FAILURE MODE INVESTIGATION AND BALLISTIC PERFORMANCE CHARACTERIZATION OF PYROTECHNIC INITIATORS USED IN AUTOMOTIVE SUPPLEMENTAL RESTRAINT INFLATION SYSTEMS.

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16. Abstract

The first goal of this project was to establish a radioisotope leak detection laboratory Development of this laboratory provides the University of Idaho with unique capabilities among North American universities to allow quantification of fine leak rates (less than $1x10^{-7}$ atm cc/s) from small cavity devices such as bridgewire initiators, microelectronic components, and micro-electro-mechanical machines. The second objective was to design, manufacture, and fabricate a population of small cavity specimens for use in leak rate studies. The third objective was to subject these specimens to a dilute mixture of ^{85}Kr and air to record the subsequent rate of decay of isotope content within the components. The observed flow rate of gas emanating from the specimens was compared to that predicted by accepted flow models.

The laboratory is complete and fully operational. Fabrication of the small cavity specimens featuring orifice diameters from 1μm to 100 μm is also complete, and initial tests are underway to determine the magnitude and duration of scintillation signal as a function of internal pressure, cavity volume and orifice diameter. Analysis of initial results indicates that experimentally-derived flow rates are often comparable to those predicted by viscous flow theory

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EXECUTIVE SUMMARY

There were three major goals of this project. Establishment of a new radioisotope leak detection laboratory featuring a Radiflo® Mark IV krypton-85 leak detection apparatus with an associated scintillation crystal gamma detection system constituted the initial objective. Development of this laboratory provides the University of Idaho with unique capabilities among North American universities to allow quantification of fine leak rates (less than 1×10^{-7} atm cc/s) from small cavity devices such as bridgewire initiators, microelectronic components, and micro-electromechanical machines (MEMS).

The second objective was to design, manufacture, and fabricate a population of small cavity specimens for use in leak rate studies. High-quality stainless steel coupons were machined, laser-drilled and laser welded to form a population of small cavity devices featuring orifice diameters from 1μm to 100 μm.

The third objective was to subject these specimens to a dilute mixture of ^{85}Kr and air using the Radiflo apparatus and to record the subsequent rate of decay of isotope content within the components using the scintillation crystal apparatus. The observed flow rate of gas emanating from the specimens was then compared to that predicted by accepted flow models.

Installation of the Radiflo and its ancillary equipment is complete and fully operational. A keyless entry system has been added to prevent entry of unauthorized personnel into the laboratory, and the leak detection apparatus has been charged with 16 curies of ^{85}Kr, anticipated as an adequate content for four years of testing.

Fabrication of the small cavity specimens is also complete, and initial tests are underway to determine the magnitude and duration of scintillation signal as a function of internal pressure, cavity volume and orifice diameter. Analysis of initial results indicates that experimentally-derived flow rates are often comparable to those predicted by viscous flow theory, and that large leak rates from very small cavities cannot be adequately measured by tracer gas methodology alone.

Additional tests are underway using newly-acquired data acquisition hardware and spectrum analysis software to allow data to be acquired in a more convenient and efficient manner.

DESCRIPTION OF PROBLEM

Small cavity devices are generally defined as components, assemblies, or packages that are characterized by internal free volumes of roughly 10^{-1} cm^3 or less. Many devices fall within this classification, including pyrotechnic bridgewire initiators, detonators, fuses and other ordnance devices, as well as integrated circuits, microelectronic components, and emerging Micro-Electro-Mechanical Systems (MEMS) devices. Most of these items must meet stringent leak rate requirements in order to ensure the integrity of critical internal components or circuitry. Pyrotechnic bridgewire initiators, for example, are small electro-explosive devices that feature fine internal wires (the bridgewires) designed to transfer electrical energy to small explosive charges. To ensure proper functioning of these devices, it is critically important that the bridgewires remain free from the damaging effects of humidity and corrosion for the intended service life of the device. Due to the inherent susceptibility of the bridgewire to corrosion induced by moisture or other contaminants, bridgewire initiators are intended to be hermetic and impervious to the surrounding environment. For this reason, manufacturers attempt to verify the hermetic integrity of each initiator through the application of tracer gas leak detection methodologies.

