

INCREASING TRUPACT-II WATTAGE LIMITS: HYDROGEN G-VALUES AND GETTERS

Eugene J. Mroz, David Finnegan, Phillip Noll
Los Alamos National Laboratory
Los Alamos, NM 87545

Sinisa Djordjevic
DJINDECO Consulting
Albuquerque, NM 87123

Cindy Loehr, Voyko Banjac, Jeff Weinrach, John Kinker
Benchmark Environmental Corporation
Albuquerque, NM 87110

Michael J. Connolly
Idaho National Engineering and Environmental Laboratory
Idaho Falls, ID 83415

ABSTRACT

A substantial fraction of the nation's inventory of contact-handled (CH) transuranic (TRU) waste cannot be shipped to the Waste Isolation Pilot Plant (WIPP) because it exceeds a wattage limit (from radioactive decay) imposed by the TRUPACT-II Safety Analysis Report (SAR) to ensure that the hydrogen concentration in the drum does not exceed the lower flammability limit of 5% (v/v).

The Matrix Depletion Program (MDP) has measured the dose dependence of the hydrogen G-value in simulated TRU waste materials and the effects of key parameters. The experimentally derived dose dependent G-values are reproducible, consistent with results of other studies, and fall within theoretically predicted bounds. The results may be used to revise appropriate sections of the TRUPACT-II SARP and TRUPACT-II Allowable Methods of Packaging (TRAMPAC) to explain and account for the matrix depletion phenomenon. The original TRUPACT-II SARP G-values will be used to establish the wattage limits for newly generated containers. When a container has attained an adequate dose level (in Watt•yr), the lower MDP dose-dependent G-values would be used to establish a higher allowable wattage limit for the container.

Analyses of MDP experimental data indicate that dose dependent G-values lie between 14% and 38% of the applicable TRUPACT-II SARP values after a dose criterion of 0.006 Watt • yr has been met, depending on the waste material. The results are consistent with theoretical expectations for G-value behavior with dose for different waste materials.

The use of hydrogen getters to remove hydrogen from drums is being investigated as another means of increasing TRUPACT-II wattage limits. Laboratory experiments have shown the DEB getter to be effective at removing hydrogen but it is susceptible to poisoning by halogenated VOCs. Chemical kinetic modeling studies are underway to predict its performance in a TRU waste drum. Approaches to mitigate the poisoning problem are under investigation.

INTRODUCTION

Approximately 95% of the waste drums containing transuranic (TRU) waste at Los Alamos National Laboratory (LANL) is considered mixed waste (1) which is waste that contains both a hazardous and a radioactive component. Almost 40% of these drums cannot currently be shipped to the Waste Isolation Pilot Plant (WIPP) because they exceed the thermal power (heat from the decay of transuranic nuclides) limits set forth in the TRUPACT-II Safety Analysis Report (SAR). These wattage limits are derived from estimates of the amount of hydrogen generated by radiolysis during the 60-day shipping period. All Department of Energy (DOE) sites with TRU waste are similarly affected.

Figure 1 shows the percentage distribution of TRU waste drums in the LANL inventory according to their thermal power ratio (T). The thermal power ratio (T) is defined as the thermal power rating of the container, as estimated from inventory information, divided by the present regulatory limit for thermal power for the waste matrix and container type. These estimates assume the TRU wastes are contained in four layers of packaging.

Only those drums with $T < 1$ (~14,400) are presently eligible for transportation to WIPP in the TRUPACT-II (provided they meet all other WIPP waste acceptance criteria). Of the remaining ~9000 drums, ~3000 fall in the range of $1 < T < 3$. An approximately equal number of drums are in the category of $3 < T < 12$. Another ~2000 drums are in the category of $12 < T < 24$. And the remaining 643 drums have $T > 24$.

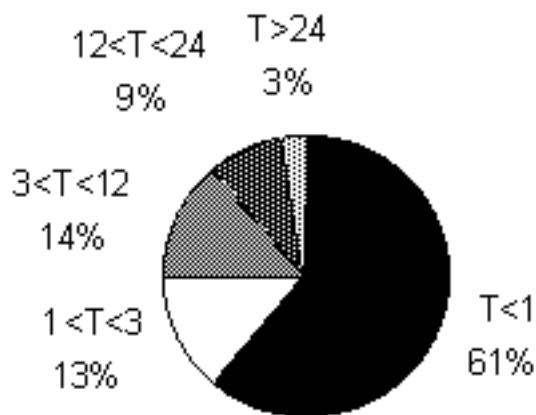


Figure 1. Distribution of TRU waste drums in LANL inventory by thermal power ratio (T).

