all of the possible mixtures of fuel, air and nitrogen in the system. In order to better illustrate the applicable curve, the line for nitrogen inerting has been highlighted in blue.

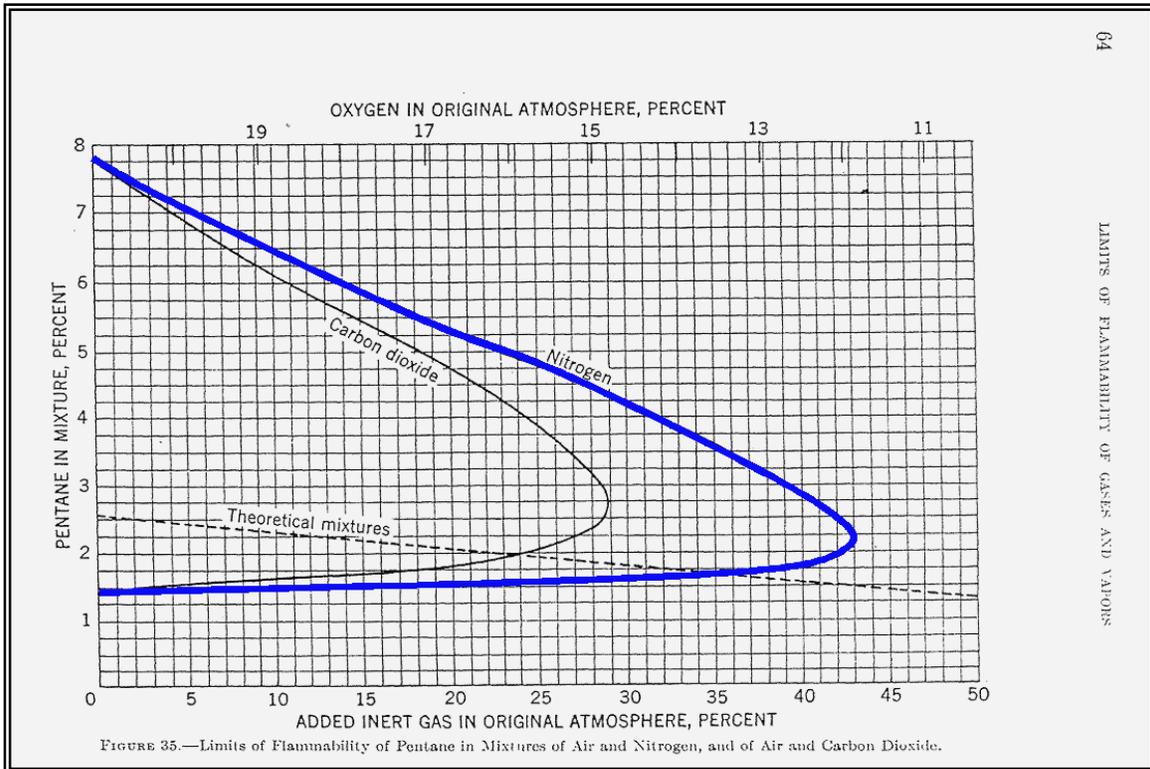


Figure 3. Limits of Flammability of Pentane in Mixtures of Air and Nitrogen.

Figure 4 has been modified to clearly identify the flammable envelope for this 3-component system. Take note of the curvature of the flammability zone, particularly in the upper region. The curvature seen here is an accurate representation of the actual behavior of the system [7]. Triangular flammability diagrams, on the other hand, use approximations to estimate the flammable envelope and do not provide the degree of accuracy seen here.

