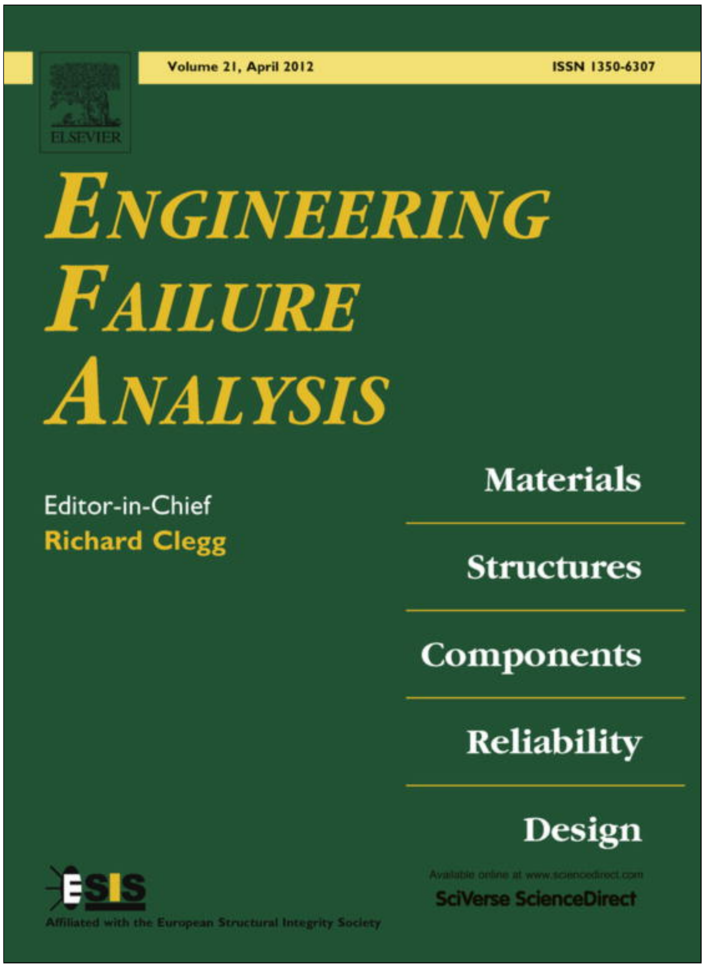
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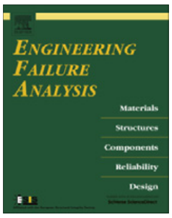

Failures in cabin type hydrocarbon heaters due to inadequate fuel control

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ABSTRACT

The causes of recent fires in hydrocarbon heaters are discussed in this paper. In particular, failures are chosen for which root causes involve trying to get around existing operational shortcomings by making changes to control, instead of carrying out a proper Root Cause Analysis to identify actual causes of deficiencies. In one case, the heater would extinguish due to the poor characteristics of fuel gas. A restart routine was devised, in which previous purging was avoided. In the other case, turning off one burner would turn off the remaining. Instead of addressing the reason why a burner would turn off, the operator modified gas inlet control so that the remaining burners would remain on. Details are given of the chain of events that led to these failures. It is concluded that heaters should be carefully chosen or designed to meet specific operation requirements. Modifications should be avoided whenever possible and carefully planned, in association with the manufacturer when they are unavoidable. In every case, safety systems should be in accordance with modern safety standards.

1. Introduction

The causes and characteristics of several recent fires in hydrocarbon heaters are discussed in this paper. In particular, these failures are chosen because root causes involve inappropriate control and safety barriers which led to service damage that eventually ended up with explosions and fires, with large economic impact. These harsh experiences could help operators to pay attention to some apparently minor operative aspects, which could build up and eventually lead to large damages.

Subsequent analysis of a failure produced during service provides information about the causes which lead to its occurrence. Determining the mechanisms involved in the failure is essential for prevention of future failures, since corrective measures can only be carried out if their causes are well known. Examples presented in this paper are the result of Root Cause Analyses of failures in the oil and gas and petrochemical industries. Experimental and modeling procedures involve establishing material and manufacturing quality on one hand, and determining operative conditions that contributed to the failure, on the other.