One strategy for drums with $T > 1$ is to remove the waste materials from these drums and re-distribute and repackage the waste among multiple drums such that each resulting drum is within the allowable wattage limit. This process would potentially result in the creation of several thousand new drums of waste. This approach is both expensive and increases health risks due to

potential exposure during repackaging. Two alternate strategies for drums with $T > 1$ are presented in this paper: 1) recognition that a phenomenon known as matrix depletion reduces the potential for hydrogen build-up and 2) the use of hydrogen getters to remove hydrogen from headspace of the drums

MATRIX DEPLETION PROGRAM

A particle of plutonium adhering to the surface of waste material is continuously irradiating the material with alpha particles. The energy of the alpha particles is sufficient to cause radiolytic changes in the chemistry of the underlying material. When the material is a hydrogenous substance such as cellulose, plastics, or aqueous sludges, the radiolysis products include hydrogen gas. The hydrogen is generated within a small volume that is determined by range of alpha particles within the material.

For any given material, the amount of hydrogen generated depends on amount of energy deposited by the alpha particles. This is called the hydrogen G-value and is expressed in units of hydrogen produced by 100ev of deposited energy. However, the hydrogen G-value for any given material is not a constant. Because of the very limited range of alpha particles within materials, the irradiated volume is being continuously depleted of hydrogen as the cumulative deposited energy. Consequently, the hydrogen G-value decreases as the cumulative dose increases--hence the use of the term "matrix depletion" to describe this phenomenon. This phenomenon has been observed in several studies (2-5).

The Transuranic Package Transporter-II (TRUPACT-II) Matrix Depletion Program (MDP) was established as a joint venture of the U.S. Department of Energy (DOE) National Transuranic (TRU) Program and the DOE Mixed Waste Focus Area, with the objective of investigating the phenomenon of matrix depletion and arriving at dose-dependent hydrogen G-values for contact-handled (CH) TRU waste material types (7). Matrix depletion is the reduction in the gas generating potential, or effective G-value, of a target material. Effective G-value is the gas generation potential of a specific material or matrix due to exposure to ionizing radiation. From experimental and empirical results available prior to the MDP, it was known that matrix depletion decreases the rate of hydrogen gas generation inside CH TRU waste containers. To confirm earlier reports of the dose dependency of effective G-values, the MDP was comprised of three major elements:

- Laboratory experiments for the assessment of effective G-value as a function of dose for several matrices and the effects of experimental conditions, including isotope and heating
- Measurements of effective G-values and hydrogen concentrations in real TRU waste drums and comparisons with effective G-values derived from the laboratory experiments.
- Theoretical analyses using a numerical model that calculates effective G-value as a function of dose by explicitly incorporating fundamental nuclear and molecular mechanisms that result in the generation of hydrogen

Experimental Design

Matrix depletion experiments were conducted at the LANL. The experimental design was an aggregate of several designs, each with two replicates. The first was a 3×2^3 in 24 units, which was a full factorial involving PE, and wet and dry cellulose. Results from this portion of testing were used to determine the effective G-values and evaluate the effects of isotope, matrix, and heating. The second portion of the design involved PVC testing under limited conditions to facilitate comparisons with other materials and to test the hypothesis that effective G-values based on PVC would not be conservative. The third portion of the design was a 2^2 factorial in four units for Envirostone, which had a reduced number of factors because agitation was not relevant. Results from Envirostone would be used to determine effective G-values and factor effects to confirm that experimentally derived G-values were consistent with the current TRUPACT-II SARP G-values for waste type I.

The total number of test cylinders (60) containing the simulated TRU waste matrix materials was determined based on DQOs developed for the MDP (Connolly et al. 1997b). Table 1 shows the breakdown of the number of test cylinders in each experimental setting depicted in the test matrix.

Table 1. Test matrix (number of cylinders of each experimental setting).

Matrix	^{238}Pu				^{239}Pu			
	Normal	Agitated	Heated	Heated and agitated	Normal	Agitated	Heated	Heated and agitated
PE	2	2	2	2	2	2	2	2
Dry cellulotics	2	2	2	2	2	2	2	2
Wet cellulotics	2	2	2	2	2	2	2	2
Cement	2	—	2	—	2	—	2	—
(Envirostone)								
PVC	2	—	—	—	—	—	—	2

The apparatus for conducting the matrix depletion tests consisted of two major components: (a) a series of 1-L test cylinders designed to contain the simulated waste material, and (b) a series of valves, tubing, and measurement apparatus for sampling generated gases and quantitatively measuring constituents. To maintain sample integrity and validity, the experimental apparatus was designed to prevent sample cross-contamination. Overall, 64 cylinders in four groups were used. Within a group, one test cylinder contained standard calibration gases for QC purposes (for a total of four QC cylinders). Figure 3 presents a schematic of the MDP experimental setup.

