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Hydrogen Gettering the Overpressure Gas from Highly Radioactive Liquids

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HYDROGEN GETTERING THE OVERPRESSURE GAS
FROM HIGHLY RADIOACTIVE LIQUIDS

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ABSTRACT

Remediation of current inventories of high-activity radioactive liquid waste (HALW) requires transportation of Type-B quantities of radioactive material, possibly up to several hundred liters. However, the only currently certified packaging is limited to quantities of 50 ml (0.01 gal) quantities of Type-B radioactive liquid. Efforts are under way to recertify the existing packaging to allow the shipment of up to 4 L (1.1 gal) of Type-B quantities of HALW, but significantly larger packaging could be needed in the future. Scoping studies and preliminary designs have identified the feasibility of retrofitting an insert into existing casks, allowing the transport of up to 380 L (100 gal) of HALW. However, the insert design and ultimate certification strategy depend heavily on the gas-generating attributes of the HALW. A non-vented containment vessel filled with HALW, in the absence of any gas-mitigation technologies, poses a deflagration threat and, therefore, gas generation, specifically hydrogen generation, must be reliably controlled during all phases of transportation. Two techniques are available to mitigate hydrogen accumulation: recombiners and getters. Getters have an advantage over recombiners in that oxides are not required to react with the hydrogen. A test plan was developed to evaluate three forms of getter material in the presence of both simulated HALW and the gasses that are produced by the HALW. These tests demonstrated that getters can react with hydrogen in the presence of simulated waste and in the presence of several other gases generated by the HALW, such as nitrogen, ammonia, nitrous oxide, and carbon monoxide. Although the use of such a gettering system has been shown to be technically feasible, only a preliminary design for its use has been completed. No further development is planned until the requirement for bulk transport of Type-B quantities of HALW is more thoroughly defined.

BACKGROUND AND STATUS OF RADIOACTIVE LIQUID WASTE GENERATION, STORAGE, AND TRANSPORTATION

Defense production and waste processing has produced approximately 353,000 m^3 (93.3 million gals) of complex radioactive waste. The majority of this waste is currently being stored in underground storage tanks (UST) at two locations, the Hanford Site and the Savannah River Site (Cruse et al. 1992). The current plan for the remediation of this waste involves characterization, pretreatment, and bench-scale testing (Straalund et al. 1992, Morford and Bridges 1993, and Barker et al. 1993). All three of these remediation processes require that the waste be transported, and in some cases this involves offsite shipment of Type-B quantities of radioactive liquid waste.

The U.S. Department of Energy (DOE) and the Nuclear Regulatory Commission (NRC) currently have no packagings certified specifically for shipment of large volumes of Type-B quantities of radioactive liquid. The largest quantity of Type-B liquid that can be transported is 50 ml (0.01 gal), using the Post Accident Sample-1 cask (PAS-1) (Nuclear Packaging 1989). However, Westinghouse Hanford Company (WHC) is currently obtaining an amendment to the PAS-1 cask certification (VECTRA 1995), allowing the transport of up to 4 L (1.1 gal) of radioactive liquid in Type-B quantities to offsite laboratories for analysis. The PAS-1 cask will primarily be used by the Hanford Site Tank Farm Characterization and Laboratory organizations to ship radioactive waste tank samples to offsite laboratories, including the Idaho National Engineering Laboratories (INEL) and Los Alamos National Laboratories (LANL). The payload will consist of tank samples, liquids and sludges, containing mixed fission products primarily Cs^{137} and Sr^{90}. In addition to the PAS-1 certification amendment, several DOE sites require bulk packagings for the transfer of Type-B quantities of radioactive liquids between different onsite storage and processing areas where no other transfer method is feasible. To meet this need, international developments in transport of radioactive liquid waste were studied.