The most common geometry for medium and large capacity heaters is the so called cabin type, Fig. 1. The process hydrocarbon being heated flows through tubes alongside the walls and roof of the cabin, combustion of the fuel gas takes place in burners located either at the bottom or at the sides of the cabin.

Fire heater incidents occur despite best efforts. A recent review of root causes for failures and explosions [1] include as a root cause poor understanding of heater operation, inexperienced operating staff, management's lack of commitment to

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Fig. 1. Cabin Type Heater.

invest in developing and implementing good operating practices. On the other hand, the benefits of good heater operation include safety, low emissions, reliability, low maintenance and equipment replacement costs and high efficiency.

Operators of hydrocarbon heaters are most concerned with the risk of leaks in the tubes, due to in-service metallurgical degradation of the materials or growth of preexisting flaws [2,3]. These leaks usually lead to explosive environments within the furnace, and the complete destruction of the heater. Although there still are examples of such failures, there are also cases in which the root cause is related to problems in the control of the mixture used to heat the hydrocarbon. Since an explosion usually breaks the tubes and the final result is the process hydrocarbon taking fire, sometimes it is difficult to determine what the root causes were. This is even more so because high temperature service in hydrogen rich environments inevitably generates metallurgical damage in the tubes. Even in the case of a detonation from the fuel side, leaks will occur in the weakest parts of the tubes, and will therefore be always related with some kind of previous metallurgical damage, cracking, etc.

2. Metallurgical degradation of tubes, most common cause for fires

Metallurgical degradation of the carbon–manganese structural steels typically used for these applications is the most common cause for leaks and bursts within burners. Cracking of tubes, bulging and stress rupture lead to escape of hot hydrocarbons into the fired heater, resulting in an external fire. Material properties of tubes, operating conditions and time all contribute to high-temperature degradation of the tubes [4]. Let us see for example a couple of examples. A propane, butane and gasoline recuperation and dehydration heater that worked at 287 °C and 28 Bar developed a leak in a tube and a subsequent fire, Fig. 2.

In this case, the initial leak originated at the welds of a nipple placed as mechanical protection for thermocouples used to measure tube skin temperature, Fig. 3. This accessory was of poor geometry, had an intermittent fillet weld, and had lost part of its mass due to thermal microstructural degradation and erosion from heater fumes. This is clearly a problem related to design or maintenance. Prior to the appearance of cracks, the material suffered high in-service temperatures for long periods; the nipple was not refrigerated by the process gas.

In another example, a fire resulted in the destruction of a JP1 heater in a natural gas processing plant. The failure occurred when a tube leaked, near the bottom of the heater, see Fig. 4. The leak was due to the in-service propagation of cracks initiated at small stress concentrations and pits in the inner surface of the tube.

Fig. 5 shows a polished and etched cross section of the tube thickness. Note cracking from both, inner and outer surfaces. Leaking occurred when two of these cracks coalesced near mid thickness. Crack initiation was due to hydrogen damage

Fig. 2. Fire in a propane, butane and gasoline recuperation and dehydration heater.

Fig. 3. Origin of failure Nipple placed as mechanical protection for thermocouples.

favored by carburization of the steel in a layer close to the inner surface of the tube. Microstructural damage by creep also helped crack initiation from the outer surface. Metallurgical analysis of cross sections revealed however that creep damage had only an important influence in the final stages of crack propagation up to the leak. Carburization and microcraking is detailed in Fig. 6. Hydrogen damage is localized to some aligned manufacturing defects. This damage was favored by a high concentration of sulphur in the JP1.

As in the previous case, failure is due to accelerated carbon diffusion from the process hydrocarbon at high temperatures, and as such is part of normal degradation during prolonged service. Hydrogen damage symptoms are not easily detectable by the usual methods of nondestructive Inspection (NDT) from the outside. A hydrostatic test at a high enough pressure could have ensured a remaining life in similar situations.