A complication in the leak detection of bridgewire initiators is that there is limited free internal volume available for introduction of tracer gases. The competing demands for minimum size, maximum performance, and low cost have led to compact initiator designs with very small internal cavities. In general, it is considered good design practice to minimize free volume within these devices[1] as many studies have emphasized that it is important that voids between the bridgewire and the surrounding pyrotechnic be eliminated in order to promote efficient heat transfer from the wire and ignition of the pyrotechnic material.[2-4] In many applications, the free volume of initiators is no greater than 10^{-2} cm^3, while in more severe circumstances, the free volumes of the bridgewire regions are reportedly less than 10^{-5} cm^3.[5]

Of primary concern is the possibility of a gross leak path into an initiator with a free volume insufficient to permit accumulation of an appreciable amount of tracer gas. In this situation, tracer gas leak detection methodologies must be used with caution to ensure that the limited tracer gas introduced into the device does not escape before the leak rate can be measured.

The possibility of this scenario occurring in all small cavity devices, including electronic components and energetic devices has been acknowledged for many years[6,7]. Although it has been argued a gross leak check may not be necessary given high quality components and robust manufacturing processes[8], most military standards require both fine and gross leak tests be performed on all components[9-12] to protect against the acceptance of grossly leaking components. Furthermore, helium mass spectrometry has not been accepted as a means for gross leak detection in these standards, and recent work has verified that it is possible for grossly leaking initiators to inadvertently escape detection when using helium tracer gas methodologoies.[13] The research described herein is part of a broader effort to investigate the phenomenon of gross leak detection in bridgewire initiators in more detail.

A comprehensive understanding of leak phenomena is difficult without *a priori* knowledge concerning a physical description of the actual leak path. This is often the case in real devices where leak paths of complex geometry or a plurality of leak paths of varying sizes and shapes may exist. A key element of the work described herein is the use of a diluted mixture of a radioisotope containing gas (0.01 percent ^{85}Kr in air) to establish the flow rate of gas emanating from specially-prepared leak test specimens. A Radiflo leak detection apparatus is used to force the radioactive gas mixture at elevated pressures into the specimens for specified periods of time, after which the specimens are withdrawn from the apparatus and their contents monitored using a scintillation crystal detection system. Since gamma rays emitted in the decay of ^{85}Kr are able to penetrate the walls of the specimens, the rate of reduction in scintillation signal can be correlated to the gas leak rate using different predictive flow models. The objective of this research is to establish a population of geometrically well-defined standards to allow further investigation of the flow of gases from small cavity devices.

APPROACH AND METHODOLOGY

Of paramount concern in this work is the fabrication of an array of test specimens that are compatible with the Radiflo test apparatus in order to produce high quality and repeatable results. Since the Radiflo process and the use of radioactive tracer gases in leak detection have been thoroughly reported in the literature[14-17], emphasis is placed on the design and manufacture of the test specimens. Future disclosures will detail parameters used in the Radiflo process and modifications made to the scintillation detection system to optimize results from this research.

Test Specimen Design, Fabrication, and Characterization

The shape of the specimens is dictated by several constraints related to the physical dimensions and sensitivity of the scintillation crystal, laser drilling and machining capabilities, welding requirements, and repeated exposure to elevated pressures. All specimens were fabricated from type 304 VAR (vacuum arc re-melt) stainless steel, chosen for its corrosion resistance, welding characteristics and lack of pores, inclusions, and imperfections. Since the scintillation crystal is most sensitive when a radiation source is positioned at the bottom of the scintillation crystal, the specimens are designed so that they can be placed flat against the lower surface of the well. Each specimen has the same external dimensions so only the internal cavity volume and leak path geometry vary between different specimens. Specimens with internal volumes ranging from one cm^3 to 0.0001 cm^3 were manufactured. A cut-away representation of a one cm^3 specimen is illustrated in Fig. 1.