Internationally, bulk-quantities of radioactive-liquid shipments have

been transported for many years. For example, between 1956 and 1962, the Commissariate A L'Energie Atomiqe in France developed and use-tested 38 models of standardized liquid packaging (the "Cendrillon" cask family). By 1974, 188 packages were certified by the International Atomic Energy Agency (IAEA) for long-distance transfer of 3 L (0.8 gal) to 200 L (53 gal) of highly radioactive liquids in Europe (WHC 1993). Recently, the Germans have begun a bulk-quantity radioactive liquid transport campaign. The intent is to remove HALW from the Karlsruhe Reprocessing Plant to the Pamela vitrification facility in Dessel/Belgium. For this purpose the CASTOR V/HAWC was developed with a capacity of 3,500 L (915 gal) (Fleisch et al. 1994 and Spilker et al. 1994). The French, who also need larger transport packaging, have developed three packagings, the LR-54-56 and -44, all larger than the largest Cendrillon cask. These large French casks range in capacity from 1,280 L (340 gal) to 19,500 L (5,100 gal). As mentioned, the United States has no equivalent packagings and these existing foreign packagings cannot be certified in the United States at the present time. However, one of the LR-series transporters, the LR-56, has been modified to the LR-56/H and procured to meet the need for onsite liquid radioactive material transfers (WHC 1995). The completed system was delivered to the Hanford Site in December 1995. Similar systems are being procured for the Oak Ridge and Savannah River Sites in 1996.

The LR-56/H system addresses many of the onsite HALW bulk transportation needs within the DOE, however it cannot be used off site because it does not have a DOE or NRC Certificate of Compliance demonstrating compliance with U.S. regulatory standards. Therefore, the potential need for a bulk packaging for offsite shipment of Type-B quantities of radioactive liquid still exists. Developmental work has been conducted by the DOE to assess the feasibility and preliminary design of a certifiable Type-B package for bulk-quantity, high-activity liquids. A feasibility study (WHC 1993) showed that a High-Activity Liquid Packaging (HALPAK) concept was technically feasible.

HALPAK CONCEPT

The HALPAK concept (Riley et al. 1994) uses certified casks as an overpack for containment vessels specifically designed for the harsh environment of HALW. Originally, it was hoped to develop a conceptual design that would represent the largest technically feasible package for HALW shipments. The cask body of the largest overpack available, the Pacific Nuclear (NUPAC) 125-B, was used for a general technical feasibility study. The scoping study (Meinert et al. 1994) demonstrated that the concept was feasible with respect to the structural, thermal, shielding, and criticality requirements of 10 Code of Federal Regulations (CFR) 71 (NRC 93). The scoping study used the 125-B cask body for the primary containment, and a simplified 5.08-cm (2-in.) -thick inner pressure vessel for the secondary containment. This configuration results in a HALW capacity of about 3,800 L (1,000 gal). However, a fully loaded 125-B weighs 400,000 kg (181,500 lbs) and a package this heavy creates several operational obstacles. Needs assessments determined that bulk quantities this large were not viable in light of the operational barriers of physical size and weight. Quantities of HALW up to 380 L (100 gal) were then identified as a target value to perform more detailed scoping studies. Two smaller overpacks were considered, the NUPAC

72-B and the General Electric GE-2000. The 72-B is designed to transport remote-handled transuranic (TRU) waste intended for the Waste Isolation Pilot Plant (WIPP), and is basically a scaled down version of the 125-B. The 72-B represents the most feasible size of package that can serve as an overpack, providing a capacity of about 380 L (100 gal). Additional calculations and a preliminary conceptual design report that analyzes several design options, showed that this smaller package concept also satisfies the intent of 10 CFR 71 (WHC 1994).

The conceptual design report concluded that additional research is required to ensure that the HALW's physical, chemical and radiological characteristics pertinent to design development are studied and documented. The characteristic most pertinent to the containment vessel insert design is the gas-generation phenomena associated with radioactive liquids. As a result of safety concerns at the Hanford Site, several USTs have been carefully studied to determine the nature, content, and generating mechanism for the gases that are produced. This information has been used to bound the gas-generating estimates for HALW that could be transported in a package.