This example, however, can also be traced to a problem in the burners. Both creep and carburization damage in the tubes is controlled by temperature, and therefore by the efficiency with which the burners distribute uniformly the heat over the whole surface of the tubes. This is impossible to achieve. Only 50% of the tube circumference receives the radiation, and the tubes that are closer to the burners are exposed to higher temperatures than the ones that are far *o* below the burners. The manufacturer of the heater deals with this problem designing the number and distribution of the burners in order to

Fig. 4. Leak in a tube near the bottom of a JP1 heater that resulted in a fire.

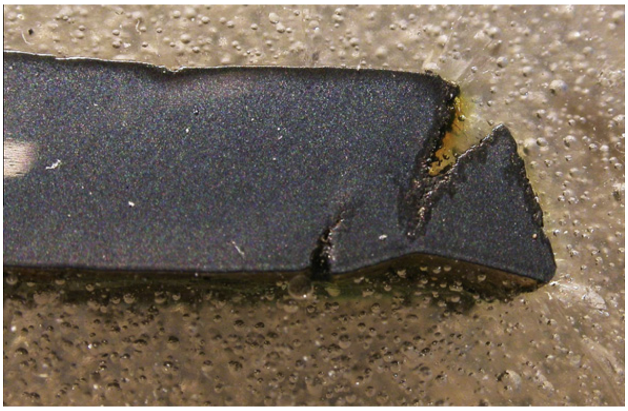

Fig. 5. Polished and etched cross section of the tube thickness.

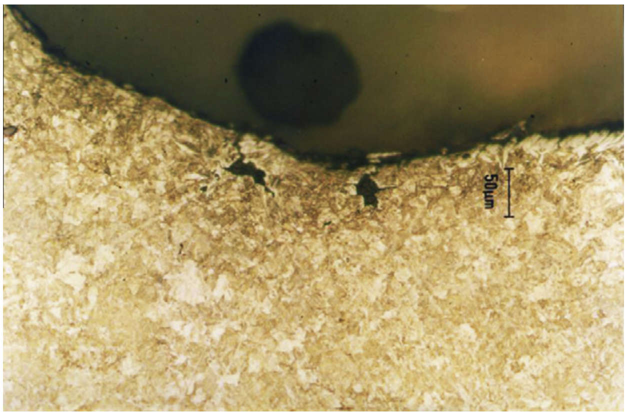

Fig. 6. Metallography of a cross section of the failed tube Carburization and microcraking can be observed.

achieve reasonable efficiencies at reasonable costs; but it is common that operators face difficulties in keeping uniform temperatures all around de heater.

3. Changes in programming lead to detonation in an oil heater

Let us now analyze a different set of mishaps, related to programming and control. This area is not often analyzed in technical literature. Our first case study is a petroleum heater (seen in Fig. 1) that had been running for less than two years when the fire occurred. Serious problems had started after only a year of service, when modifications to original programming began to be made. The last modification of the program of the PLC was done two days before the oil heater detonated. The explosion is the most recent of a series of problems associated with the control of the flame and re-igniting, resulting even in small detonations with minor consequences.

Oil temperature is controlled by a control loop which regulates the gas pressure and the air input of the burner. There are two PID (Proportional, Integral and Derivative) controllers, one for the main control loop whose control action is the burner gas pressure and another which controls the gas pressure by means of a proportional valve.

Combustion efficiency of fired heaters reduces considerably if the air supply is significantly higher or lower than the theoretically required air. Several operating variables influence the amount of excess air used in the furnace [5].The heater operates normally with a forced vent. It can also operate with a natural vent and a reduced thermal regime but only in the case of failure. In forced vent operation, the input damper of natural air is closed, the forced vent blower is on, and the aperture of the input damper is directly related to the aperture of the gas control valve (there is a Look Up Table in the Programmable Logic Controller, PLC). In natural vent operation, the input damper is completely open, the forced vent blower is off, and the thermal regime is limited to the 30% of the maximum aperture of the gas valve.

In forced vent mode the blower and the air flux are monitored. Furthermore, the shutdown of the air damper is continuously checked. In forced vent mode, the PLC program automatically changes from forced to natural vent if the forced system fails. This changing can be commanded by hand from the local panel. The change form forced to natural vent is done with the heater in operation. On the other hand, the change from natural to forced vent can be done only if the heater is stopped.

