EVALUATING FIRE DAMAGED REGULATORS:

HOW RELIABLE IS POST-FIRE TESTING?

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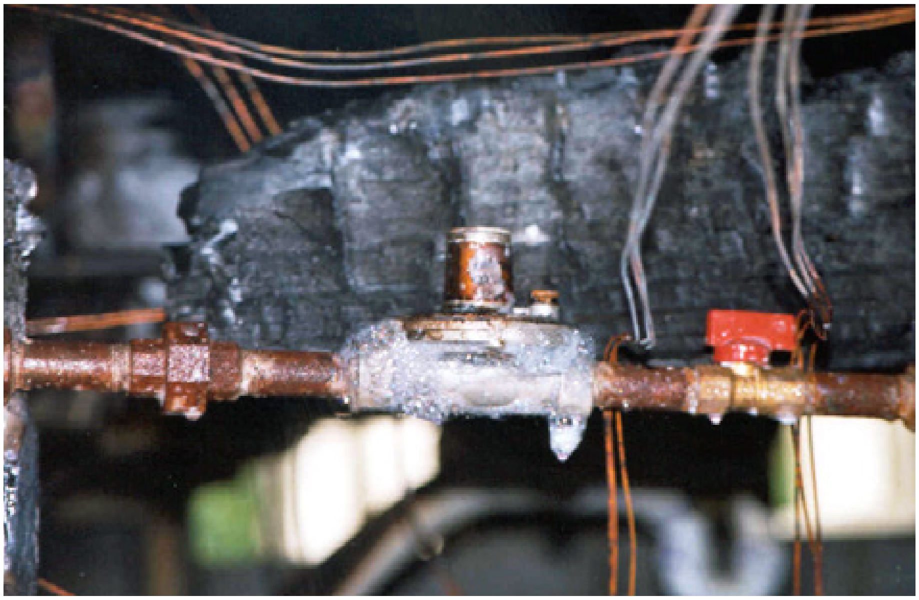

ABSTRACT

Gas regulators are typically considered the “heart” of propane and natural gas systems and have a history of being reliably engineered and manufactured as well as a history of reliable safe operation provided they are properly installed and maintained. When there is a fire or an explosion incident where gas is possibly involved, it is standard practice to test the operation of gas system regulators that are present and in a condition that allows them to be tested. Very often, because they are generally located on the exterior of a structure the regulators are undamaged by the fire and their operation can be reliably tested. In some cases, regulators are catastrophically destroyed and it is clear that no reliable operational testing can be performed.

Still yet, a third category exists and that is a regulator that is subject to some degree of fire exposure, but not catastrophically destroyed. It is in these cases that the question must be asked: how reliable are the results of the testing with respect to indicating how the regulator was functioning before exposure? Great care should be exercised prior to concluding that a regulator which has been exposed to uncontrolled fire conditions either failed or was in a defective condition prior to the exposure.

This paper evaluates the impact of heat impingement to the integrity of a selected gas regulator model. Multiple oven tests were completed on a specific lever style regulator model to determine (1) the range of temperatures and exposure times under which the regulator can be expected to remain operable and (2) the range of temperatures and exposure times under which the integrity of the regulator can be expected to fail. Pre and post exposure comparative analysis and testing on the regulators and their internal components was completed and the results discussed. Laboratory oven testing is combined with existing research literature on heat degradation of various material parts within the regulator to evaluate the reliability of any post fire testing of the regulator. Recommendations are made to investigators evaluating regulators that have been exposed to heat or flame but are being considered as a potential causative factor in a fire or explosion incident.

INTRODUCTION

It seems a relatively intuitive concept that a regulator consisting of aluminum and plastic parts, when exposed to an uncontrolled fire event, for example a structure fire, stands a very strong chance of failing and leaking. It is well known that gas piping systems and components can, and frequently do sustain damage in the course of a fire, and subsequently leak and release highly flammable fuel into the fire, causing localized intense burning that is not necessarily indicative of the origin area.[1,2] It is therefore very important for any investigator to consider all the data carefully before concluding that a regulator which was exposed to an uncontrolled fire environment failed, or was in an otherwise defective and leaking condition prior to the fire event. Although it is possible for lever style residential regulators to fail in some situations[3,4] these devices are in widespread use and have a long history of being safe and very reliable.