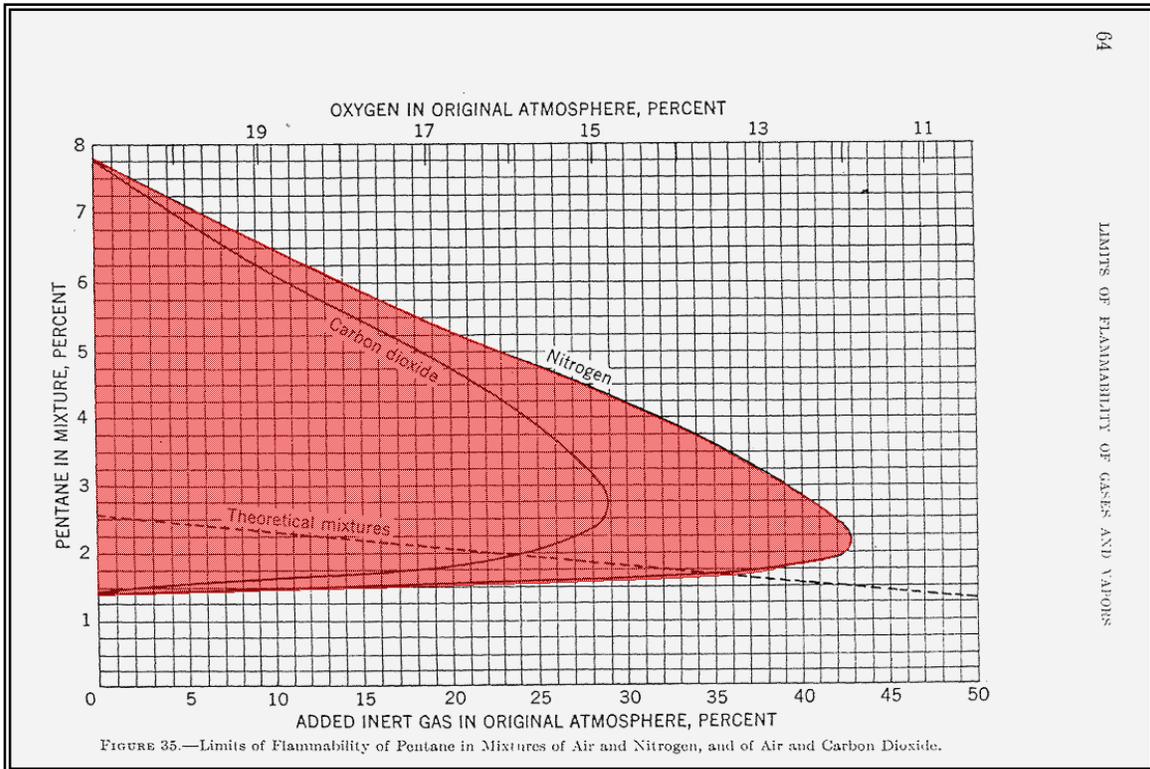


Figure 4. Flammable envelope highlighted.

A line has been drawn on Figure 5 to determine the “Out of Service Fuel Concentration” (OSFC). This is done by starting at a point representing ‘air’, and extending a straight line out just below the flammable envelope. In this instance, the line will extrapolate to a value of approximately 4.5% pentane in nitrogen. This is the maximum concentration of pentane in nitrogen that will not pass through the flammable envelope when diluted with air.