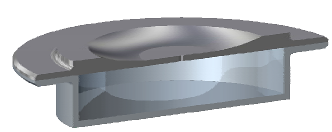

Figure 1. One cm^3 test specimen.

Since the test specimens contain both an internal cavity and a leak path, each specimen is fabricated from two individually-prepared coupons. Base coupons contain cavities machined using a CNC lathe, while lid coupons feature the laser drilled orifices. Mating surfaces are polished with 1200 grit sandpaper attached to a datum table, as surface grinding is not practical due to extreme heating generated in the process, which causes warping of the coupons.

A primary concern with the two-piece design is the possible distortion of the two mating surfaces during the welding process used to join the coupons. Excessive heat can warp or distort the sealing surfaces, possibly leading to porous or otherwise non-hermetic welds that will ultimately affect the leak rate measurements from the specimens. Therefore, to facilitate welding, the base and lid coupons are fabricated so that a thin 508 μm thick lip of material is retained along the periphery of each item. The increased thickness of the coupons toward the center of each item is required to firmly retain the coupons during the machining processes, as well as provide sufficient material for creation of the required cavity volume in the case of base coupons.

Orifices are laser drilled by GSI Lumonics of Northville, Michigan and Resonetics of Nashua, New Hampshire. To produce well-defined approximately cylindrical orifices, the laser drilling process is limited to an aspect ratio of 25:1, defined as the length of the orifice divided by its diameter. Therefore, to aid the laser drilling process, the material thickness of the lids is not constant and reduces from about 1.27 mm (0.05 in) near the outside diameter to 508 μm at the center. Given this thickness of material, successful production of orifices with diameters smaller than 20 μm in diameter can not be guaranteed. Nevertheless, imprecise orifices with diameters measuring approximately 10 μm or less have been fabricated.

Prior to welding, both the cavity volume and the orifices are photographed in an attempt to verify their dimensions. Depending on the size of the orifice, dimensions are measured using two different apparatuses. The largest orifices (100 μm, 50 μm, and 25 μm) are measured using an Olympus PMG-3 Inverted Metallograph Inspection Microscope. Characterization of the small orifices is considered particularly important since any geometrical information will likely become important to help explain anomalies in leak rate measurements. Orifices less than 25 μm are measured using an AMRAY 1830 scanning electron microscope. Orifice images are taken on both the inlet side (the side oriented towards the laser) and the exit side.

Examination of these images indicates that orifices with intended diameters of 100 μm, 50 μm, 25 μm, are quite accurate, with only slight aberrations from circular geometries. As expected, orifices with smaller diameters begin to deviate substantially from an ideal cylindrically shaped passage to a more conically shaped channel. The smallest orifices attempted appear to resemble porous, torturous paths.

Verification of Hermetic Welds

Since the test specimens are a two-piece design, it is necessary to verify that the circumferential weld used to join the lid and base components constitutes a hermetic seal. A procedure was developed in which the Radiflo operating cycles are manually manipulated so that a known amount of ^{85}Kr can be introduced into individual test specimens. Specimens are first evacuated in a 0.5 mm Hg vacuum environment for prolonged periods of time (usually 24 hours), after which they subjected to the tracer gas mixture at atmospheric pressure for a period of time determined by their expected leak rate. Special metal disks are then carefully bonded in place such that the orifice is temporarily sealed. The gas concentration in the specimens can then be monitored as a function of time using the scintillation crystal apparatus. A reduction in scintillation counts as a function of time can be attributed to a leak through the temporary seal covering the orifices or a leak in the circumferential weld of the specimen. This technique is also used in the determination of concentration of ^{85}Kr within the test specimens during leak tests.

FINDINGS; CONCLUSIONS; RECOMMENDATIONS

Preliminary work indicates that the rate of gas loss from the test specimens can be resolved using the scintillation crystal detection apparatus. Initial experiments have been performed on the one cm^3 test specimen with a nominal 10 μm diameter orifice, subjected to the tracer gas mixture with a specific activity of 235 μCi/atm cm^3. In this case, the test specimen was subjected to a pressure of 929 kPa (135 psia) for an 18-minute period. Upon completion of this pressure soak cycle, the specimen was delivered to the scintillation crystal in approximately 20 seconds. The well crystal was continually purged with dry nitrogen and evacuated to remote surroundings so that any residual krypton gas was removed from the environment. Fig. 2 illustrates the reduction in scintillation events as a function of time. The reduction in scintillation is quite rapid, apparently indicative of a large leak rate.