GAS GENERATION INSIDE USTS

Radioactive liquid wastes generate a variety of gases as a result of radiolysis, thermolysis, and organic and chemical activity. For example, Hanford Tank 101–SY, produces approximately 30 to 35 percent H_2, 25 to 30 percent N_2O, 20 to 25 percent N_2, 12 to 18 percent NH_3, and less than 1 percent CH_4 (Babad et al. 1992 and McDuffie 1994). Most gases do not pose a problem for packaging safety. However, hydrogen and nitrous oxide, when combined in quantities exceeding their lower flammability limit, can deflagrate. A hydrogen/nitrous oxide deflagration, depending on the concentrations, can typically exceed a factor of ten increase in pressure. For stoichiometric mixtures of hydrogen and nitrous oxide, it is possible to achieve a detonation (Cashdollar et al. 1992). For these reasons, the NRC (1984) has released Information Notice No. 84–72, *Clarification of conditions for waste shipments subject to hydrogen gas generation*. This notice outlines the method to ensure that hydrogen gas generated will not exceed 5% by volume and that any portion of a package (secondary container) exposed to hydrogen will have a 5% by volume oxygen limit. Given the fact that HALW produces hydrogen gas, and that NRC certified packagings cannot be vented, several possible methods exist to overcome the hydrogen-accumulation problem (Henrie et al. 1986). These include: 1) limiting the shipping time, therefore not allowing the generated gases to exceed the lower flammability limit, 2) reducing the amount of waste per package volume, thus providing a large void space, or 3) providing gas mitigation, permanently or temporarily canceling the gas generation.

The moment that a HALW package is sealed, the gases begin to concentrate, and potentially flammable concentrations must be accounted for, from both certification and safety (operations) points of view. A package with a gas-mitigation system will provide a safer package and yield several benefits, i.e., larger quantities of materials can be shipped in a smaller package, shipping times are more flexible and operational safety is improved.

SOLUTIONS TO HYDROGEN ACCUMULATION

Passive gas-mitigation systems, i.e., hydrogen recombiners, have been used for many years and are very effective at combining hydrogen with oxides (Henrie et al. 1986, Nuclear Packaging 1991). Their only shortcoming is that an oxide must be present. In a sealed package containing a gas-producing waste and hydrogen recombiners, the hydrogen will combine with oxides until either the hydrogen or oxide is consumed. Hydrogen is typically produced more abundantly than oxides in radioactive waste. This imbalance causes the oxide to be consumed and hydrogen to continue to accumulate. Although no oxide will be present to allow a deflagration to initiate, a safety problem exists. It is generally assumed that a radioactive hydrogen pressure vessel should be avoided, and in fact, is the NRC's intent with Notice No. 84–72.

To develop a strategy to assess the most likely to-be-certified cask insert design for HALW transportation, several design alternatives were considered. Table 1 is a matrix showing the HALPAK insert concepts. Each concept is for an insert that serves the same basic function; to provide primary containment for HALW during shipping and handling. The interface system is identical for all four concepts. Each vessel is loaded and unloaded in the vertical position, manually coupled to liquid and gas piping, and remotely operated from a control room. The concepts do vary in specific areas, such as maximum allowable waste volume, inherent shielding, and vessel design pressure.

Concept (a) includes gas-mitigation hardware to control hydrogen gas accumulation, but will also safely contain the pressure generated in the event of a mitigation hardware failure. Concept (b) also includes gas-mitigation hardware; however, the vessel design pressure assumes that the passive mitigation hardware always works properly. Concept (c) does not rely on gas-mitigation hardware; this concept limits the allowable HALW shipping volume and relies on an inert gas overpressure to dilute the percent of hydrogen present in the vapor space. Concept (d) uses shipping volume control as the method of pressure control and gas-mitigation to control the presence of hydrogen in the vapor space.

Table 1. – Matrix of HALPAK Insert Concepts and Features.

Concept Feature	Concept (a)	Concept (b)	Concept ©	Concept (d)
Waste Volume	367.2 L (97 gal)	367.2 L (97 gal)	113.6 L (30 gal)	56.8 L (15 gal)
MNOP[1]	9.0 MPa (1,300 psi)	9.0 MPa (1,300 psi)	19.3 MPa (2,800 psi)	0.55 MPa (80 psi)
Design[2] Pressure	24.1 MPa (3,500 psi)	13.8 MPa (2,000 psi)	24.1 MPa (3,500 psi)	1.0 MPa (150 psi)
Off-Design Condition[3]	19.3 MPa (2,800 psi)	9.0 MPa (1,300 psi)	19.3 MPa (2,800 psi)	0.86 MPa (125 psi)
Vessel Weight	32,917 N (7,400 lbf)	24,465 N (5,500 lbf)	32,917 N (7,400 lbf)	5,338 N (1,200 lbf)
Gas Mitigation	Required	Required	Not Required	Required
Inherent Shielding	Included	Not Included	Included	Not Included
Head Thickness	12.7 cm (5 in.)	10.8 cm (4.25 in.)	12.7 cm (5 in.)	3.175 cm (1.25 in.)
Shell Thickness	5.1 cm (2 in.)	3.5 cm (1.4 in.)	5.1 cm (2 in.)	0.6 cm (0.25 in.)