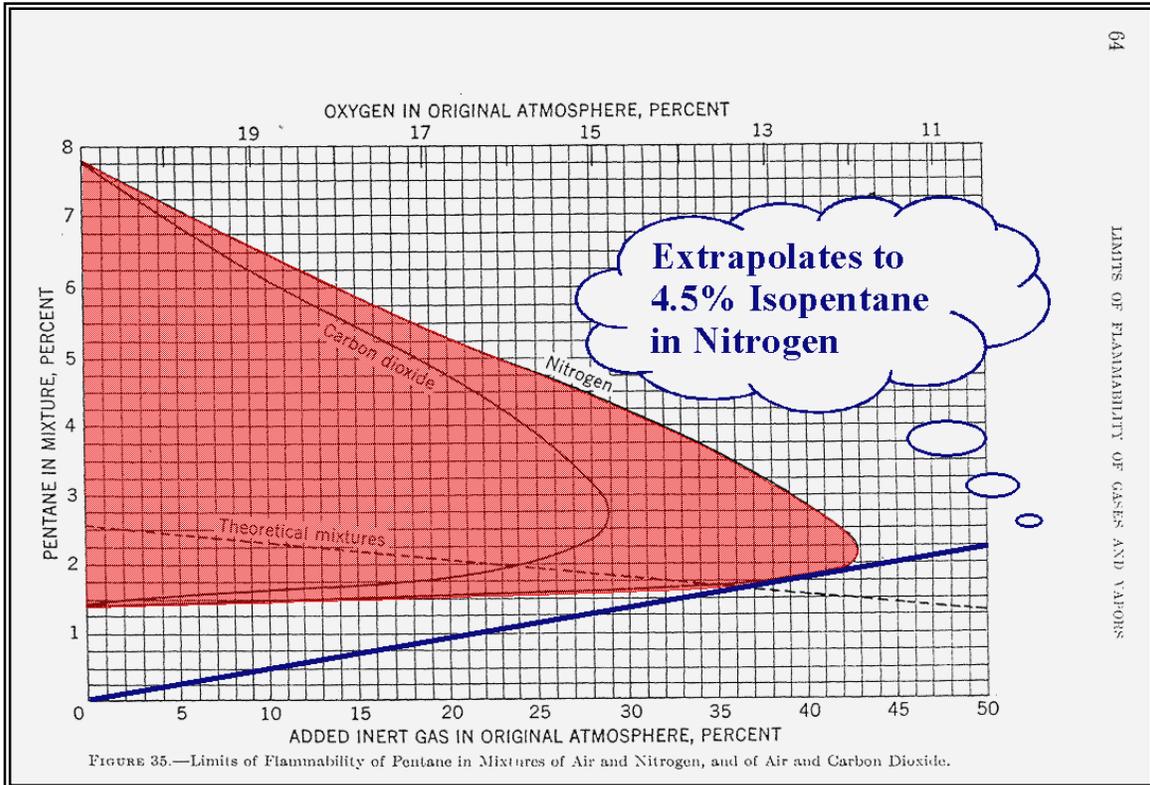


Figure 5. Out of Service Fuel Concentration (OSFC).

INCIDENT DESCRIPTION

The design of the vent collection header upstream of the CatOx was unique, in that the HVOC and LVOC streams were intended to mix together before entering the combustion chamber. This is illustrated in Figure 6, which shows a simplified flow diagram for the system. The three LVOC streams (*contaminated air streams*) are shown in yellow, and the two HVOC streams (*contaminated inert-gas streams*) are shown in orange (note: a third HVOC stream, to be added later, is also shown in the diagram). The turbulent region in which these two streams mix is just upstream of the bag house and represented in green.

