

Appendix C

RADIOLYSIS

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C.1 Background

The TMI-2 canisters evolve hydrogen and other gases due to radiolysis. This phenomenon has been documented and measured, and has been discussed within numerous licensing and technical documents. (For example, see Reference C.1.) There are three different types of canisters: *fuel*, *knockout*, and *filter*. All three types of canisters may evolve hydrogen gas due to the radiolysis of water. Drying of the canisters will be performed prior to their placement in dry storage. There is only water within the debris, consistent with the criticality analysis. However, conservatively for radiolysis, water is assumed to be present in the interstices of the debris. In addition, water of hydration may be present within the Licon concrete that fills the void area outside the former plates of the *fuel* canisters. (Neither the *knockout* canisters nor *filter* canisters contain this concrete.) All of this water may serve as a source of hydrogen from radiolysis. The lack of water in the debris of the actual material will provide a significant margin of safety since water will not be present to absorb the energy.

All of the TMI-2 canisters contain hydrogen recombiner assemblies that were provided during their initial construction. These recombiners use precious metal catalysts (e.g., platinum, palladium) on inorganic substrates to recombine gaseous hydrogen and oxygen that may be present in the canisters as a result of radiolysis. However, these recombiners have been submerged in both the TMI-2 and INEL pool waters for many years. While the recombiners are not necessarily damaged by this extended submergence, for conservatism they are assumed to be inoperable during the future dry storage period.

Since the recombiners within the canisters are assumed to be inoperable, and it is desired to have a passive storage system to the greatest possible extent, hydrogen within the system may be safely controlled by diffusion. Under the proposed plan, the canisters will be vented to the DSC via their two existing penetrations for venting and dewatering. The DSC will, in turn, be vented to the outside atmosphere via a HEPA-filtered vent. In addition, the purge port from the DSC will also be connected to a HEPA filter and also serve as a passive vent. A number of calculations and studies are performed to evaluate the theoretical generation rate of hydrogen within the canisters, and to evaluate the expected transport of hydrogen gas within the proposed dry storage equipment.

C.2 Canister Gas Generation Rates

After being loaded with radioactive core materials, all of the canisters were monitored for gas production prior to their shipment from the TMI-2 to the INEL. This monitoring was performed to ensure that the canisters' atmospheres would remain at a concentration of less than the lower flammability limit of hydrogen during the shipping period. The canisters were then inerted with two atmospheres of argon prior to shipment. In order to more accurately evaluate hydrogen gas production rates, eight of the canisters were subjected to a "long-term"

gas sampling study at the INEL. Reference C.2 is a summary of the results of that study. The highest hydrogen gas generation rate that was measured at the INEL was 1.95 cc per hour (0.00195 liters per hour) for canister number D-188. During all of the gas generation testing that was done to the various canisters, hydrogen recombiners were present. Since the recombiners were installed in the canisters during their initial construction, there is no field data on hydrogen gas generation rates within these canisters without the recombiners present.

The storage canisters will evolve gases as a result of radiolytic decomposition of residual water and any organic materials that may be present. The rate of gas production is a function of the energy emitted by the canister's contents, the fraction of the energy absorbed by the material that decomposes, and a gas generation constant or 'G-value' (typically expressed as the number of molecules of gas or free radicals formed per 100 eV of energy absorbed).

The gas generation rate will also be a function of the quantity and location of the water that is present. The fraction of decay heat energy that is absorbed by the water will affect the amount of hydrogen generated by radiolysis. In order to estimate the amount of water that could be in the canisters after drying, information on the canisters' void volumes was analyzed. The void volume of the fuel debris particles determined during the TMI-2 cleanup ranged from 8 to 31%. It was assumed that water filled the entire void volume of 31%. This is a conservative assumption for radiolysis evaluation because the canisters will be dried consistent with the criticality analysis prior to loading in the DSC.

Considerable data is available on appropriate 'G' values for water. The most commonly supported value, and the one generally accepted in this type of analysis is for a hydrogen production (or G_{H_2}) of 0.44 molecules per 100 eV absorbed [C.3]. Similarly, previous analyses have assumed that hydrogen and oxygen gases are produced by water radiolysis in stoichiometric proportions ($G_{O_2} = 0.22$). The assumption of a G_{O_2} of 0.22 is an acceptably conservative approach for safety analyses. Current calculations also considered the total radiation emitted (i.e., alpha, beta, and gamma) because of the close proximity of the water to the radiation source.