[1]MNOP: The pressure that would develop inside the HALPAK insert after 1 year.

[2]Design Pressure: Sections III and VIII maximum pressure based on shell and head thickness

[3]Off-Design Condition: Concept (a): The pressure that would develop after 1 year during a design-basis fire and with a nonfunctional gas-mitigation system. Concept (b): The pressure that would develop after 1 year during a design basis fire and with a functional gas-mitigation system. Concept (c): The pressure that would develop after 1 year during a design-basis fire. Concept (d): The pressure that would develop after 1 year during a design-basis fire.

A detailed representation of HALPAK Concept (a) is shown in Figure 1 (WHC 1994). This figure represents one of the four options presented in Table 1. The vessel shown in Figure 1 is the containment vessel designed to hold the HALW, and is inserted into a cask overpack, i.e., the 72-B. As can be seen on the left side of Figure 1, there is a volume dedicated for a gas-mitigation system. This volume represents the upper limit of mitigation hardware required when the containment vessel is filled with the most reactive HALW. This volume has an attached stinger that allows hydrogen gas to be exposed to the volume regardless of cask orientation. At the time of the preliminary design, how the gas-mitigation system would react to the physical presence of the
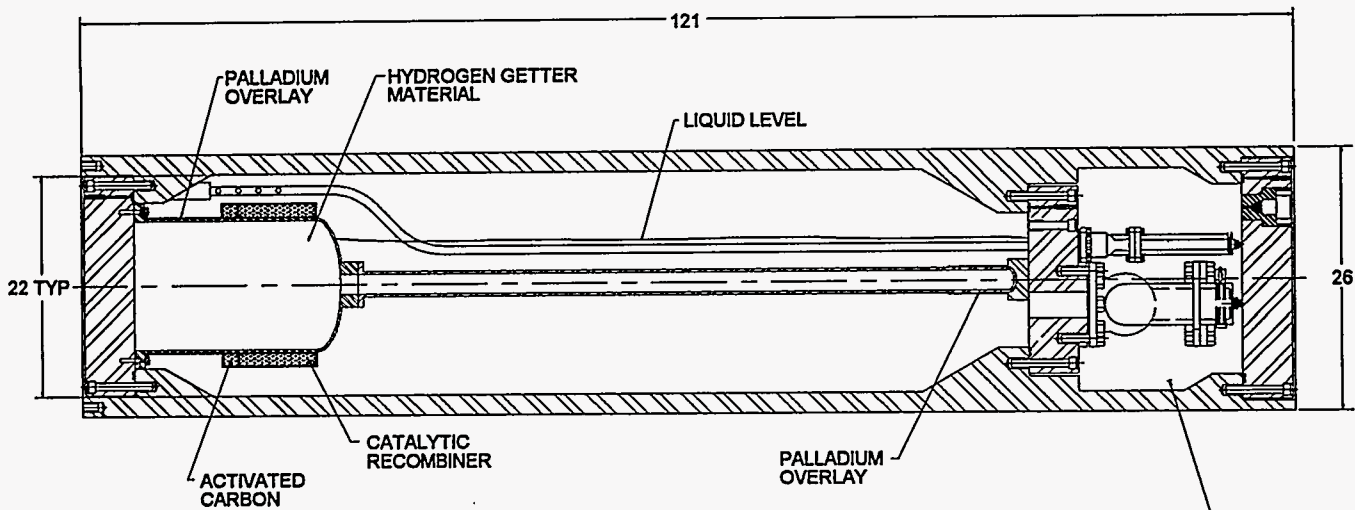
Figure 1, HALPAK Gas-Mitigation Concept 1/4 (simplified); All Mitigation via Getter/Recombiner.

HALW or the other gasses that are generated by the HALW was not known. A test program was initiated to access the potential inhibition that the HALW products could create on the mitigation system.

HYDROGEN GETTERING BACKGROUND

Hydrogen accumulation in the absence of oxides can be prevented by using getters. Crystalline getters (Courtney and Harrah 1977), will irreversibly remove hydrogen by catalytic hydrogenation of unsaturated organic compounds without the need or existence of oxides.