The plastic and cellulosic matrix configurations were prepared by sprinkling the radioactive isotope powders over the matrix materials, folding the matrix materials over the contaminated surfaces, securing them, then placing them in the test cylinders. For the cement matrix, Envirostone was mixed with a solution of dissolved plutonium oxide, water, and a small amount of sodium hydroxide to adjust the pH. Each cylinder was loaded with approximately 450 g of Envirostone, 300 g water, and 20 ml of sodium hydroxide. The loaded cylinders were allowed to

cure for 24 hours. All plutonium operations were performed in a glove box to contain the plutonium and ascribe to as low as reasonably achievable (ALARA) guidelines.

The entire matrix depletion testing apparatus was controlled by a single IBM-compatible personal computer (PC) through LabVIEW software. The PC was configured to allow remote access by other selected PCs. Three LabVIEW virtual instruments were developed initially for the operation of the MDP experiments: manual controller, autosequencer, and volume autosequencer. This allowed computerized sampling and associated data acquisition of the test cylinders. The manual controller provided operator manual control and data acquisition for nonsequenced operation of the experiment. The autosequencer provided system control, data acquisition, and data recording for fully automated sampling operation of the experiment. The volume autosequencer provided fully automated measurement and reporting of the sample line volumes for each test cylinder in the experiment. The purge (evacuation) and backfill autosequencer provided fully automated evacuation of test cylinders and backfilling of the cylinders with room air at ambient atmospheric pressure.