Low and localized intense burn patterns combined with a fire damaged and now leaking regulator at the center of the patterns does not in itself conclude a defective regulator as the origin and cause of the fire.[1,2] However, incomplete and or subjective analysis and possibly even expectation bias[5] occasionally lead some to that conclusion while at the same time overlooking or ignoring significant data such as other indicative burn patterns, fuel type and distribution and structural geometry, witness statements and electrical arc-map data. Useful data can also be obtained through materials analysis of the different components that make up the regulator. Such analysis can provide a range of temperatures[6] to which the regulator was exposed and an understanding about the environmental conditions under which the components can be anticipated to fail. The investigator is cautioned however to remember that exposure time as well as the intensity of the exposure will impact the overall damage to the component observed after the fire.[7]

There are seemingly an infinite number of possible environmental scenarios that a regulator may be exposed to in uncontrolled fire conditions. Fire environmental ambient temperatures and durations of those temperatures will vary substantially dependent upon available fuels, changing ventilation conditions, proximity to the burning fuel and any shielding or protection of target objects. A regulator can be impacted by factors such as direct flame impingement, hot gas and smoke impingement (convective heating), radiant heating, water or water spray from a ruptured domestic water line or water from fire fighting efforts, localized ventilation effects, structural collapse or shielding, insulation or protection of the regulator or part of the regulator from exposure. The testing herein only evaluates a small number of possible environmental conditions using the repeatable controlled environments of a lab oven. Although limited, the testing data obtained does provide useful information to the fire investigator in terms of validating temperature analysis principles discussed in NFPA 921[6] as well as validating or refuting subjective evidences one might be presented with in the course of investigations or litigation. The data obtained also helps in understanding that there is a range of temperatures and exposure times under which a particular regulator can be expected to remain operable as well as a range of temperatures and exposure times under which the integrity of regulators can be expected to clearly fail.

Description of Regulators Tested and Evaluated

The subject regulators tested are all new line pressure regulators of the same model and manufactured in the year 2010. The nominal inlet pressure rating for the regulators is 2 psi with an outlet pressure range of 7 to 11 inches water column. The specification sheet for the regulators indicates an available operational range in ambient temperatures of -40 to 205°F. The housing or body of the regulators is composed of upper and lower halves (clam shell style) constructed of die cast aluminum UNI 5076 (Aluminum Association 384.0-F). The two halves of the body are held together by six aluminum rivets equally spaced around the perimeter. The regulator diaphragm incorporates an integrated seal ring that is compressed in a channel between the upper and lower body when they are riveted together. The regulator diaphragm is composed of Nitrile Butadiene Rubber (NBR). The balancing (lever) arm, spring adjustment screw and the diaphragm plate are all composed of Hostaform C13021 (Polyoxymethylene or POM). Figures 1 through 4 below depict the regulator and some of the individual components of the regulator.

REGULATOR MATERIAL ANALYSIS

POM Regulator Parts

Polyoxymethylene (POM) is a thermoplastic polymer[8,9] material and subsequently has a range of temperatures over which it can be softened or melted down, reformed and allowed to harden repeatedly without irreversible effects to the physical and chemical properties of the material. Beyond a specific temperature, a thermoplastic material will irreversibly degrade resulting in permanent changes to the physical and chemical properties of the material.

The manufacturer's literature for the POM used in the regulator components indicates a melting point temperature of 331°F and a melt flow temperature of 374°F.[10] Kusy and Whitley[11] determined that POM starts to degrade at a temperature of approximately 482°F and decomposes primarily into formaldehyde. Formation of formaldehyde and physical changes such as material discoloration and embrittlement are indicators of POM degradation. While sophisticated physical or chemical material laboratory analysis or testing might be performed which would distinguish between the occurrence of melt versus degradation; for simplicity, analysis in this paper is limited to visual observations of (1) discoloration, (2) embrittlement, and (3) in some cases clear partial or complete POM mass loss (further indicated by the pungent odor of formaldehyde produced during testing). We find these indicators to be practical and sufficient in most cases as well as delineated by the melting and degradation temperatures already established in published literature.

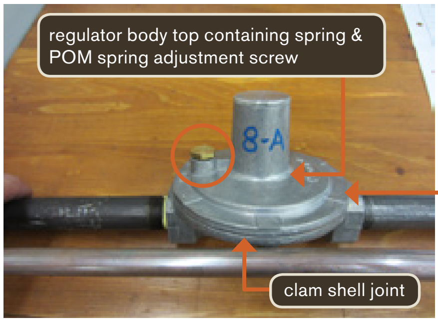

FIGURE 1
Intact regulator connected for testing. *Circled is the vent limiter.*

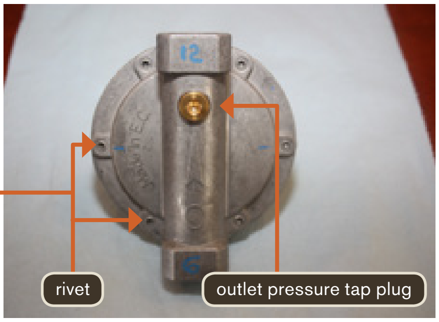

FIGURE 2
Bottom of regulator. *The tap plug was used to install an internal thermocouple.*

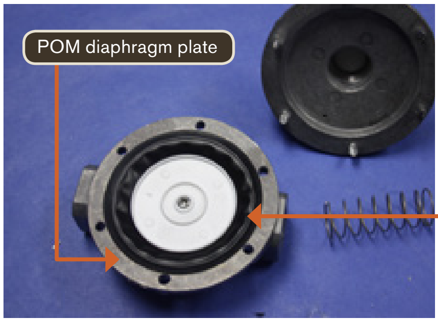

FIGURE 3
Disassembled regulator. Upper body.