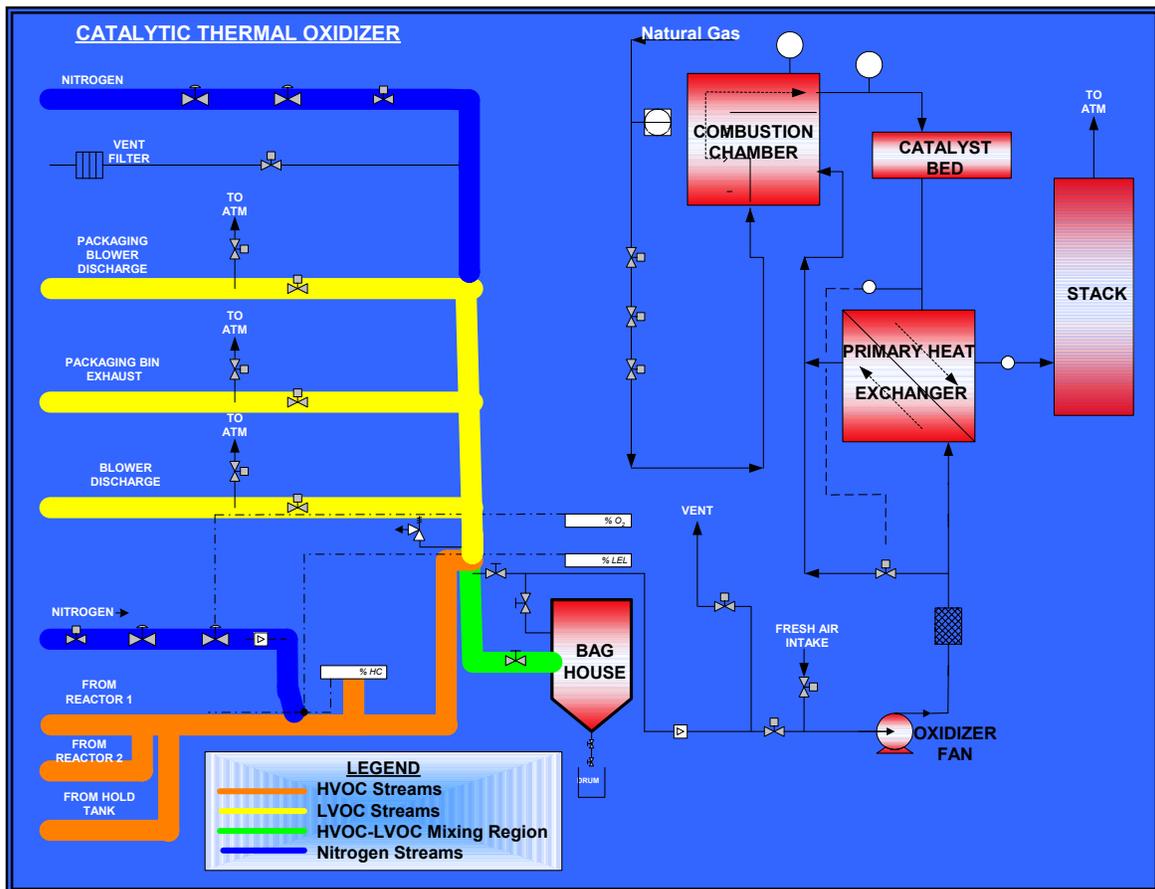


Figure 6. Catalytic Thermal Oxidizer Simplified Flow Diagram.

A concern was raised among plant personnel regarding this design due to the fact the HVOC and LVOC streams would not enter the combustion chamber separately. Their concern was the formation of a combustible mixture in the combined region of the header. The project team carefully examined this question through the use of the flammability diagram presented in an earlier section. Using the Basic Design Data presented in Figure 1, the HVOC stream can be plotted at its average value of 6.7% Isopentane in nitrogen (extrapolated value to the right of the diagram, corresponding to 6.7% Isopentane, 100% added inert gas, and 0% original oxygen). Furthermore, the combined HVOC-LVOC stream (after complete mixing) can be calculated and plotted on the same diagram as shown in Figure 7. Clearly the mixed stream in the header would pass through the flammable envelope before reaching its final (well-mixed) composition.