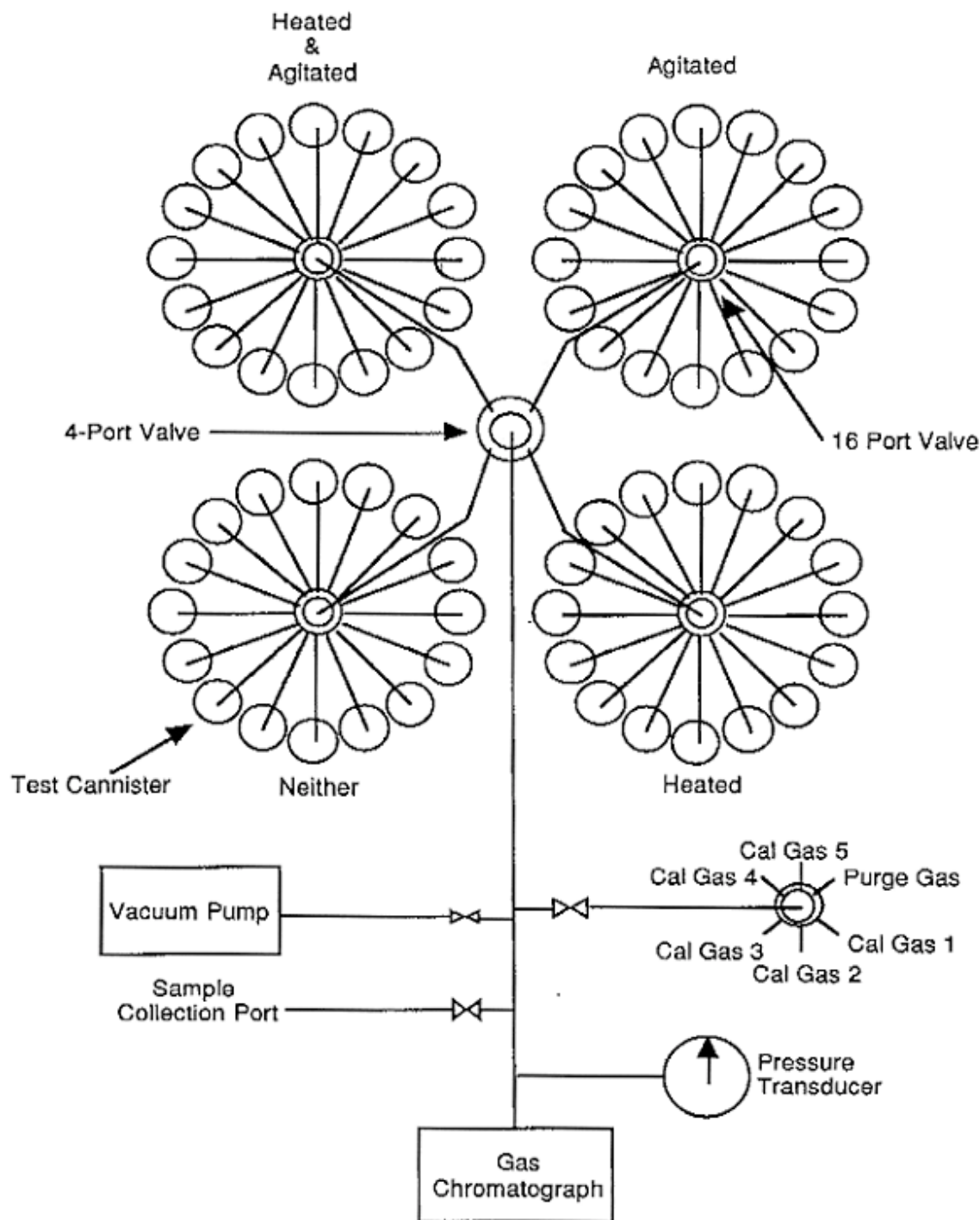


Figure 2. Schematic of the MDP Experimental Setup.

To simulate venting of the containers and introduction of oxygen into actual containers, test cylinders were evacuated (i.e., purged) and backfilled to ambient air oxygen concentrations $\pm 5\%$ when the cylinders had become significantly depleted of oxygen. The objective of the purging and backfilling was to evaluate whether reintroduction of oxygen would impact the G-values. Two conditions had to be met before the purge and backfill procedure was performed on a test cylinder: (a) the oxygen concentrations had to be less than 1.0 volume percent; and (b) the

G-values must have stabilized. The statistical tests were performed at the 95% confidence level and assessed whether the slopes of individual cylinder G-values are all equal to zero and the regression model error associated with modeling G-value behavior is less than 0.1. Cylinder purging and backfilling with ambient air oxygen concentrations were performed on 21 test cylinders. The test cylinders were sampled and analyzed for oxygen and hydrogen immediately prior to and following the procedure.

Biweekly data were collected over a 24-month period, totaling 34 sampling episodes. The data were validated and effective hydrogen G-values were calculated for each cylinder and sampling cycle.

Results

The MDP was successful in quantifying the effective G-values of waste materials after matrix depletion has occurred. Full discussion of the results can be found in reference 7. Table 2 summarizes various statistics for the effective G-value for each waste matrix. The tabulated statistics include the number of observations, the mean G-value, the standard deviation of the G-values, the standard error of the mean, the 95% upper confidence limit (UCL95) of the mean G-value, the 95th percentile G-value, and the 95% upper tolerance limit (UTL95). The statistics are based on only steady state effective G-value data, which were determined by the effective G-value exhibiting a zero slope with dose (tested at the 0.05 significance level) by experimental condition (e.g., unheated cylinders with PE and ²³⁹Pu). Analysis of the results indicated that the zero slope condition for G was achieved after exposure to a dose of .006 watt-years.

Table 2. Experimental G-value Statistics (molecules/100 eV).

Matrix	Number of observations	Mean	Standard deviation	Standard error of mean	UCL95 of mean	95 th percentile	UTL95
Cement	202	0.25	0.18	0.01	0.27	0.49	0.58
Dry cellulose	302	0.27	0.18	0.01	0.29	0.49	0.59
PE	186	0.23	0.22	0.02	0.26	0.56	0.64
PVC	99	0.14	0.19	0.02	0.17	0.44	0.50
Wet cellulose	276	0.44	0.36	0.02	0.48	0.99	1.09

The dose dependent G-values were compared with results from other experimental programs and with current TRUPACT-II SARP G-values. Analyses of MDP experimental data indicate that dose dependent G-values lie between 14% and 38% of the applicable TRUPACT-II SARP values, depending on the waste material. In general, the results are consistent with theoretical expectations for G-value behavior with dose for different waste materials.

The MDP effects analysis indicated that only the waste matrix has a significant effect on the G-value. At the 95% confidence level, isotope and temperature (i.e., heating) did not have significant effects on the G-values. The effects of agitation on G-values were not evaluated because the proposed agitation of test cylinders would not represent the agitation experienced by actual TRU waste containers during movement and transport. Comparisons with hydrogen concentration and G-value data derived from TRU waste drums demonstrate that the G-values obtained from these laboratory experiments are, in fact, greater than the G-values measured in real waste.