The AlliedSignal Aerospace Co. Federal Manufacturing & Technologies, formerly the Kansas City Division (AS–KCD), has had extensive experience in crystalline organic getter technology since 1978 developing organic hydrogen getters for the DOE Nuclear Weapons Complex (Smith 1987). The compound DEB; 1,4-bis(phenylethynyl)benzene (Havens et al. 1981) is the fourth generation of getter development and is the standard DOE production hydrogen getter material. DEB has been fully characterized for use inside dry weapon environments (Tinnel and Leckey 1989). In addition, DEB has been characterized for use as a tritium getter (Shepodd et al. 1990). There is however, limited experience in using AS-KCD getter technology with certified packaging. Sandia National Laboratories, Albuquerque, New Mexico, has obtained a DOE certification for the H1616 tritium container. This container supports the limited life component exchange program for tritium bottles. The design of the H1616 container uses two O-rings to provide a leak-tight containment vessel. Tritium, however, can permeate an elastomer O-ring. This could lead to a violation of the tritium containment criteria of 10 CFR 71 (NRC 1993) if the O-rings become exposed to the tritium environment. The solution was to fill the area between the inner and outer O-rings with DEB getter. The DEB would react with all the hydrogen (tritium in this case) escaping through the first O-ring and not allow any to reach the second O-ring. In this application, the DEB is sealed in, protected by an O-ring from both the contents and the environment (Gilliom et al. 1992).

DEB getter has also been successfully used at Argonne National Laboratories/West to protect spent enriched uranium metal fuels from hydrogen and water corrosion. This application placed the DEB in direct contact with the dry fuel inside an O-ring-sealed container.

For radioactive waste shipments requiring hydrogen control in the vapor space, the getter needs to be located in the containment vessel. It may be possible for getter materials to be isolated from the HALW, yet still react with it. WHC has filed an Invention Disclosure for an externally located Gas Control Unit. This unit would have a gas-permeable splash shield covering a thin palladium plate that would release hydrogen (much like a hydrogen purifier) into a isolated getter environment. This external gas control unit has not been tested or developed.

If the getter is placed in the containment vessel, it is exposed to the gases and potentially comes in direct contact with the waste form, e.g., liquid. This contact with both the liquid and vapor could poison the getter, making it unable to remove the hydrogen. The location of the DEB getter in the HALPAK concept can be seen in Figure 1. The conceptual design was finished before the getter testing outlined in the following paragraphs, and shows an attempt to isolate the getter material from the HALW while the mitigation system is located inside the vessel. How the getter material would react to the HALW was not known. As a result of this concern, WHC asked AS–KCD to perform hydrogen-getter (DEB) inhibition testing (Schicker 1995, and Riley et al. 1995).

To qualify the DEB getter for the environment in a typical radioactive transportation package, two environments were simulated:

1) a vapor environment consisting of the potential getter poisons in representative concentrations generated from the waste in a typical UST (McDuffie 1994), e.g., ammonia, nitrous oxide, and carbon monoxide, and 2) the waste environment, consisting of a simulated nonradioactive synthetic liquid waste, constructed from a hypothetical recipe representing a typical UST.

AS-KCD has already tested the effectiveness of DEB getter in a high-radiation environment. Its performance begins to deteriorate noticeably when it is exposed to greater than 1,000 Mrad of gamma radiation. Also, long-term tritium (beta) radiation was evaluated before the H1616 tritium shipping container was accepted (Gilliom et al. 1992). The radiation content in a transportation package will not exceed this value.

The synthetic waste used in the DEB inhibition tests was a highly saturated and alkaline aqueous solution with a 5-molar sodium ion concentration (Delegard 1994). The following table shows the constituents of the synthetic waste used to test the DEB getter, the quantities listed are for a 1-L sample solution.

Table 2. Nominal Composition, Hanford Waste Solution Used as a Synthetic Waste for DEB Testing

Chemical	Concentration	Weight
$NaNO_2$	0.029 M	7.8 g
$NaNO_3$	2.44 M	207.1 g
NaOH	1.53 M	61.4 g
Na_2CO_3	0.06 M	6.5 g
$NaAl(OH)_4$	0.23 M	27.0 g
$Na_3PO_4*12H_2O$	0.13 M	49.4 g

Four evaluations on three getter configurations were performed to determine if certain gases generated by the radiolysis and thermolysis of liquid hazardous waste have a negative impact on DEB getter performance. Also, DEB getters were tested after being wetted by a simulated waste supernate.