Root Cause Analysis revealed five aspects of relevance:

1. The heater is designed for natural gas as fuel; possible pockets of CO_2 in the well gas used as fuel in the failed oil heater can produce flame extinction by lack of fuel.
2. Monitoring systems for position actuators in the intake air dampers (natural and forced) and tube skin temperatures are mechanically unreliable and susceptible to errors by breakage and displacements.
3. Air intake dampers have a design flaw and interfere. After cuts done by maintenance staff, both gates could get stack both open and closed, see Fig. 7. The mechanical design does not accept the simultaneous and complete aperture of both dampers because their trajectories interfere. However, heater operation states that both dampers should be simultaneously open in more than one situation.
4. PLC programming was repeatedly modified to allow the immediate re-igniting of the oil heater, without venting and purge prior gas. This is not recommended by the manufacturer.
5. There is a concurrency of failures. A failure in the switch from forced to natural air intake resulted in the detonation since control and safety systems also failed.

A similar failure was recently reported in a natural gas fired industrial oven that exploded during an attempted restart [6]. The oven had a fully-automated control system, and the start, shutdown, and restart were controlled by process controls and a flame safeguard system. In that case, a malfunction of the flame detector allowed the automated controls to complete the start sequence and establish normal operating status without a flame present in the burner.

As a result of the analysis of the programming of the PLC control system, the following inconsistencies were detected

1. Error in switching from forced air to natural air intake.
2. Max. gas pressure to burner during re-igniting.
3. Sequence of ignition of the pilot different from design.
4. Unsafe sequence for flame re-ignition.
5. Error in sensing opening of the damper for natural air intake.

Fig. 7. Intake dampers after cuts done by maintenance staff both gates could get stack both opened and closed.

The following conclusions can be deduced from the analysis of PLC program versions.

(1) The PLC program was designed to stop the heater if no flame is detected during operation.
(2) Recent versions include a repetitive turn-on sequence which energizes the ignition transformer in order to return the flame.
(3) In these versions when the heater is in forced operation, after first execution of the repetitive turn-on sequence, the system could no more be switched to natural vent operation. Because of a program bug, the execution of the repetitive turn-on sequence produces the inhibition of changing from forced to natural vent mode.
(4) As a consequence of items (2) and (3), it is concluded that if flame expires, the heater flame is turned on. Then, if the forced vent fails, the heater continues operation without air input (at maximum thermal regime). This way, flame is inhibited because combustible mix is very rich, above the Upper Ignition Limit (UEL). In these conditions, without flame and with gas entering at maximum regime, the gas is accumulating in the interior of the heater, with the system intending to turn on the flame (up to 10 intents of 60 s each, that is, 10 min). This situation is dangerous because the environment in the heater can become very unstable if an unexpected air flow is produced (for example if an intermittent force blower exists) or if any element of the heater is at temperature upper than the self-ignition temperature of the combustible mix.
(5) The fuel gas used in the heater is gas of the oil yard. It includes batches of CO_2 which is inert. This explains flame extinction, which made it necessary to greatly modify the heater design and the PLC program.

The immediate cause of the incident is the intersection of the following causes:

(1) Frequent flame extinction due to bad combustion.
(2) Failure of forced air intake fan.
(3) Error in the PLC programming, which inhibited the automatic passage form forced to natural air intake in the event of a failure in the fan.
(4) Dangerous re-igniting sequence in absence of flame (10 attempts of 1 min each) [7].
(5) Lack of control, alarm and shutdown in case of hazardous conditions.

The most likely sequence of events during the detonation is as follows:

(1) Heater starts up.
(2) Sometime after start up, the flame extinguished, which was very frequent due to the poor quality of fuel gas.
(3) Flame extinction gave rise to the first execution of the sequence for re-igniting. This first sequence, due to an error of PLC, programming, impeded from then on the automatic passage from forced to natural air intake in case of a failure in forced intake.
(4) Forced air intake failed and natural intake was not allowed, then there was no air going into the combustion chamber.
(5) Flame extinguished due to bad combustion.
(6) Fuel gas continued going into the heater chamber at full regime.
(7) The PLC enabled the sequence of re-ignition; in the absence of air it was ineffective. This sequence continued trying to ignite the flame during a maximum of 10 min.
(8) During the re-ignition process, with the chamber full of fuel gas, the forced air intake rehabilitated from its failure, injecting air. Therefore the fuel –air mixture inside the heater became unstable. Alternatively, with the forced air intake still faulted, the fuel air mix could have made contact with hot parts of the heater, which exceeded the self-ignition temperature of the mixture.
(9) Either through intermittent failure of the forced air intake or a hot point in the heater, the unstable atmosphere produces a detonation inside the heater.