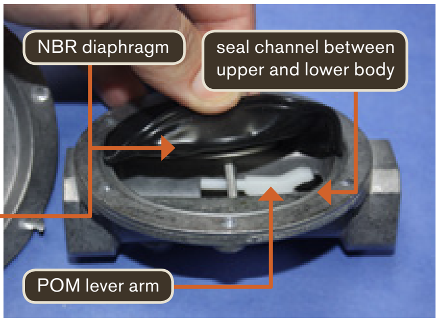

FIGURE 4
Disassembled regulator. Upper body.
Note flexibility of NBR Diaphragm.

NBR Diaphragm

Nitrile Butadiene Rubber (NBR) is a common thermoset synthetic rubber (elastomer) polymer[8,9] and subsequently *does not soften or melt,* but rather undergoes a complex progressive degradation process under elevated temperature exposure. The rate and amount of degradation is dependent upon the exposure temperature and duration of the exposure as well as the atmosphere under which degradation occurs. Sunol[12] et. al. concluded that the thermal degradation of NBR can be divided into four stages with the onset temperature of the first stage beginning around 446°F. Mass loss in the first stage degradation process is low and attributed to loss of plasticizers and other low temperature volatiles in the NBR compound. The on-set temperature for second stage degradation begins around 572°F and is characterized by polymer chain breaks (scissions) and a continuing slow mass loss rate. The on-set temperature for third stage degradation begins around 725°F and is the stage at which the main material mass loss occurs with oxidative degradation as the main reaction. The on-set temperature for fourth stage degradation begins around 1058°F and is related to reactions of "inorganic metallic oxides."

The product catalog for the regulator indicates that the incorporated NBR diaphragm is designed to work in ambient temperatures of -40°F to 205°F. Available industry literature and publications[13,14,15] related to NBR seals indicate comparable operational ranges of -40°F to 212°F with tolerance to exposures of up to 250°F for brief periods. Callister[8] indicates a useful temperature range for NBR of -60°F to 300°F. Industry literature however warns that temperatures higher than approximately 250°F can result in extrusion, compression set, degradation, and hardening of the material causing the seal to be highly susceptible to failure. Elastomers such as NBR are notable for their property of rubberlike elasticity which is characterized by their ability to repeatedly undergo large elastic deformations without permanent material distortion (plastic deformation). Callister[8] reports an elongation range of 400-600% for NBR. Plasticizers are incorporated into elastomers to improve their flexibility and reduce stiffness and brittleness in the material. The first stage degradation process of NBR results in the loss of plasticizers and therefore it is expected that the material will loose flexibility and become progressively embrittled at sustained temperatures exceeding approximately 446°F.

As noted by the industry literature, NBR utilized in sealing applications undergoes mechanical degradation and deformation changes under conditions exceeding maximum operating temperatures (212°F to 250°F). Temperatures elevated substantially above these maximum operating temperatures can therefore be expected to result in extrusion, compression set, degradation and hardening at sealing surfaces with the subsequent high likelihood of seal failure.

Aluminum Body

The UNI 5076 (Aluminum Association 384.0-F) aluminum body of the regulator has a solidus melting point of 961°F[16]. Sustained temperatures in this range will result in obvious catastrophic damage to the regulator including complete vaporization of the POM, complete or near complete destruction of the NBR as well as melting and distortion of the regulator body.

DESCRIPTION OF THE TESTING

Pre-Testing

Twenty new regulators of the same model and approximate same age were divided into two sets of ten; identified as test set A and test set B. Test set A was labeled 1-A through 10-A and designated for oven testing. Test set B was labeled 1-B through 10-B and designated for radiant heat testing the analysis and results of which will be presented in a future paper. The housing of each regulator was marked with a paint pen corresponding to the numbers on a clock; the gas inlet being the 6:00 position and the gas outlet being the 12:00 position. Gap measurements were made at the mating joint between the upper and lower clam shells around the exterior perimeter of each regulator. The measurements were made with a standard set of feeler gages. The smallest gage available on the set was 0.0015 inches and thereafter measurement increments of 0.0005 inches were available. Maximum gap measurements for each quadrant of the marked clock on the regulators were made both before and after testing. A summary of the measurements associated with test set A are recorded in Table 1. Greater details of the measurements corresponding to the exact positions and expanse of the gaps were made and recorded, however, lack of space prohibits publication.