The original NRC-approved safety analysis for the defueling canisters [C.4] calculated a maximum canister theoretical gas generation rate of 0.076 liters per hour of hydrogen and 0.038 liters per hour of oxygen. There was significant conservatism used in this earlier calculation that may be relaxed today. First, the maximum theoretical gas calculations assumed that the canister was loaded to its maximum design payload of 800 kg (1764 lb). Those calculations were performed prior to actual loading of any canisters, while we may now calculate a gas generation rate using known measured payload data. The earlier calculations used a decay heat load for the core debris for a date of March

1986. Thirteen more years of decay will have occurred, significantly reducing the decay heat and gas generation rate. Current calculations use a total core decay heat load obtained for the year 1999 (a projected time of actual fuel transfer).

The projected hydrogen and oxygen generation rates (in liters per hour) may be calculated by the following formula:

$$Rate = E_{watts} \times P \times F \times \frac{1eV}{1.6 \times 10^{-19} \text{ watt} - \text{sec}} \times G \frac{\text{molecules}}{100eV} \times \frac{22.4 \text{ liters}}{6.02 \times 10^{23} \text{ molecules}} \times \frac{3600 \text{ sec}}{\text{hour}}$$

where:

E is the decay heat energy of a single canister and is obtained by multiplying the total TMI-2 core decay heat of 4776 watts (for year 1999) by the canister payload weight divided by the total core mass of 127400 kg.

P is the peaking factor or the ratio of the peak energy from the debris in a canister to the energy in the same quantity of average fuel. This value is 1.9.

F is the fraction of the alpha, beta, and gamma energy (i.e., the decay heat) absorbed by the water assumed to be in the canisters. For these canisters, this value is calculated to be 0.0345 [C.5].

The above equation was used to calculate the gas generation from all of the canisters. The maximum calculated gas generation is from a single *knockout* canister at 0.008 liters of hydrogen per hour. (There is only a single canister at this 0.008 liter per hour maximum rate.) The maximum fuel-type canister has a calculated generation rate of 0.007 liters per hour.

C.3 Other Possible Sources of Hydrogen

There are possible sources of hydrogen in the canisters' atmospheres other than that from radiolysis of water. However, these sources are not expected to be significant for the TMI-2 core canisters for the following reasons:

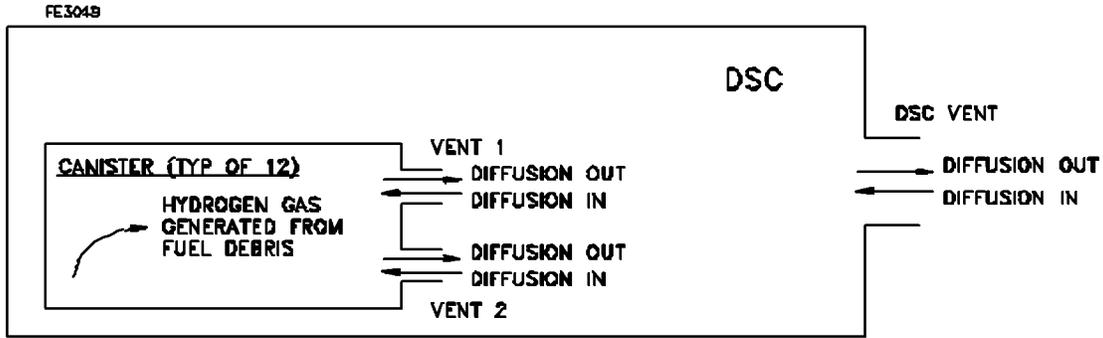
- Corrosion of the canisters is not expected to be the source of a significant quantity of gas. The canisters were manufactured from stainless steel and will not be subjected to a corrosive environment while in dry storage. The core materials are not expected to significantly corrode when subjected to ambient atmospheric conditions. The fuel

itself is uranium dioxide and is, thus, already oxidized. In summary, corrosion is not expected to provide a hydrogen source term that is significant relative to the hydrogen source term from radiolysis.