Most relevant root causes related to the re-ignition attempts are:

1. Incorrect selection of the heater type, apparently not specifically designed for well gas with potential CO_2 batches.
2. Incorrect programming of re-ignition in the PLC.
3. Constructive errors:
   - failures in position and temperature sensors
   - re-ignition spark plug failures
   - design error in the air dampers and inadequate repair thereof, that made it possible for the dampers to get locked.

4. Changes in ignition control lead to explosion and fire in oil heater

In this case, the heater that originated the fire had been running for more than ten years, after retrofitting. Fig. 8a and b shows the heater shortly before and shortly after the explosion. Paraffin Chemtherm 550 Oil (hot oil) circulated inside the furnace tubes. This hot oil furnace was installed in amine sweetening plant for natural gas. Heat is extracted from the hot oil and used in the regeneration of the amine, stabilization of gasoline and in the gas dryer for venting. The heater increases oil temperature by 70 °F, for a flow of 3000 gallons/min or 680 m^3/h. The necessary heat is 60 million calories an hour, efficiency is 73%. Heat is provided by 8 treated natural gas burners, located in the cabin floor.

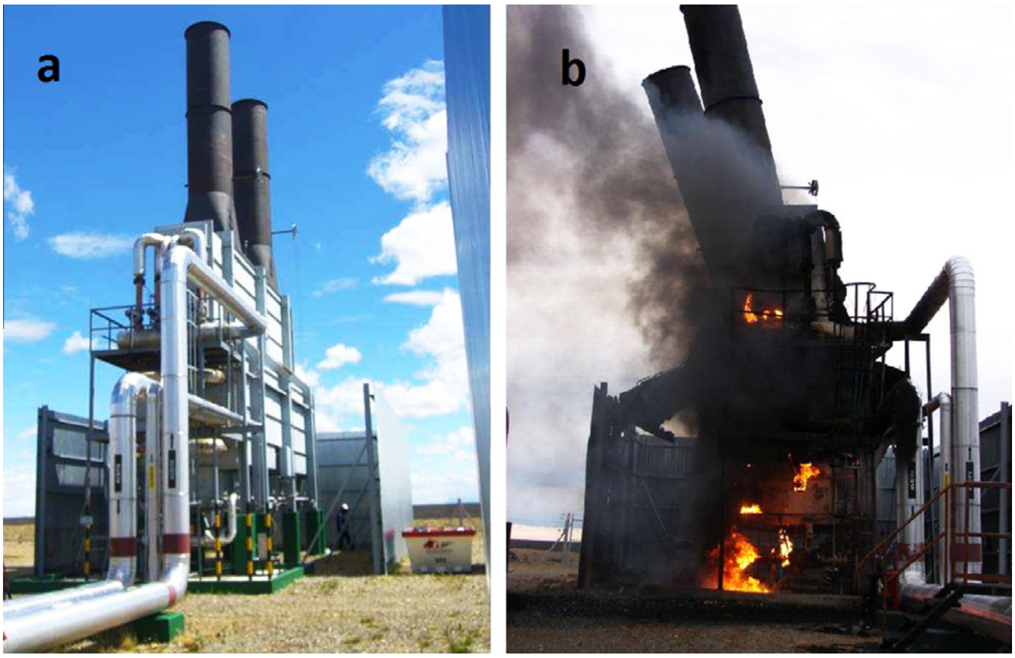

Fig. 8. Oil heater shortly before (a) and shortly after (b) the explosion.

The heater was subjected to several surveys and maintenance during previous lifetime. A relevant aspect detected in a late 2009 assessment was an excess of global warming in the front part of the heater shell, indicative of possible degradation of the refractory wall, and also service near the upper power ranges. There is no history of oil leaks in the tubes.