HYDROGEN GETTERS

Hydrogen Getters are solid materials that scavenge hydrogen from the gas phase and chemically and irreversibly bind it in the solid state. They belong to a class of organic compounds called alkynes that are characterized by the presence of carbon-carbon triple bonds. In the presence of suitable catalyst systems such as palladium on carbon (Pd/C), hydrogen will add across the unsaturated bonds to form the corresponding saturated alkane.

Compounds of this class were originally developed for use in nuclear weapons by Sandia National Laboratory and the Kansas City Division of Allied-Signal. They are used to protect electronic components in sealed assemblies from hydrogen corrosion. They are also currently being used to provide secondary confinement for tritium shipping containers.

Many compounds and formulations have been tested (6). The best performance has been achieved with 1,4-bis(phenylethynyl)benzene (DEB) (Figure 2). It has a capacity of 240-330 cm³ (STP) hydrogen per gram DEB. DEB is a non-toxic, non-mutagenic, crystalline solid. Because it is a di-alkyne (containing two triple bonds), one mole of DEB reacts with 4 moles of hydrogen. It melts at 179°C; whereas the fully hydrogenated product melts at 87°C. The standard formulation for the DEB getter is a mixture of 75% DEB and 25% palladium-carbon catalyst (5% Pd on carbon). The production process involves mixing the two materials together in a ceramic jar mill for several hours, after which the DEB getter is ready for use. It has been shown to be stable in the absence of hydrogen for up to 18 months (at 70°C, under N₂). The DEB formulation has been successfully incorporated into several forms including powder, pellets, shaped polyethylene composite, a urethane adhesive film and a castable RTV silicone. The material has been in regular production for use in DOE components and assemblies since 1977.

In order to determine the effectiveness of hydrogen getters in the removal of hydrogen from TRUPACT-II waste containers, the initial study was to determine whether any of the other gases identified as being present in the containers could potentially poison or inhibit the getter reactions. Also, an analytical model of the getter reactions was developed and tested in order to assist in the experimental data interpretation and to study the roles of poisons or inhibitors on the effectiveness of the getters. Finally, an initial assessment of getter packages that would enhance the getters' performance as it relates to poisoning effects as well as possible water (or ice) formation from competing hydrogen recombiner reactions has been carried out.

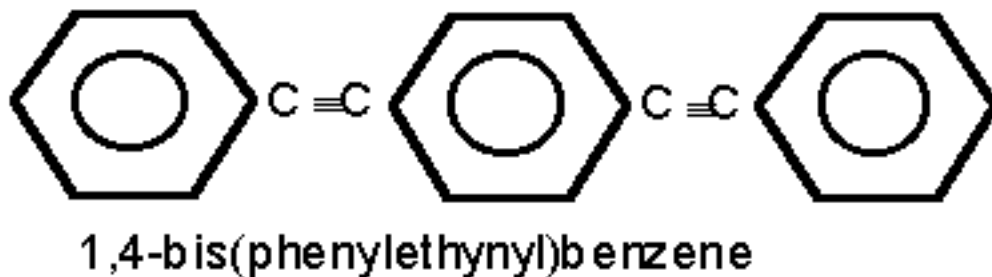


Figure 3. Structure of 1,4-bis(phenylethynyl)benzene (DEB)

The DEB getter reacts rapidly, exothermically and irreversibly with hydrogen. The reaction is nearly stoichiometric and proceeds to >90% of the theoretical capacity. The reaction rate with hydrogen is temperature dependent and proceeds more rapidly as the temperature is increased.

Experimental Design

Experiments have been carried out to determine whether volatile organic compounds (VOCs) known to be present in TRUPACT-II containers have either poisoning or inhibiting effects on the ability of DEB to irreversibly remove hydrogen. Figure 4 is a sketch of the experimental setup. Experiments were carried out by passing mixtures of hydrogen and the potential poison at a known flow rate through a temperature-controlled column containing DEB getter. A hydrogen analyzer was used to measure concentration vs. time profiles for hydrogen exiting the column. From the known values of the in-going hydrogen concentration, the flow rate, and the time of hydrogen appearance at the outlet, the reaction capacity of the getter for hydrogen and the reaction rate can be derived. Samples containing no VOCs were used to determine the optimum capacity and reaction rate of the getter that can be used as an experimental control.