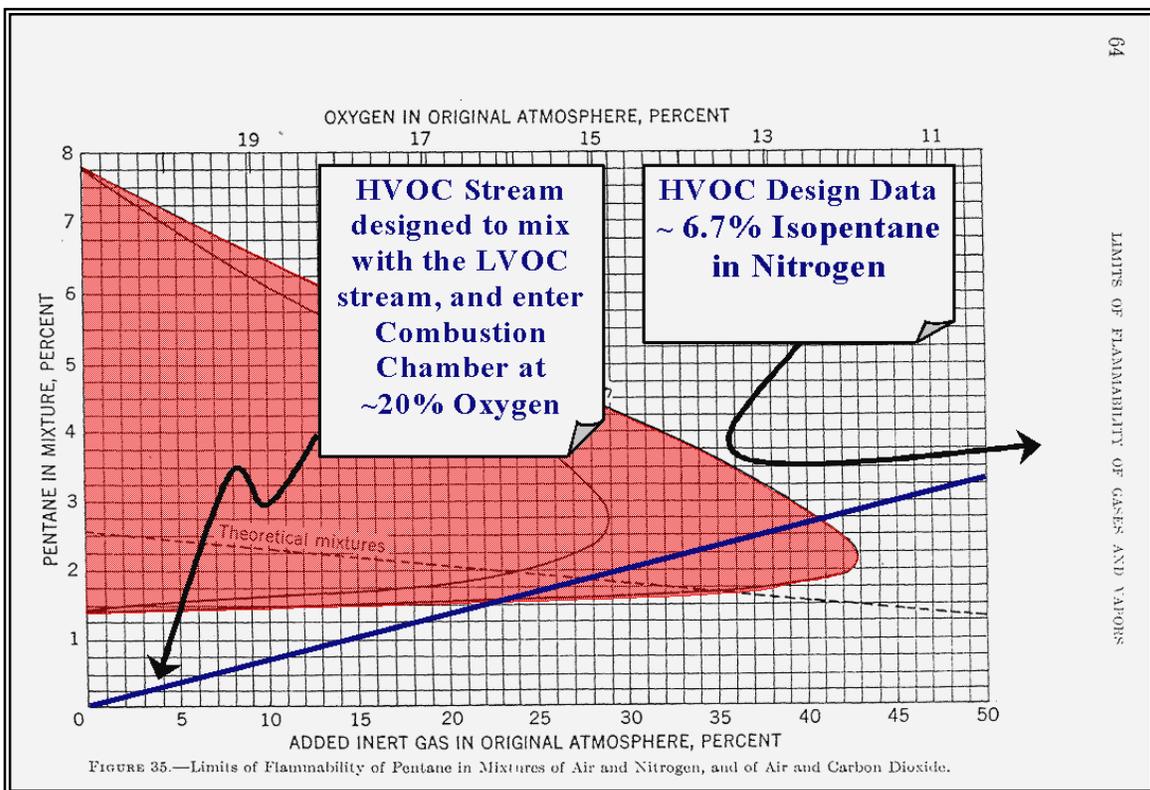


Figure 7. Designed operation of the Catalytic Thermal Oxidizer.

A risk assessment was conducted to determine the acceptability of this design. Although the project team recognized the streams in the header would pass through the flammable envelope, the risk of ignition was negligible. Figure 6 helps explain this conclusion: the HVOC and LVOC streams mix together in a very short region of the header (several feet of 14" duct) where no reasonable ignition sources exist. This mixing region, represented in green on Figure 6, is upstream of the bag house and at a significant distance well upstream of the combustion chamber. The team could not identify any reasonable ignition sources in this short distance of header, and therefore the design was accepted. The project moved forward towards construction and commissioning of the CatOx.

The initial startup of the CatOx was conducted safely using the LVOC sources. Operations intended to use the same approach for the HVOC stream, by venting a single reactor to the CatOx without any additional contributing fuel sources. However, the first time a single reactor was vented to the thermal oxidizer, the flame in the combustion chamber was immediately extinguished and a chain of events began which ultimately led to a confined deflagration inside the equipment. In order to understand how this occurred, the BDD must be examined relative to the actual operating conditions.

The BDD obtained by the project team for the HVOC sources stated the average and maximum flow rates for reactor venting and purging steps were 55 and 68 SCFM, respectively. These values were based upon a "summary report" that was generated by an Environmental consultant years earlier to support the facility's emissions permit. These flow rates were merely averaged values, and in fact were a fraction of actual values regularly witnessed in the plant. When the first reactor vented to the CatOx, the actual HVOC flow rate was approximately 600 SCFM over the first five seconds of venting.

The 600 SCFM flow of Isopentane and nitrogen from the reactor immediately extinguished the combustion chamber flame, and initiated a series of safety interlocks. Two dampers automatically closed to isolate the reactor and the combustion chamber. Unfortunately, this valve sequencing also caused an over-pressure in the header between the closing dampers. The over-pressure was relieved when a rupture panel on the bag house burst, which now exposed the header to the surrounding atmosphere. Figure 8 illustrates the interlocking damper valves where the over-pressure occurred. The region between the closed damper valves is shown in orange to emphasize the fact that this section of header still contained HVOC gases trapped between the damper valves.