Fig. 9 shows the location of the fire subsequent to the initial explosion. Breaks produced by the blast were found in steel beams that hold the heater shell and in concrete housings, showing a large released energy. The power of the explosion caused ruptures of the thinner metal envelope, but only in a part of the wall of the heater. The force of the explosion caused displacement and deformation in oil tubes, both inside and around the heater, which provoked leaks in some bolted flanges. Oil leaks ignited immediately, causing a second explosion and subsequent fire. This fire was circumscribed to the front of the heater. Burners placed closest to the burnt front show the effects of fire.

Fuel gas pressure is controlled by an inlet valve, common to all eight burners. Line pressure is 60 psi. Without flow of fuel gas, the valve reduces pressure to 30 psi. With the normal fuel gas flow, the pressure drops to 15 psi. Each burner is controlled by a valve. Some valves were found broken and let air go into the burners even when they were closed. Just before the explosion, an operator observed that some valve controllers were in failure mode.

A survey of the relevant operational events in hours prior the detonation was conducted. Also, the modifications made to hardware equipment for the addition of solenoid valves in burners were analyzed. The experts also discussed the changes made to the control system for the management of these new valves (Honeywell controllers, heater PLC and plant PLC). Possible evidence that the heater may have been operating in anomalous situation was detected, even though the PLC of the furnace and control elements were destroyed during the fire.

Fig. 9. Location of the fire subsequent to the initial explosion

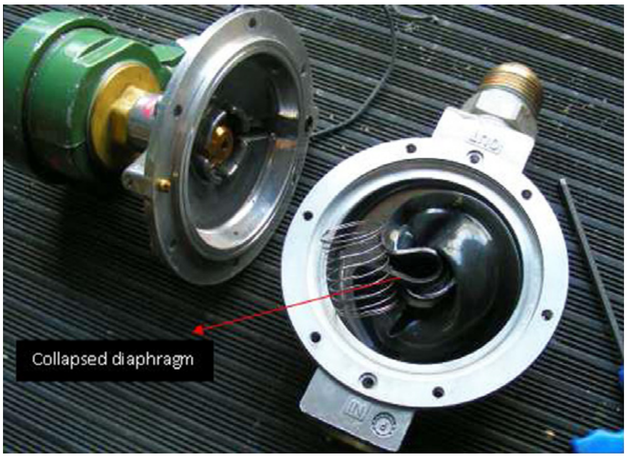

Fig. 10. Collapsed rubber diaphragm of solenoid valve.

In particular, the verification of Scada historical data (heater temperature, oil flow and plant gas consumption) compared to the operators statements and the preliminary inspection of the burner solenoid valves allowed defining several anomalous conditions.

The heater was designed to operate on natural draft. Expert control system analysis verified the operation of the control system, the changes that were made to it and the effects of these changes. According to the disabling signal of the plant PLC, It was concluded that after the PLC software modifications the heater main safety valve stopped working and the heater state signal started to incorrectly indicate the on/off status.

This also clarifies that the heater state signal was not generated from a safety valve switch as was assumed (so, the day of the event, the fact that Scada system showed the heater status off, does not mean that the main safety valve was necessarily closed).

Expert safety conditions analysis examined the most relevant aspects affecting adversely the heater safety conditions [8]:

- Individual supplies of gas for each burner and pilot did not have double safety valve and venting.
- Solenoid valves installed on each individual burner supply had no visual indication of opening and closing nor closed test switch.
- Solenoid valves installed on each individual burner supply were not ranged for the maximum pressure upstream of the pressure regulator.
- The fuel gas low pressure switch was not installed.
- Heater air supply was not verified. There were no switches to determine the possible closed state of air dumpers.
- The closed state of any solenoid valves or the main safety valve was not checked during the heater purge.
- There was no determination on what was the minimum quantity or pattern of burners on for a safety heater operation.

All of these requirements are already part of the standard NFPA 86 for a heater with these characteristics, if it were designed today. Failure in this case is not a direct consequence of material deficiencies, assembly or design errors, or inadequate maintenance procedures. The relevant root causes related to the attempt to reignite the heater after the plant shutdown are discussed below.