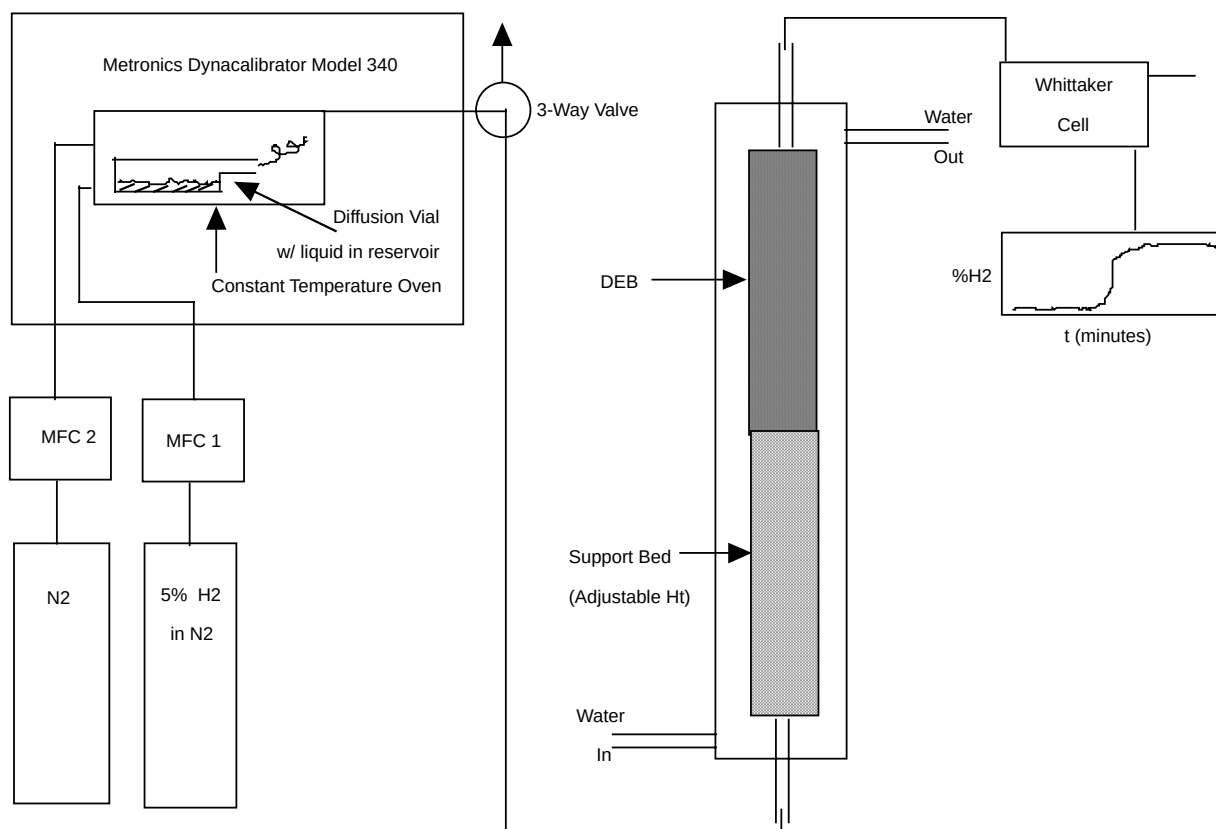


Figure 4. Schematic diagram of experimental setup for conducting experiments with DEB hydrogen getter.

In order to test the poisoning potential of the VOCs, test compounds were classified into categories based on common chemical functional groups (hydroxyls, halogens, etc.). For each category, a single test compound was selected through an evaluation of which compound in that category would be expected to be highly reactive towards the DEB based on structure, reactivity, and steric effects. The function groups and representative test compounds that were selected for testing are:

Inorganic Gases: carbon monoxide
 Halogenated Olefins: trichloroethylene
 Halogenated Alkanes: carbon tetrachloride
 Alcohols: methanol
 Ketones: acetone
 Aromatics: toluene

Preliminary Results

Previous studies at the Allied-Signal Kansas City Plant indicated that carbon monoxide was an inhibitor to the getter reactions. Using the flow system described above, the effect of adding CO to the hydrogen flow resulted in an apparent reversible inhibition effect. The reversibility of the

CO was studied by systematically opening and closing the CO inlet valve while hydrogen was being bled into the reaction chamber and monitoring the effects on the hydrogen concentration observed exiting the reaction chamber. With an inhibitor present, the assumed effect on the hydrogen concentration would be a dramatic increase in hydrogen exiting the reaction vessel while the inhibitor is in the inlet stream with a corresponding decrease in hydrogen (observed as a return to the expected baseline) when the inhibitor inlet stream is shut. (Unlike inhibitors, poisons would not show the hydrogen decrease when the inlet stream is shut.)