The regulators of each test set were fitted with 6-inch black iron nipples on the inlet and on the outlet sides. Each nipple/regulator assembly was then connected to a test manifold. Sealing tape appropriate for gas piping was applied to all joints for thread sealing. The test manifold included an air supply, a supply pressure regulator, an inlet pressure gage, an inlet flow meter, an outlet low pressure manometer, a set of outlet control valves and orifices for controlling flow rates or allowing lock up conditions.

Data loggers were used to record temperatures at one minute intervals for the oven testing. Temperatures measured and logged included lab ambient air, oven internal ambient air, external regulator housing and internal regulator air temperatures. In addition to the gap measurements made, before each oven heat exposure test, the flow and lock up performance of each regulator was evaluated and recorded. All regulators performed within manufacturer prescribed parameters during flow and lock up pre-exposure testing. None of the regulator housings leaked prior to exposure testing.

Speculative Arguments

In evaluating the condition of regulators post-fire, the investigator may be challenged by any number of speculative arguments concerning the post-fire conditions observed and the conclusions that can be drawn from such observations. Three such speculative arguments and their associated speculative conclusions that we have seen put forth in the past concerning regulators are presented below and will also be addressed in our conclusions of this paper. The first speculative argument is that the split regulator housing and rivets are all aluminum and will therefore uniformly expand with the fire and cool back down after the fire without causing warping, permanent distortion or any gaps in the clam shell joint. The speculative conclusion from this argument was that any warping, distortion or gaps existing in the clam shell joint post-fire were the result of a manufacturing defect as opposed to being caused by the fire exposure event itself. A second speculative argument, similar to the first, is that the presence of any gaps in the clam shell joint will result in leakage of the regulator housing (ie. gaps = leakage). The speculative conclusion again is that the presence of any gaps in the clam shell joint therefore constitutes a manufacturing defect which will result in gas leakage pre-fire. A third speculative argument is that gas flowing through the regulator at the time of the fire provided a cooling effect for the internal components of the regulator itself. The speculative conclusion from this argument was that the cooling effect of the flowing gas prevented the internal temperature of the regulator from damaging the NBR material including the seal ring to the point of degradation since the material was still “soft and pliable to the touch” after the fire.

Oven Testing

Figure 5 depicts a drawing of the test manifold set-up used in the oven testing. Figures 6 and 7 depict general photographs of the oven test set up. Table 2 provides a summary of the conditions to which each regulator was exposed during oven testing. The upper practical test temperature achievable with the oven was limited to approximately 600°F and therefore temperatures beyond second stage degradation of the NBR material were not reached. The enclosed nature of the oven necessitated the use of air as the regulated gas for safety purposes.

Post-exposure Testing and Comparative Analysis

After each exposure test, the test manifold assembly and regulator clam shell housing were tested for any leakage. Flow and lock-up conditions were also tested and recorded. The gaps in the regulator clam shell joints were measured and recorded. The regulators were then disassembled for examination. The POM components were visually examined for evidence of melt or degradation (discoloration, embrittlement and mass loss). The formation of formaldehyde was noted via a pungent odor during some of the testing. The NBR diaphragm and seal ring was examined visually and microscopically for evidence of degradation (extrusion, compression set, mass loss, cracking or other damage). In addition, qualitative observations were made with respect to loss of flexibility and embrittlement of the NBR material.

TABLE 1 Gap measurements before and after oven testing. Oven exposure temperatures and regulator housing integrity. *Note exposure times vary from test to test.*

Regulator	Pre/ Post Test	Max Gap (in) 12 to 3	Max Gap (in) 3 to 6	Max Gap (in) 6 to 9	Max Gap (in) 9 to 12	Max. Exposure Temp (F) Note 2	Clam Shell Joint Leakage
1-A	Pre	0.0015	Note 1	Note 1	0.0015	500	Yes
	Post	0.0030	0.0015	0.0015	Note 1		
2-A	Pre	0.0025	0.0025	0.0015	0.0015	500	Yes
	Post	0.0030	0.0030	0.0020	0.0020		
3-A	Pre	0.0015	Note 1	0.0015	0.0025	500	No
	Post	0.0050	0.0015	0.0040	0.0055		
4-A	Pre	0.0025	0.0015	0.0015	0.0025	345	No
	Post	0.0040	0.0025	0.0030	0.0030		
5-A	Pre	0.0025	0.0025	0.0020	0.0015	250	No
	Post	0.0025	0.0040	0.0040	0.0060		
6-A	Pre	Note 1	0.0015	Note 1	Note 1	295	No
	Post	0.0015	0.0020	0.0015	0.0015		
7-A	Pre	0.0020	0.0015	Note 1	Note 1	600	Yes
	Post	0.0025	0.0020	Note 1	0.0015		
8-A	Pre	0.0025	0.0025	Note 1	0.0015	600	Yes
	Post	0.0040	0.0030	0.0015	0.0015		
9-A	Pre	0.0030	0.0030	0.0015	0.0015	600	Yes
	Post	0.0040	0.0040	0.0040	0.0040		
10-A	Pre	0.0025	0.0015	Note 1	0.0015	450	No
	Post	0.0030	0.0040	0.0030	0.0050		