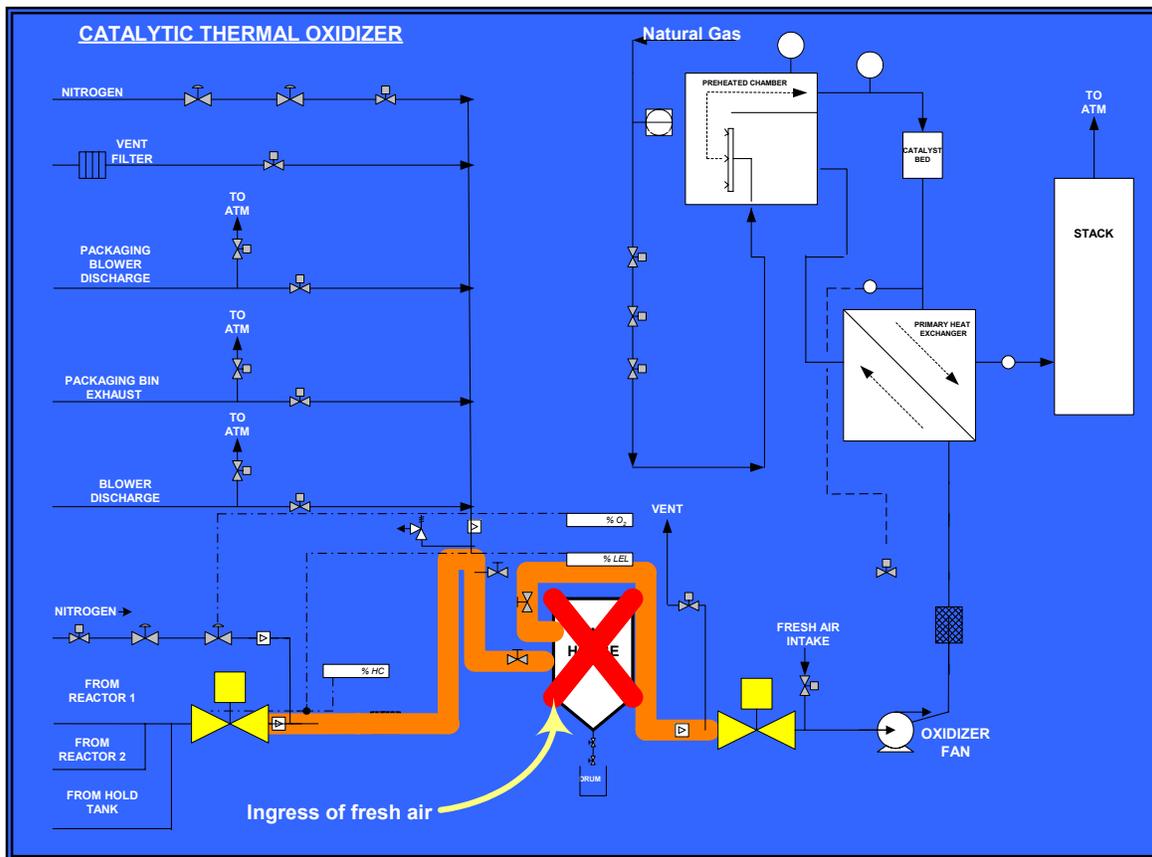


Figure 8. Trapped HVOC gases between closed damper valves with burst rupture panel.

The rupture panel on the bag house was neither set up to alarm locally or remotely. The previous sequence of events had occurred in less than one minute of the reactor vent valve being opened to the CatOx. Operations had no indication the rupture panel had burst and opened up to atmosphere. In just two minutes after the CatOx shut down on ‘flame out’, the manual reset was pushed and the startup sequence was again initiated. However, this time the trapped HVOC gases in the header were mixed with fresh air entering through the bag house rupture panel. The composition of this stream – a result of “inadvertent mixing” – was approximately 13.5% oxygen, corresponding to a point inside the flammable envelope (Figure 9). The combustible mixture of HVOC gases and fresh air entered the combustion chamber and ignited immediately. The over-pressure from the deflagration damaged a section of the CatOx structure between the combustion chamber and catalyst bed.