According to the classification of organic compounds described above, experiments were tested on the effects of methanol, acetone, toluene, trichloroethylene, and carbon tetrachloride. Acetone, toluene, and methanol appeared to have no effect on the effectiveness of the getters. In similar experiments to the addition of CO, the hydrogen concentration exiting the reaction vessel was unaffected by the presence of these contaminants. Carbon tetrachloride, on the other hand, had a dramatic poisoning effect on the gettering reaction. Unlike the carbon monoxide experiments, when the carbon tetrachloride inlet stream was shut, the hydrogen concentration exiting the vessel did not return to a baseline; the effect was not reversible. After the carbon tetrachloride experiments were carried out, other chlorinated aliphatics and olefinic compounds were tested including chloroform, methylene chloride, 1,1,1-trichloroethane, and trichloroethylene. In all cases, poisoning was observed with the greater effect occurring as the number of chlorine atoms increased.

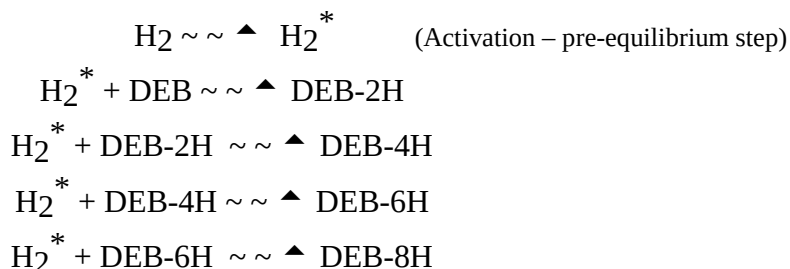
Spectroscopic analysis of the DEB after exposure to chlorinated organics was carried out to try to determine the chemical effects of these contaminants. Preliminary data gathered through Gas Chromatography/Mass Spectrometry, Scanning Electronic Microscopy, and Energy Dispersive X-ray Analysis indicated that the chlorinated organics were not reacting with the DEB or forming Pd-Cl salts. The hypothesis at this point is that the organics are impeding the addition of the activated hydrogen to the DEB. The "absorption" of the chlorinated hydrocarbons to the DEB/catalyst mixture appears to be quite strong with gentle heating not successful in removing the chlorinated material.

Preliminary tests with tedlar as a possible filtering medium indicate that the chlorinated hydrocarbons and carbon monoxide are preferentially filtered from the getter while hydrogen is passing through. Specifications from the manufacturer of tedlar indicate that the diffusion coefficient of hydrogen through tedlar is ~5300x higher than that of carbon tetrachloride. The tedlar does seem to reduce the rate of gettering as a result of some reduction in the hydrogen diffusion rate to the getter compared with the gettering rate. It is our intent to study getter substitutes as well as other filtering media to minimize the poisoning effects.

In order to differentiate between poisoning (reducing capacity) and inhibiting (reducing rate) effects, a kinetic model has been developed and initial tests have been carried out to generate theoretical hydrogen concentration vs. time plots. The model can also address temperature and flow rate effects on the hydrogen plots.

The model involved developing an initial mechanism for the reaction of hydrogen with the getter. The mechanism was based on a sequential series of hydrogen additions to the two triple bonds with each irreversible step having a particular rate constant. It was assumed that hydrogen initially absorbs to the Pd/C catalyst with an equilibrium constant representing absorption and

desorption steps in a pre-equilibrium process. Once absorbed to the surface, the hydrogen can then be subsequently activated to form an intermediate (perhaps hydrogen radicals) which, in the presence of DEB, will add across the unsaturated carbon-carbon bonds. The proposed mechanism is provided below:



In order to develop the model, several key assumptions were made:

- The model would use a three-stage batch process in lieu of a hydrogen flow. The three stages are 1) addition of hydrogen aliquot to reaction vessel with DEB present, 2) reaction of hydrogen with DEB, and 3) purging of unreacted hydrogen to be measured at analyzer.
- Since experimental data are not available that provides specific rate information on the initial step, the model does not address the pre-equilibrium absorption-desorption reaction. If data are collected in the future specific to the initial step, then the model will be modified to include that step.
- At various stages of the reaction, the model predicts that intermediates (DEB-2H, DEB-4H, and DEB-6H) are present with calculated concentrations. For each addition of hydrogen to the reaction vessel, the amount of hydrogen that will react with each DEB form is directly proportional to the relative concentrations of those intermediates. This assumption implies that all available DEB forms are equally accessible to hydrogen. If, through further experimentation, it is determined that the DEB forms are not equally accessible, the model will be modified accordingly.