Note 1	Less than 0.0015 inches.
Note 2	Internal pressure regulation failed at all exposure temperatures above approximately 315 F. Pressure regulation was maintained only in regulator 5-A and 6-A testing.

TESTING RESULTS

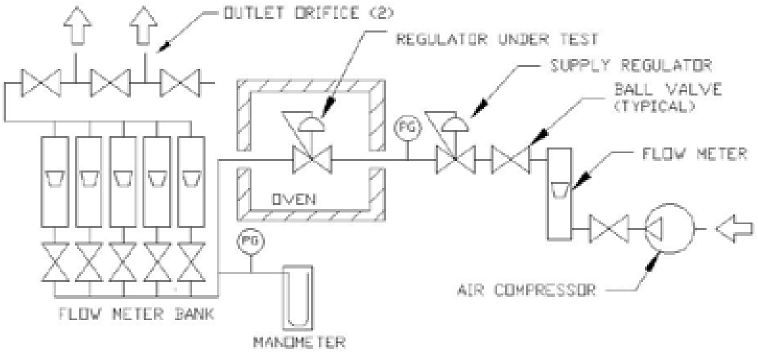

FIGURE 5
Drawing of test manifold used in oven and radiant heat testing.

FIGURE 6
Oven exposure test set-up.

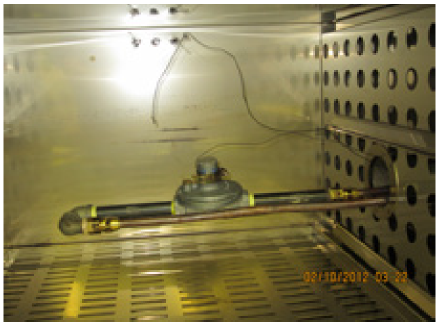

FIGURE 7
Oven exposure test set-up.

The internal temperatures of regulators 1-A and 2-A were taken up to 490 °F and 500 °F and held for 10 minutes and 5 minutes respectively. Note these tests were predicated on the internal temperature of the regulators reaching and remaining at 490 °F and 500 °F for the specified time; therefore, oven ambient temperatures were maintained at approximately 500°F until the internal temperatures of the regulators equalized to the desired temperatures. In this manner, the overall total oven exposure time to the regulators is much longer than simply basing it on the time periods at the specified internal regulator temperatures.

Regulator 1-A was allowed to air cool while regulator 2-A was cooled with a water spray on top of the regulator. Both regulators failed in pressure regulation and both leaked through the clam shell joint during testing. Although the NBR diaphragm and seal ring remained pliable on both regulators, the seal rings for both exhibited evidence of degradation. In addition, evidence of POM residue was present on the sealing surfaces of the seal ring indicating leakage of vaporized POM through the joint during the exposure testing.

Air flow at 18 scfh was set through regulator 3-A and the oven ambient temperature was taken to 500°F and held for approximately 15 minutes. The internal temperature of the regulator exceeded 446°F seeing a maximum temperature of 450 °F for a total of approximately 8 minutes. This is just at the threshold for first stage degradation of NBR. During the testing, when the internal regulation failed, the flow rate increased to 38 scfh. At the end of the heating period, cold water was poured on one-half of the top side of the regulator. While internal pressure regulation failed during exposure testing, the clam shell joint was not observed to leak. The NBR diaphragm material remained pliable, although evidence of degradation was observed on the sealing ring. It is also noteworthy that while the clam shell joint did not leak, the joint gaps opened substantially more than those of tests 1-A and 2-A which did leak. The internal temperature of regulator 4-A was taken to approximately 335°F and held for 10 minutes. During the test, pressure regulation failed as the POM lever arm melted however the housing of the regulator never leaked.

Post-testing disassembly and examination indicated POM melting but no evidence of POM or NBR degradation. No evidence of cracking, hardening or mass loss was observed on the NBR seal ring. Although the POM components were melted, they maintained their basic shapes and the material did not flow (See Figure 9). The internal temperatures of regulators 5-A and 6-A were taken to approximately 250°F and 295°F respectively and held for 6 hours. The regulators functioned normally after the exposure and neither leaked. No evidence of POM melting or POM or NBR degradation were noted during post-testing disassembly and examination. No evidence of cracking, hardening or mass loss was observed on the NBR seal ring. It is again noteworthy that there were significant increases in the gaps of the clam shell joint for regulator 5-A, although without any leakage of the joint.