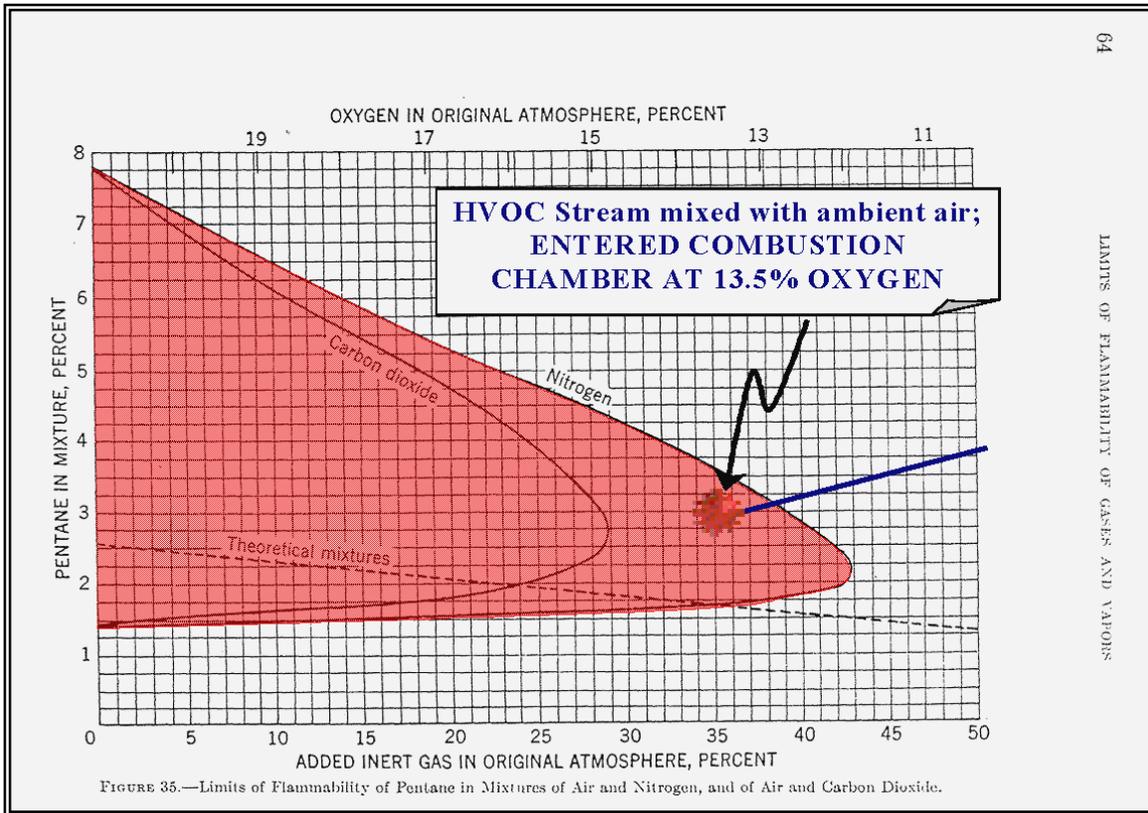


Figure 9. Combustible HVOC-fresh air mixture at the time of the incident.

LESSONS LEARNED

The initiating event in this incident was the application of incorrect Basic Design Data in the earliest phases of the project. The average values used for the HVOC sources established a foundation for the remainder of the design and operation of the Catalytic Thermal Oxidizer. When actual plant conditions differed from these design values, a sequence of events followed that led to the explosion.

Following the incident, several Hazard Reviews were conducted on the system, prompting some significant changes in both the design and operation of the Catalytic Thermal Oxidizer. Although there were many lessons to be learned from this incident, a few in particular stand out in importance:

- ✚ The HVOC flow rate from the reactors must be measured and controlled, independent of reactor pressure;
- ✚ The maximum concentration of Isopentane in nitrogen that can be safely diluted with air without passing through the flammable envelope is ~4.5%; and
- ✚ Bag house rupture panel failures must have remote indication and alarming.

CONCLUSIONS

1. Basic Design Data (BDD) must be auditable, i.e., the data and its source must be documented and made available in a format that allows for easy retrieval [1].
2. Critical BDD should be confirmed independently [1].
3. Persons responsible for collecting experimental BDD should ensure the data has been interpreted correctly by designers [1].
4. Measures to prevent explosions in Fired Equipment must include minimizing accumulations of unburned fuels during combustion upsets – particularly on the fired-side of the equipment [3].
5. Flammability diagrams must be used when designing Fired Equipment, such as Vent Collection and Destruction Systems (VCDS).

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