It is important to understand the ramifications of the duration of the pressure soak cycle on the initial pressure, and therefore initial tracer concentration, within the specimen. The effect of different pressure soak times on the initial scintillation count for the one cm^3, 10 μm orifice specimen is shown in Fig. 3. Initial scintillation rate decreases if the duration of the

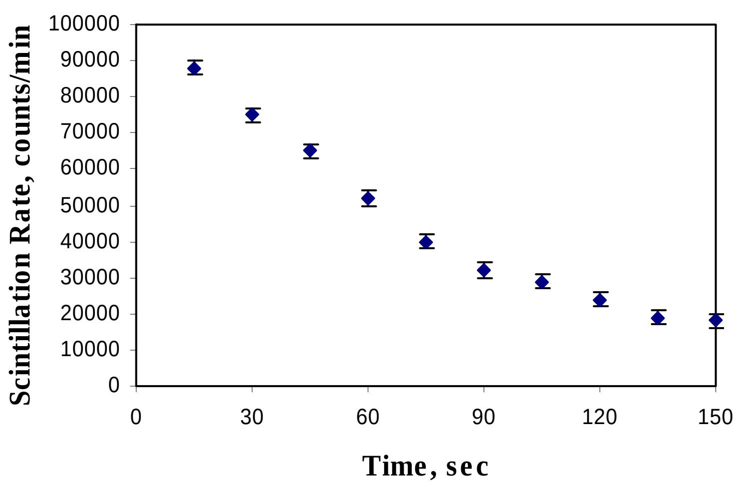

Figure 2. Scintillation rate for a one cm^3, 10 μm orifice small cavity specimen.

pressure soaking cycle is less than approximately 3 minutes. Thus it appears that the leak rate is large enough to essentially equilibrate conditions within the cavity for pressure soaks times in excess of three minutes. This information can be used to infer the magnitude of the gas leak rate.

Although the exact leak rate from this specimen is not initially known, and passage geometry may have an affect on the flow, the rate can be estimated using viscous flow theory[18]:

$$Q = \frac{\pi\, r^4}{16(\mu)(L)}\left(P_i^2 - P_o^2\right) \qquad (1)$$

where Q is the actual leak rate, μ is the gas viscosity, r is the radius of the (cylindrical) leak path, L is the length of the leak path, P_i is the internal pressure within the cavity, and P_o is the external pressure. Substituting values for the 1 cm^3 specimen with a 10 μm orifice, assuming ideal gas behavior at 300 K, and taking the initial pressure in the specimen as 929 kPa, actual leak rate is

$$Q = 9.4 \times 10^{-4}\ \frac{\text{Pa m}^3}{\text{sec}} \approx 1 \times 10^{-3}\ \frac{\text{Pa m}^3}{\text{sec}}$$

Following Ruthberg[14], after a period of pressure soak (T), the gas flow rate from a cavity as a function of time can be expressed as:

$$P_i = P_B\left\{1 - \exp\left(\frac{-Q_s T}{P_s V}\right)\right\}\exp\left(\frac{-Q_s t}{P_s V}\right) \qquad (2)$$

where Q_s is the standard leak rate and V is the cavity volume. The behavior of Eq. (2) is shown in Figure 4 for three different assumed values of standard leak rate. The results indicate that a standard leak rate of magnitude of 1 x 10^{-3} Pa m^3/s approximately matches the pressure decay indicated by the reduction in scintillation rate. A leak rate an order of magnitude larger would result in complete escape of the gas initially within the cavity in approximately 50 sec.