The NBR diaphragm of Regulator 7-A remained soft and very pliable, though some loss of plasticizer is indicated in the fact that the material could be fairly easily torn or pulled apart with some applied force. Multiple points of cracks or splits and mass loss were also observed at in the diaphragm sealing surface of 7-A.

TABLE 2 Exposure summary conditions for oven testing

Regulator	Test Description
1-A	Lock-up condition. Take internal temperature of regulator to 490°F and hold for approximately 10 minutes. Shut oven off, open door and allow cool down to lab ambient.
2-A	Lock-up condition. Take internal temperature of regulator to 500°F and hold for approximately 5 minutes. Shut oven off, open door, water spray top of regulator and allow cool down to lab ambient air temperature.
3-A	Flow 18 scfh air through regulator. Take oven ambient temperature up to 500°F and hold for approximately 15 minutes. Shut oven off, open door, pour water (at room ambient temperature) on ½ of the top of the regulator between 6 and 12 and allow cool down to lab ambient air temperature.
4-A	Lock-up condition. Take internal temperature of regulator up to 335°F and hold for approximately 10 minutes. Shut oven off, open door and allow cool down to lab ambient air temperature.
5-A	Lock-up condition. Take internal temperature of regulator up to 250°F and hold for 6 hours. Shut oven off, open door and allow cool down to lab ambient air temperature.
6-A	Lock-up condition. Take internal temperature of regulator up to 290°F and hold for 6 hours. Shut oven off, open door and allow cool down to lab ambient air temperature.
7-A	Lock-up condition. Take oven ambient temperature up to approximately 600°F and hold for approximately 8 minutes. Shut oven off, open door and allow cool down to lab ambient air temperature.
8-A	Take internal temperature of regulator up to approximately 600°F and hold for approximately 10 minutes. Shut oven off, open door and allow cool down to lab ambient air temperature.
9-A	Lock-up conditions. Take oven ambient temperature up to approximately 600°F and hold for approximately 8 minutes. Shut oven off, open door and allow cool down to lab ambient air temperature.
10-A	Lock-up conditions. Take oven ambient temperature up to approximately 450°F and hold for approximately 20 minutes. Shut oven off, open door and pour water (at room ambient temperature) on one side of the top half of the regulator, allow cool down to lab ambient air temperature.

Regulator 8-A sustained embrittlement and hardening of the NBR diaphragm to the point that it broke like peanut brittle. Multiple points of cracks or splits, mass loss and substantial POM residue deposits were observed on the NBR sealing surface of 8-A. The internal temperature of 8-A was in the range of second stage degradation for a time period of approximately 8 minutes while 7-A was in that range for only 3 minutes. More significant is that the internal temperature of 8-A was above first stage degradation temperatures for 30 minutes compared to only 16 minutes for 7-A. During these relatively short time periods of similar exposure temperatures, substantial differences exist in the pliability and hardness of the NBR materials. In addition, the POM components of both regulators were substantially discolored and brittle. The pungent odor of formaldehyde was also evident in both tests. While the POM components in 8-A were nearly completely degraded and vaporized, the material loss in 7-A was substantially less. And while the NBR diaphragm of 7-A remained soft and pliable substantial degradation, visible through magnified examination, occurred to the NBR sealing material. Regulator 9-A was a repeat of Regulator 7-A test conditions with similar results. The oven ambient temperature of test 10-A was taken to 450°F and held for approximately 20 minutes and the oven was shut off. Ambient room temperature water was poured over half of the top side of the regulator and the regulator was allowed to cool to room ambient temperature. No observations of cracking, splitting or mass loss was observed on the NBR seal ring. There was a slight roughness on the top side of the seal ring in some areas. The regulator housing did not leak.

Where internal temperatures of the regulators exceeded the POM degradation temperatures the pungent odor of formaldehyde was clearly evident. In addition, in some cases, vapors were observed exiting the piping system in the clear tubing portions of the test assembly as well as discharging from the vent limiter on top of the regulator and in some cases through the joint of the clam shell itself. For all tests there was a clear temperature differential between the external shell of the regulator and the internal ambient temperature of the regulator. The maximum oven testing exposure temperatures were approximately 600°F and therefore never exceeded NBR second stage degradation temperatures (ranging from 572°F and 725°F) in any of the tests. NBR mass loss for these tests was therefore expected to be low and in fact was low.