- The TMI-2 core materials do not contain significant quantities of hydrogen in comparison to the radiolysis of water within the canisters. The two materials for which the various canisters were designed were defueling water and fuel debris; organic and hydrogenous materials were avoided during both the design and use of the TMI-2 canisters.
- Hydrogen generated by chemical reaction with the boric acid solution of a fuel pool is not a likely scenario for the TMI-2 canisters. The present plan is that the TMI-2 canisters will be loaded in the DSC while dry. Therefore, it is unlikely that the chemical reaction scenario that has occurred for some dry storage systems will be repeated during the loading of the TMI-2 canisters.
- The production of hydrogen from the radiolysis of waters of hydration within the Licon cement should also be of a negligible quantity relative to that from the water in the interstices of the fuel debris. The Licon cement is separated from the fuel debris by a 0.135" boral shroud, which is sandwiched between 0.04" thick and 0.08" thick stainless steel plates [C.6]. This shroud will prevent essentially all alpha and beta radiation emanating from the core debris from reaching the concrete. The alpha and beta radiation comprise the majority of the debris decay energy. A considerable quantity of the gamma radiation will be attenuated by the shroud materials, or will be absorbed by the "non-water" substances (e.g., the aggregate, the calcareous and silicate portions of the cement crystal) within the concrete. Given the above, it is assumed that the presence of the Licon concrete within the debris canisters does not constitute a hydrogen generation concern relative to the water interspersed in the debris.

C.4 Gas Transport Assumptions and Calculations:

The following is a graphical presentation of the proposed canister/DSC arrangement, with an explanation of the various diffusion flows of hydrogen gas that were assumed in the analysis model.

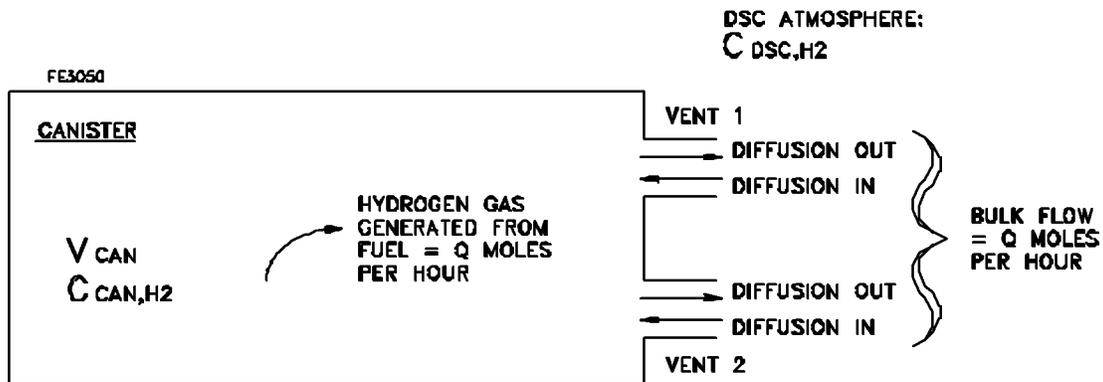


The canisters will have internal hydrogen gas being generated at the generation rates previously described. For the purposes of the gas transport model, the generated gas will be assumed to be pure hydrogen.

There are two possible vent paths from the canisters, one vent penetration and one dewatering penetration. The diffusion flow through these two vents will be assumed to be equimolar counter diffusion. That is, hydrogen will diffuse out of the canisters while air will diffuse into the canister. For every molecule of hydrogen that diffuses out, a molecule of air (i.e., nitrogen, oxygen, etc.) will diffuse into the canister.

Along with the generation of hydrogen gas in the canisters, and the diffusion flow from their vents, there will be a “bulk” flow of gas out of the canisters due to the evolved gas. That is, for every cubic centimeter (cc) of hydrogen that is evolved from the waste debris within the cans, a cc of gas will be pushed out the vents. In summary, isobaric conditions for the canister, DSC, and outside atmospheres are assumed.

In summary, the flow paths from the canisters are:



A hydrogen gas balance may be written for the canisters:

Hydrogen **in** - Hydrogen **out** = Hydrogen **accumulated** in the canister

This may be further elaborated as:

(Hydrogen in due to gas generated) - (Hydrogen diffusing out of Vent #1) -

(Hydrogen diffusing out of Vent #2) - (Hydrogen out with “bulk flow”) =

Hydrogen accumulated.