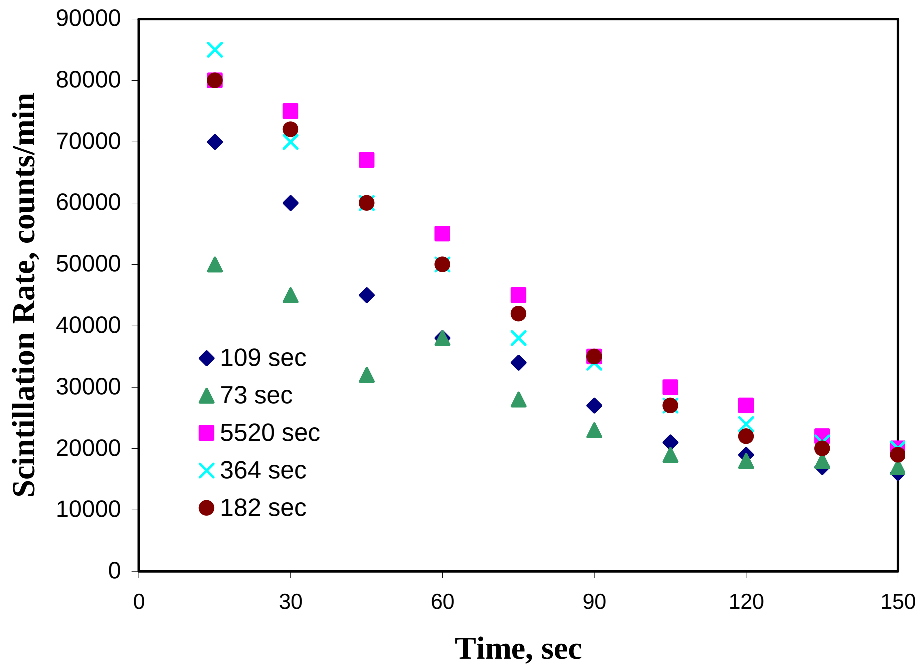

Figure 3. Influence of pressure soak duration on initial scintillation rate**.**

Conversely, Fig. 4 indicates a leak rate one order of magnitude would fail to completely fill the cavity with tracer gas given a pressure soak duration of three minutes.

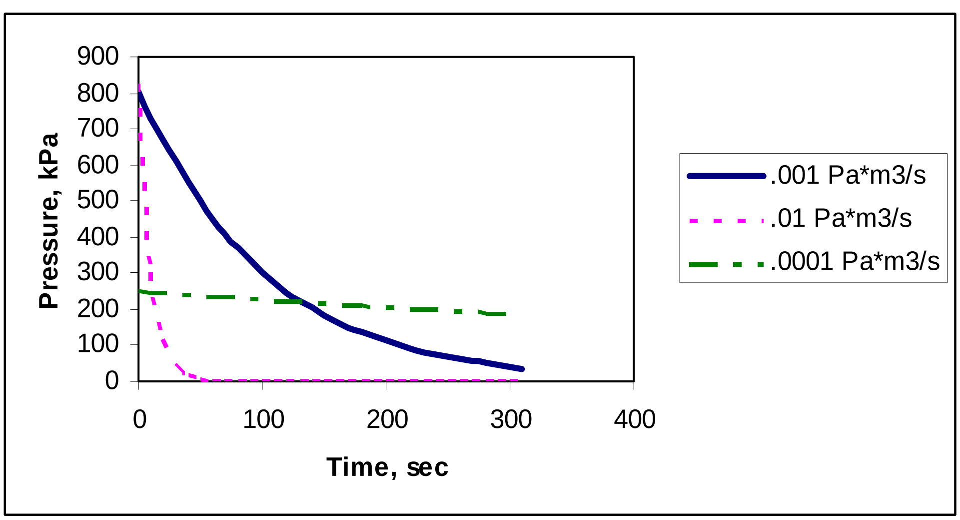

Figure 4. Internal pressure as a function of leak rate.

These results help validate the concept of monitoring scintillation rate as a function of time as a method of quantifying gross leak behavior from small cavity devices. To correlate predictive leak rates, scintillation rate must be directly related to tracer gas concentration.

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