During test 1-A, which was in lock up conditions, there was a slight and short temperature drop when the clam shell joint failed and relieved the heated air that was locked up in the housing as new air moved in. However the flow rate of the leak through the clam shell joint was insufficient to maintain any cooling effect and the temperature immediately rose back up. During test 3-A, which occurred under initial flow conditions (18 scfh), there was no noticeable cooling effect inside the regulator until internal regulation failed and the flow rate increased to 38 scfh. With a flow rate of 38 scfh the internal temperature of the regulator still continued to climb, though there was some moderate cooling effect noted. As discussed above, although the regulator housing in test 3-A did not leak, the NBR sealing ring did in fact sustain degradation. Furthermore, only a short portion of the test assembly piping was in the oven and heated during the testing. In an actual fire condition, it is likely that much more of the piping system would be heated and any gas flowing into the regulator would be first pre heated.

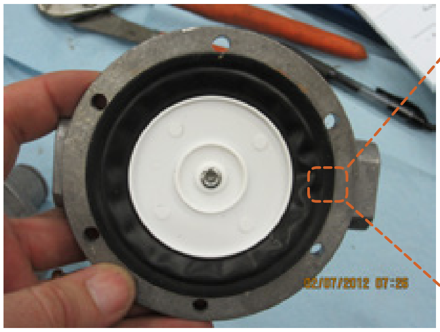

FIGURE 8
POM diaphragm plate from an untested regulator.

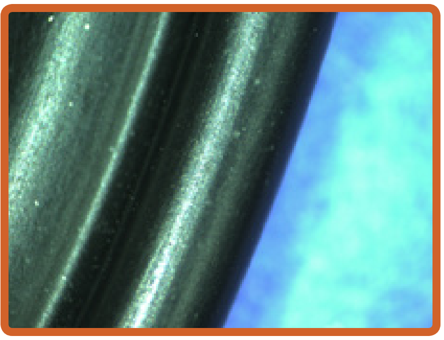

FIGURE 11
Microscopic photograph of the NBR diaphragm seal ring from an untested regulator (bottom/gas side). Smooth, rounded and undamaged.

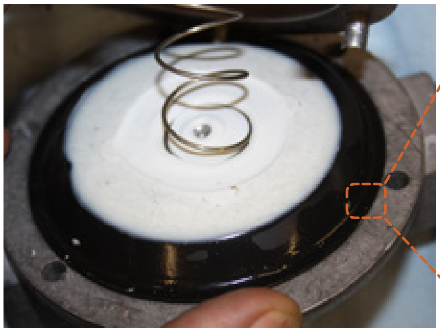

FIGURE 9
Regulator from Test 4-A. No degradation of POM diaphragm plate. Melted but not discolored or embrittled.

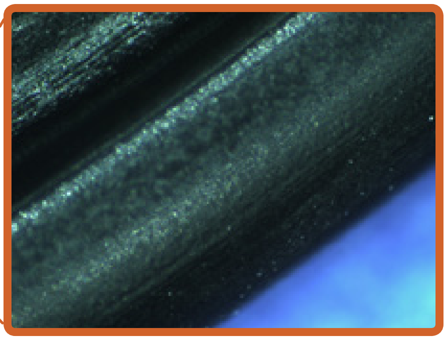

FIGURE 12
Microscopic photograph of the NBR diaphragm seal ring (bottom/gas side) from Test 4-A. Smooth, rounded and undamaged.

FIGURE 10
Regulator from Test 8-A. Extensively degraded POM diaphragm plate with significant mass loss. Substantial hardening and embrittlement of NBR diaphragm plate. *Note the fracture on the lower left side.*

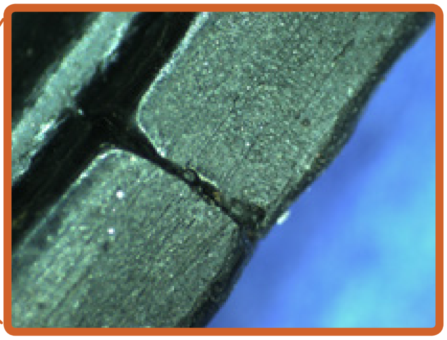

FIGURE 13
Microscopic photograph of the NBR diaphragm seal ring (bottom/gas side) from Test 8-A. Compression set, extrusion, mass loss and splitting observed in the seal ring (Compare to Figures 8 and 9). The width of the seal ring is approximately 2mm.

CONCLUSIONS

1 Regulators tested at internal temperatures of 250 and 295°F for over 6 hours continued to operate and test normally and without housing leakage during and after heat exposure. No evidence of melting of POM components or degradation of POM or NBR components was observed in these temperature ranges and for the specified exposure time. Therefore, regulators of the type tested could be expected to likely remain operable and without housing leakage for short time exposures to temperatures between approximately 250°F and 300°F.

2 Pressure regulation failure occurred between 315 and 335°F on all regulators where internal temperatures in this range were reached. Pressure regulation failure was anticipated at and above this temperature range as a result of melting of the POM lever arm.