The heater was subjected to increasingly tougher requirements due to increased operational demand of hot oil. The furnace is natural draft and has 8 gas burners, which were controlled by a single system of control and safety valves. Each burner had a pilot and a flame control. The failure of a burner used to cause the shutdown of the heater, closing the general fuel inlet valve. This was a common cause of service interruption and plant shutdown.

The burners were accessible at the bottom of the furnace and could be disassembled with the heater on. This was done to fix the failure of a burner without a plant shutdown. To increase operational reliability of the heater and maintenance safety, in 2009 operators began a series of modifications and improvements to the system of gas fuel. The most relevant modification for this study was the replacement of the sole control of the fuel gas by the installation of 8 solenoid valves, one for each burner, controlled by the PLC of the heater. An error in PLC logic modifications led to a heater shutdown condition not envisaged after a plant emergency shutdown. A bad selection of valves caused some of them to breakdown during this shutdown.

Prior to the incident, the plant emergency shutdown was due to a failure of the plant PLC. This PLC had already shown some unusual behavior. Historic records of fuel gas flow and operators statements indicate that fuel gas continued entering the heater during the plant shutdown, without hot oil flow. The investigation verified that the heater was on before the manual safety valve closed, prior to the re-ignition. This was due to an error in the operation of the fuel gas control and rupture of the solenoid valves. An error in the PLC program modification allowed the safety valve to continue opened.

Inspection of the solenoid valves revealed that some were broken. Failures are related to collapse of the rubber diaphragm, see Fig. 10. Burst testing of a new valve verified that the failure was due to a wrong pressure range selection. Valves were operating at pressures more than 10 times larger than the design pressure for the installed valves.

The nominal pressure of valve solenoids was much lower than the maximum possible pressure in inlet gas. The valves were working since 2009 without failures detected, but failure would be likely in the event of an increase in fuel gas pressure. This is the case of the shutdown caused by the PLC when closing these valves without previously closing the safety main valve. This sequence of events involves an unfortunate combination of failed valves and errors in the control system. Uncontrolled gas intake through some burners created an explosive mixture inside the heater. Underlying causes are limitations of the heater safety systems as compared with the requirements of modern safety standards, and problems of traceability of the information and communication with suppliers.

5. Conclusions

Explosions and fires have large economic impact. Operators of hydrocarbon heaters are most concerned with the risk of leaks in the tubes, due to in-service metallurgical degradation of the materials or growth of preexisting flaws.

Leaks and fires in cabin type heaters are usually due to the in-service propagation of damage, most commonly metallurgical degradation and cracking of heater tubes. Root causes of explosions recently occurred are in some cases associated to this in-service degradation, but in others they are related to a combination of factors that include deficiencies both in the design of the control system and in the performance, and in errors introduced by modifications carried out to deal with these deficiencies.

Those failures associated to in-service degradation are mostly due to propagation of defects that could not be detected by regular NDT (although incidents could have been avoided with an adequate hydrostatic test). This degradation has historically been the main reason for heater failures and, although impossible to eradicate, they could be diminished by a proper design and maintenance.

The most interesting failures analyzed in this article were caused by a combination of factors that include deficiencies in design, control system and heater performance, and errors introduced by modifications done to deal with these deficiencies. Deficiencies in heaters performance were related in one case to a bad choice of the heater according to the fuel it was supposed to work with and, in the other, to steadily increasing operational requirements.

Control system design deficiencies include mechanically unreliable monitoring systems and dampers interference. The modifications in the control system involved deliberately removing safety barriers in both cases and errors introduced either in the PLC logic or in the choice of control valves that eventually resulted in the inhibition of a second safety barrier.

These last failures involve trying to get around existing operational shortcomings by making changes to control, instead of carrying out a proper Root Cause Analysis to identify actual causes of deficiencies. It is common wisdom that heaters should be carefully chosen or designed to meet the specific operation requirements. Modifications should be avoided whenever possible; when unavoidable they should be carefully planned, in association with the manufacturer. In every case, safety systems should be in accordance with modern safety standards.

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