This may be further written as the following differential equation:

EQUATION 1 (Canister Unsteady- state):

$$Q - \left[D \frac{(C_{CAN,H2} - C_{DSC,H2})(\text{vent 1 area})}{(\text{vent 1 length})} \right] - \left[D \frac{(C_{CAN,H2} - C_{DSC,H2})(\text{vent 2 area})}{(\text{vent 2 length})} \right] - Q(C_{CAN,H2}) = V_{CAN} \left(\frac{dC_{CAN,H2}}{dt} \right)$$

where:

Q = Canister hydrogen generation rate

D = Diffusion coefficient for hydrogen in air

$C_{CAN,H2}$ = hydrogen concentration in canister

$C_{DSC,H2}$ = hydrogen concentration in DSC

vent 1 area = cross-sectional area of canister vent 1

vent 1 length = length of canister vent 1

vent 2 area = cross-sectional area of canister vent 2

vent 2 length = length of canister vent 2

$\frac{dC_{CAN,H2}}{dt}$ = time rate of change of hydrogen concentration in canister, and

V_{CAN} = free volume of canister

At steady state (where the right hand side of the equation is zero), we find:

EQUATION 2 (Canister Steady State):

$$C_{CAN,H2} \text{ (at steady state)} = \frac{Q + D \left(\frac{\text{(vent 1 area)}}{\text{(vent 1 length)}} + \frac{\text{(vent 2 area)}}{\text{(vent 2 length)}} \right) \cdot (C_{DSC,H2} \text{ (at steady state)})}{Q + D \left(\frac{\text{(vent 1 area)}}{\text{(vent 1 length)}} + \frac{\text{(vent 2 area)}}{\text{(vent 2 length)}} \right)}$$

A similar model is derived for the DSC and for a mass balance around the entire DSC/canisters system. These models give us the unsteady-state and steady-state equations for the DSC:

EQUATION 3 (DSC Unsteady-state):

$$\left[12Q(C_{CAN,H2}) + 12 \left[D \frac{(C_{CAN,H2} - C_{DSC,H2})(\text{vent 1 area})}{(\text{vent 1 length})} \right] + 12 \left[D \frac{(C_{CAN,H2} - C_{DSC,H2})(\text{vent 2 area})}{(\text{vent 2 length})} \right] \right] - \left[D \frac{(C_{DSC,H2} - C_{OUTSIDE,H2})(\text{DSC vent area})}{(\text{DSC vent length})} + 12Q(C_{DSC,H2}) \right] = V_{DSC} \left(\frac{dC_{DSC,H2}}{dt} \right)$$

where:

V_{DSC} = Free volume of the DSC

Q = Canister hydrogen generation rate

D = Diffusion coefficient for hydrogen in air

$C_{CAN,H2}$ = Hydrogen concentration in canister

$C_{DSC,H2}$ = Hydrogen concentration in DSC

$C_{OUTSIDE,H2}$ = Hydrogen concentration outside the DSC = 0.0

vent 1 area = Cross-sectional area of canister vent 1

vent 1 length = Length of canister vent 1

vent 2 area = Cross-sectional area of canister vent 2

vent 2 length = Length of canister vent 2

DSC vent area = cross-sectional area of the DSC vent

DSC vent length = length of the DSC vent

$\frac{dC_{DSC,H2}}{dt}$ = Time rate of change of hydrogen concentration in the DSC

EQUATION 4 (DSC Steady-state):

$$C_{DSC,H2} = \frac{12Q}{12Q + \left[D \frac{(\text{DSC vent area})}{(\text{DSC vent length})} \right]}$$

for the steady state.

These equations show that the hydrogen concentrations in both the canister and the DSC depend heavily on their vent geometries and the hydrogen generation rate (G), as well as the canister vent paths to the DSC atmosphere.