The three getter configurations included: 1) a heat-sealable polyolefin bag filled with 5 g of granulated DEB getter, 2) 5 g of 2.8-mm (0.110- in.) -diameter by 3.05-mm (0.120-in.) -tall right cylindrical pellets as produced for standard DOE production getter products, and 3) a silicone boot made from tough silicone rubber filled with 1 g of granulated DEB powder and capped with a thermoset plastic stopper. Five boots were used to keep the getter quantity constant at 5 g per test.

The first two evaluations used standard AS-KCD getter production hydrogenation test equipment to establish a baseline for the three proposed getter configurations both wet and dry. This test equipment records the pressure change of a closed system that has a measured quantity of getter, a known volume, and a specified initial pressure of 100-percent hydrogen gas. The system records the pressure change as the getter reacts and hydrogen is removed from the gas phase. The percent of reaction for a given getter sample is determined by pressure change and gas law calculations.

The last two evaluations used a special test set-up to evaluate getter performance when exposed to specific gas mixtures. The gases were selected based on UST measurements taken at the Hanford Site. These gases were evaluated individually with hydrogen and as a combined mixture to assess any change in DEB getter performance. Also, several of the samples were subjected to the simulated waste to ascertain if the wetting the DEB getter will substantially hinder the hydrogen-DEB reaction. The test atmosphere was measured for remaining hydrogen as percent by syringe extraction and analysis by gas chromatography.

Baseline testing in a 100-percent hydrogen atmosphere identified two items of interest. First, the silicone rubber in the boot is permeable to hydrogen, but it does slow the hydrogen-DEB reaction down when the rate is compared to the granulated getter in a polyolefin bag or loose pellets in a sample tray. The slow down may be of no consequence when dealing with a gradual hydrogen production rate as opposed to the 100-percent hydrogen atmosphere used in this test. The second observation was that the getter does not readily wet when exposed to a simulated 5-molar sodium ion concentration of supernate synthetic waste. The pellets float and the surface tension of the bag and boot keep the solution from wetting them.

The getter inside the bag will wet, however, when the liquid is forced inside the bag by vacuum. Vacuum is used at the beginning of all tests to remove oxygen before adding hydrogen. When tests were performed with the bag under a layer of synthetic waste after evacuation to 15-20 mm Hg, the rate of hydrogenation dropped considerably. However, when the same bag was retested wet but not submerged the rate doubled. Because the granules of getter were now wetted during the previously applied vacuum, the hydrogen was forced to diffuse through this liquid layer to reach the catalyst on the getter. Although the total uptake at 24 hours was only 20 percent of the value obtained by the dry bag, the rate of hydrogenation increased steadily over time. If the test had been continued for possibly 72 hours, the getter would have reached the same total capacity as seen with the surface-wetted part or the dry part.

Testing with the gas mixtures expected to be generated during transportation of the liquid indicated that only carbon monoxide would be of concern for the getter. Carbon monoxide (CO) reduced the overall rate at which the getter would remove the available hydrogen, but the CO did not stop the getter from reaching its hydrogen capacity. Typically, with all the getter samples the hydrogen concentration would be reduced to levels below 0.1 percent within the first hour if CO was not part of the mixture. When CO (1 percent by volume) was part of the mixture, achieving less than 0.1-percent remaining hydrogen would take from 2 to 10 times as long. The longer times were typically obtained after the same getter had been exposed to CO twice before. CO does not appear to poison the catalyst. The reaction that occurs is more of a temporary blockage of the catalyst site by the CO as it is absorbed by the carbon portion of the catalyst mixture. It was also observed that the ammonia and nitrous oxide were absorbed by the carbon. However, no slowdown

of the hydrogen-DEB reaction was identified when either or both of these gasses were present in quantities as high as 30 percent by volume.