3 Clam shell joint leakage did not occur in testing where the temperature for the on-set of first stage degradation of NBR was either not exceeded (4-A, 5-A, 6-A) or just slightly exceeded within the regulator and maintained for a short period of time (3-A and 10-A). Significant increases however were observed in the gap sizes of the clam shell joints of several of these regulators as a result of heat exposure, although they did not leak during or after heat exposure. The speculative argument that the presence of any gaps in the clam shell joint will result in leakage of the regulator housing is false.

4 In test 3 A and 10-A, evidence of the initiation of degradation of the NBR seal rings was clearly observed however the degradation was insufficient to cause joint leakage. A longer exposure time at these temperatures would likely have increased degradation of the seal rings and resulted in joint leakage.

5 The gap sizes in the clam shell joints increased in most every test case after exposure to heat and did not return to the pre-exposure gap size. The speculative argument that the split regulator housing and rivets are all aluminum and will therefore uniformly expand with the fire and uniformly cool back down after the fire without causing warping, permanent distortion or gaps in the clam shell joint is clearly false. hese tests were performed in a laboratory oven to intentionally create some degree of control uniformity. Uncontrolled fires and their impingement upon target objects within them would clearly not be uniform.

6 All of the regulators have some degree of measurable pre-existing gaps in the clam shell joints as part of the normal manufacturing process. In some instances these original gaps doubled or quadrupled in size after exposure without leakage through the joint. The presence of such gaps either before or after exposure is not an indication of a defect and certainly not an indication that a regulator necessarily leaked before the fire. While a large enough gap will most certainly result in leakage through the joint, testing at temperatures well above the on-set of first stage degradation of NBR indicates that seal ring degradation is the more likely cause of joint leakage.

The internal temperatures of regulators 1-A and 2-A well exceeded the temperature for the on-set of first stage degradation and the clam shell joints leaked. Microscopic observations of the seal rings of these regulators indicate evidence of substantial degradation. However, overall increases in the joint gaps of regulators 1-A and 2-A due to exposure were less, and considerably less at some points, than in regulators where joint leakage did not occur. Furthermore, the gaps post-exposure were less in some cases than the pre-exposure gaps of other regulators.

Regulators 7-A, 8-A and 9-A were all exposed to temperatures exceeding the on-set of second stage degradation and all exhibited evidence of substantial degradation of the seal rings with subsequent joint leakage. Increases in the gaps of the joints of these regulators were again moderate compared to the gap increases in regulators where joint leakage did not occur or even in joints measured pre-exposure. Therefore joint leakage is most likely due to degradation of the NBR seal ring and not the joint gap. The speculative conclusion that gaps existing in the clam shell joint post-fire were the result of a manufacturing defect is false.

7 Where exposure temperatures approach or exceed first stage degradation of NBR sealing components within the regulator, joint leakage is likely.

8 The speculative argument of gas flowing through the regulator at the time of the fire providing a cooling effect for the internal components of the regulator and that cooling effect in turn preventing the internal temperature of the regulator from damaging the NBR material including the seal ring to the point of degradation is false. While some cooling effect may occur, any such effect would be negligible, short lived or ineffective in cooling the NBR sealing ring. The seal ring is clamped between and in direct contact with the aluminum body and not exposed to any flow of gas within the regulator. Heat transfer into the seal ring is enhanced by the direct contact with the aluminum housing. Furthermore, the piping system within a room or a space containing an uncontrolled fire will likely heat all or a large portion of the piping system up and subsequently the gas within that piping system as well. Therefore any gas entering the regulator will have first been preheated by the fire exposed piping system.

9 When fire investigators are attempting to determine effective fire temperatures or evaluate the post fire integrity of regulators, the investigator is cautioned to remember that thermoset materials such as NBR do not soften or melt, they undergo a complex thermal degradation process. Furthermore, there may be substantial differences in the stage of degradation over relatively short periods of time. While NBR may still be pliable one moment under specific exposure conditions, it may become embrittled shortly thereafter under the same conditions.

10 When the fire investigator is examining thermoplastics, the melting temperature is not the only material property that should be taken into consideration. Consideration should also be given to the on-set degradation temperature of the plastic. It is noteworthy that while the melting temperature of POM (331°F) is well below the on set degradation temperature of NBR (446°F), the degradation temperature of POM (482°F) is above the on-set degradation temperature of NBR (446°F). The condition of the POM can therefore be an indicator of the temperature range to which the NBR was exposed. For example, if the POM has exceeded melting and undergone degradation (above 482°F) then the NBR material was likely exposed to temperatures exceeding the on-set of first stage degradation for NBR (446°F) and the sealing ring is clearly subject damage and leakage.

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ENDNOTES

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