The parameters that were used to calculate the theoretical plots were:

- four rate constants (one constant for each of the four sequential hydrogen additions)
- the initial amount of getter in the reaction vessel
- the hydrogen aliquot added for each cycle (the first step in the three step process)
- the time interval for the hydrogen reaction (the second step).

Data from a selected experimental plot was initially used to test the model. It was expected that the four rate constants that would generate a similar curve to the experimental plot would follow the trend $k_1 > k_2 > k_3 > k_4$. One reason for this expected trend is due to electronic effects. As the DEB transforms from di-alkyne to di-alkene to di-alkane, the statistical potential for pairwise addition of hydrogen to an unsaturated carbon-carbon bond diminishes. In fact, this trend was observed for the initial generation of theoretical plots comparable to the experimental plots. The flow rate for hydrogen (5% hydrogen/nitrogen mixture was typically used for the experiments) was addressed in the model through a combination of two parameters: the hydrogen aliquot added during the first step and the time interval for the reaction during the second step

The model can potentially distinguish between inhibitors and poisons (inhibitors only slow the getter reaction but ultimately hydrogen would be completely getterred, poisons reduce the amount of hydrogen that can be getterred). If a poison were present, its effect would be comparable to reducing the available amount of DEB for gettering reactions. If an inhibitor were present, its effect would be comparable to reducing the four rate constants involved in the gettering reactions. The model predicts different effects on the hydrogen plots by these two possibilities. In general, changing the amount of getter shifts the hydrogen curve along the horizontal axis. Changing the rate constants has a greater effect on the curvature of the plot as opposed to a plot shift.

CONCLUSIONS

The Matrix Depletion Program has demonstrated matrix depletion in simulated TRU waste materials, and the effects of key parameters have been quantified. The experimentally derived dose dependent G-values are reproducible, consistent with results of other studies, and fall within theoretically predicted bounds. The results may be used to revise appropriate sections of the TRUPACT-II SARP and TRUPACT-II Allowable Methods of Packaging (TRAMPAC) to explain and account for the matrix depletion phenomenon. The original TRUPACT-II SARP G-values will be used to establish the wattage limits for newly generated containers. When a container has attained an adequate dose level (in Watt·yr), the lower MDP dose-dependent G-values would be used to establish a higher allowable wattage limit for the container. The data demonstrate consistency with TRUPACT-II SARP limits for waste type I. Reduced G-values can be supported for waste types II and III after a dose criterion of 0.006 Watt · yr has been satisfied.

REFERENCES

1. P. B. SCHUMANN, G. BACIGALUPA, B. J. SINKULE, S. T. KOSIEWICZ, AND D. M. BOAK, "Key Regulatory Drivers Affecting Shipment of Mixed Transuranic Waste from Los Alamos National Laboratory to the Waste Isolation Pilot Plant," Proceedings of Waste Management '97 Conference, Tucson, AZ (1997).
2. A. ZERWEKH, "Gas Generation from Radiolytic Attack of TRU-Contaminated Hydrogenous Waste," LA-7674-MS, Los Alamos National Laboratory, Los Alamos, NM (1979).
3. S. T. KOSIEWICZ, "Gas Generation from Organic Transuranic Wastes. I. Alpha Radiolysis at Atmospheric Pressure," Nuclear Technology, 54, 92-99, (1981).
4. A. ZERWEKH AND J. L. WARREN, "Gas Generation and Migration Studies Involving Recently Generated Pu-238-Contaminated Waste for the TRU Waste Sampling Program," LA-10732-MS, Los Alamos National Laboratory, Los Alamos, NM, (1986).
5. MARSHALL ET AL., "Determining Site-Specific Drum Loading Criteria for Storing Combustible ^{238}Pu Waste," LA-UR-94-409, Los Alamos National Laboratory, Los Alamos, NM (1994).
6. H. M. Smith, T. J. Shepodd, L. R. Gilliom, "Organic Getter Materials for the Removal of Hydrogen and its Isotopes," Minerals, Metals, and Material Society Fourth International Conference on Hydrogen Effects on Material Behavior, (1990).
7. TRUPACT-II Matrix Depletion Program Final Report, INEEL/EXT-98-00987, Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID (1998).