When the gas inhibition tests were performed on synthetic waste-wetted samples, the same type of rate reduction seen with the 100-percent hydrogenation tests was observed. The gettering rate was reduced but not stopped. The slowest rate occurred when the getter was tested completely submerged. The same diffusion problem occurs where the hydrogen has to diffuse through the layer of liquid to get to the catalyst on the getter. When the excess fluid is shaken off or the part is allowed to dry, the rate of reaction goes right back up to where less than 1 percent of the hydrogen remains after 1 hour of exposure. When the boots are used the rate is further reduced because of the layer of silicone rubber. Repeated additions of CO slow the hydrogenation rate each time, but this type of test does not simulate the way the gasses would be generated from the actual hazardous waste liquid. CO would not be added in large quantities. The rate would be gradual and much less than the rate of hydrogen generation. The slowest tested rate in this study is expected to be several times faster than the actual generation rate of both the hydrogen and the carbon monoxide.

Figure 2 represents the observed inhibition effects that CO has on DEB getter inside a polyolefin bag. The same observations were identified on the pellets and silicon boot parts. The pellets tracked at the same reaction rate, the silicone boot parts had an observed time lag of approximately 240 minutes to achieve the same level of percent hydrogen remaining. Note: When ammonia or nitrous oxide is part of the gas mixture, the measured hydrogen values are higher because the overall volume of the mixture is reduced by approximately 5 percent because of the absorption of these gases onto the catalyst component of the DEB getter.
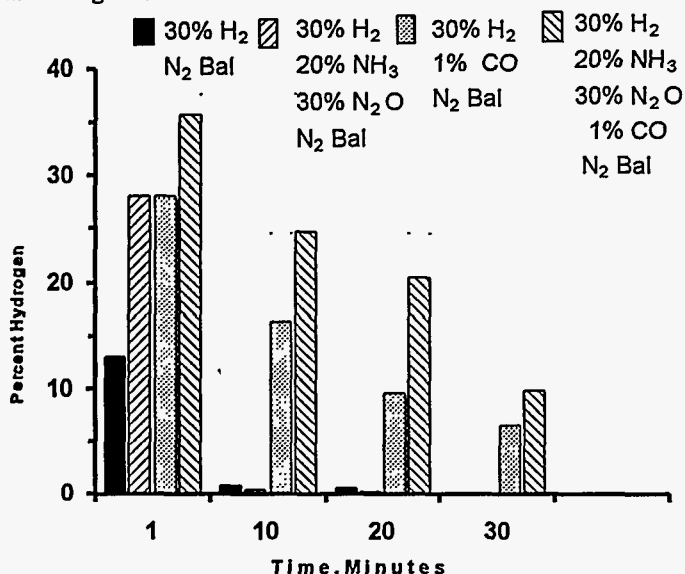

Figure 2, Hydrogen Reaction (% Remaining) vs Time with Different Gas Mixtures Using 5 Grams of DEB Inside a Dry Polyolefin Bag.

CONCLUSIONS AND RECOMMENDATIONS

These studies assessed getter performance when the test atmosphere had been fully developed. Testing while the gasses are generated at the estimated evolution rate would provide the final evidence that the DEB getter will provide the required hydrogen mitigation. Also, wet testing without vessel evacuation should be evaluated to ascertain if the hydrogenation rate changes observed would repeat if the parts had not been subjected to vacuum while in direct contact with the synthetic waste solution.

The recommended getter configuration for the transport of liquid waste would be either the polyolefin bag or the silicone boot. The pellets, although very reactive, would be an extra processing expense that appears unnecessary. The boot part kept the synthetic waste completely away from the getter; however the boot is an extra design feature that also may not be necessary. The boot configuration by design will have a slower hydrogenation rate because of the diffusion characteristics of the silicone rubber. The polyolefin bag, therefore, may well be the most cost-effective and rate-effective choice. The liquid waste did not soak through the material until vacuum was applied. Several layers of this material would keep the bag floating on the liquid, or if desired, the bag could be attached to both ends of the container. Possibly, a long-term test could be devised where several bags of DEB getter are placed in a waste environment that would be agitated in a random fashion for several months. The bags could then be evaluated for hydrogenation and integrity (radiation damage) at the conclusion of the cycle and compared to a control part.

Based on these test conclusions, and pending the outcome of potential future tests, it appears that an external gas control unit, or a carefully designed internal HALW isolated gettering system is not necessary. The getter is not inhibited by the HALW or the by products associated with it, except for the rate reduction caused by carbon monoxide. This rate reduction will only slow down the reaction, not stop it. The combination of a gettering system with a recombiner system will provide a gas-mitigation technique that solves the problem of hydrogen accumulation in sealed containers.

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