C.5 Canister Vent Paths

There are two possible “bottlenecks” for the diffusion process in this system: the canister vents and the DSC vent. It is important that the hydrogen concentration in both the DSC and the canister atmospheres remain below 5%. An analysis of the canisters’ vent and drain paths has indicated that the fuel debris-type canisters have the design with the least hydrogen diffusivity (i.e., this canister has the highest resistance to diffusion). A description of the existing debris canister vent paths is as follows:

The *fuel* canisters have (from inside the canister to outside) a drain/dewatering line that is nominally 142” long and 0.527” I.D. . The bore through the head of the canister is 0.500” in diameter and is 7/8” long. (This 0.500” bore is tapped for 3/8” NPT threads.)

The *fuel* canisters have a head space vent path that consists (from inside the canister to outside) of an 1/8” diameter bore that is 1/4” in length, then a bore of 27/64” that is 1-1/8” long. (This 27/64” bore was tapped with 1/4” NPT threads.)

Given the above geometries for the possible vent paths, it is possible to convert these paths to equivalent lengths of 1/2” I.D. tubing as shown in Table C.5-1 below. This is done because diffusion of a gas proceeds at a rate proportional to the ratio of the cross-sectional area of a pipe to its length. For conservatism, add 10% to the equivalent length of 1/2” I.D. tubing to account for entrance and exit losses, despite the fact that hydrogen generation rate and hence diffusion is a very slow process (the diffusion of a few cc’s of gas per hour) and would not expect significant entrance losses.

Table C.5-1 Equivalent Length of 1/2” I. D. Tubing

<u>Item</u>	<u>I.D.</u> (in)	<u>Length</u> (in.)	<u>Cross- Sectional Area</u> (sq. in.)	<u>Area/length</u>	<u>Equivalent length of 1/2” I.D. tube.</u> (Area=0.196 sq. in.)
<i>Fuel Canister Dewatering/Drain Tube</i>					
Drain Tube	0.527”	142”	0.218	.00153	128
Head Boring	0.50”	7/8			0.875
					Subtotal: 129”
					+10% = 13”
					TOTAL: 142”
<i>Fuel Canister Head Space Vent</i>					
Head Boring	0.125”	.25	0.0123	0.049	4
Head Boring	0.421”	1.125	0.139	0.124	1.6
					Subtotal:5.6”
					+ 10% = 0.6”
					TOTAL: 6.2”

C.6 Calculations

Equations 2 and 4 are used to evaluate the maximum steady-state canister and DSC hydrogen concentrations that can be expected for given canister and DSC vent geometries. By substituting into the equations it can be demonstrated that a DSC vent geometry equivalent to 5" diameter and 14" length provides a low steady state DSC concentration (about 1%). Calculations in Section C.7 show that this DSC vent geometry requirement is satisfied. Utilizing a DSC vent of this size, and removing the Hansen fittings on the TMI-2 canisters, steady state hydrogen concentration in the DSC and TMI-2 canisters is calculated as shown below:

Using the steady state formula for the DSC (Equation 4):

$$\text{Hydrogen Conc. in the DSC} = 12Q / (12Q + D(\text{DSC vent area} / \text{DSC vent length}))$$

where:

12 = the number of canisters in a DSC

Q = the hydrogen generation rate in cc/hr per canister = 7 cc/hr

D = the diffusion coeff for hydrogen in air @ 0°C = 0.611 sq. cm/sec = 2,200 sq. cm/hour

Canister vent 1 area = 1.27 sq. cm (½" I.D. pipe equivalent)

Canister vent 1 length = 142" = 361 cm (from preceding table)

Canister vent 2 area = 1.27 sq. cm (½" I.D. pipe equivalent)

Canister vent 2 length = 6.2" = 15.7 cm (from preceding table)

DSC vent area = 126.7 sq. cm (5" I.D. pipe equivalent)

DSC vent length = 14" = 35.6 cm

Canister vent cross-sectional areas and lengths are from the table above.

$$C_{\text{DSC}} = (12*7) / [(12*7) + 2200(126.7 \text{ sq. cm} / 35.6 \text{ cm})] = 0.01 = 1.0 \%$$

Substituting this steady-state DSC concentration into the equation for the canister (Equation 2):

$$C_{\text{canister}} = \frac{7 + (2200((1.27 / 361) + (1.27 / 15.7))(0.01))}{7 + 2200((1.27 / 361) + (1.27 / 15.7))} = 0.046 = 4.6\%$$

This shows that a DSC vent with this geometry (or equivalent from a diffusion standpoint) will maintain both the DSC and canister atmospheres at less than 5% hydrogen.

Note: The above calculations do not include the Hansen quick-disconnect fittings presently installed on the canisters' vent ports. These fittings make the diffusion path from the canisters

more difficult, and increase the expected steady-state hydrogen concentration in the canisters and, will be removed from the canisters prior to dry storage.

The following are the input parameters to the model, and a brief discussion of the values that have been analyzed:

Canister free volume: Reference C.7 indicated that the canisters would be dried to the extent that the average *fuel* canister has a void volume of 3.85 cubic feet, the *knockout* canisters have an average void volume of 7.35 cubic feet, and the *filter* canisters have an average void volume of 5.96 cubic feet. To be conservative, a canister free volume of 100,000 cc's, or 3.53 cubic feet is used in the radiolysis evaluation. The use of low canister free volume is conservative in these calculations. Note that the canister free volume does not enter into the final steady state concentration of hydrogen in the canister (see Equation 2). The canister free volume affects only the rate at which the hydrogen concentration builds up in the canister (i.e., before it reaches steady state). Also, to meet criticality requirements the free water will be removed from the canisters prior to loading into a DSC. Therefore, these calculations are based on a conservatively high volume of free water and low canister free volume.

Canister initial hydrogen concentration: An initial concentration of 0% by volume is assumed.

Single canister hydrogen generation rates: The generation rate of hydrogen within a canister, Q , is the dominant input parameter to these calculations. 7
cc/hr/canister is used as the design basis hydrogen generation rate.

Diffusion coefficient of hydrogen in air: A value of .611 sq. cm/sec at 0°C (32°F) from Reference C.8 is used. This is a conservative value since diffusion rate will increase with temperature. (The average annual temperature at the INEL site is approximately 42°F per Reference C.9.)

Canister vent 1 cross-sectional area, Canister vent 1 length, Canister vent 2 cross-sectional area, and Canister vent 2 length: See the previous section on canister vent paths.

Number of canisters per DSC: A total of 12 canisters will be stored per DSC. All 12 of the canisters are assumed to have the same geometry (i.e., vent sizes) and hydrogen generation rates.

DSC free volume: 3,200,000 cc is used as the internal free volume of the DSC. Note, however, that the DSC free volume does not enter into the final steady state

concentration of hydrogen in the DSC (see Equation 4). The DSC free volume affects only the rate at which the hydrogen concentration builds up in the DSC (i.e., before it reaches steady state).

DSC initial hydrogen concentration: An initial concentration of 0% by volume is assumed.

DSC vent cross-sectional area: The cross-sectional area of the DSC vent is an important parameter in the evaluation of the hydrogen transport from the DSC.

DSC vent length: The length of the DSC vent is an important parameter in the evaluation of the hydrogen transport from the DSC.

C.7 DSC Vent Filtration

The hydrogen transport from the canister/DSC system is highly dependent on the vent geometries. A proposed DSC vent filter may be added to the “equivalent pipe length technique” (similar to those methods used for pump calculations) wherein the proposed filter is “converted” to a pipe of similar hydrogen diffusivity.

The DSC vent will exhaust to the outside atmosphere. Thus, it must provide a particulate capture efficiency that is equivalent to that provided by HEPA filters that are inservice at other nuclear facilities. It also must have sufficient hydrogen diffusivity and flow ratings to allow for proper diffusion of hydrogen.

The DSC vent filters will have essentially the same specifications as the Drum Filter Vents (DFVs) and similar filters presently being utilized by the DOE. These DFVs and similar filters are used to exhaust hydrogen from radwaste containers in which hydrogen generation is a concern. The Trupact-II SAR [C.10] has described carbon composite filters designed for high efficiency particulate air (HEPA) filtration with tested hydrogen diffusivities. (These filters are manufactured by Nuclear Filter Technology, Inc.) Recent work by Pall Corporation has described all stainless steel HEPA filters with tested hydrogen diffusivities [C.11]. Either of these filters will provide sufficient hydrogen diffusivity for this application.

Under the conservative analysis described earlier, the DSCs will have a steady state hydrogen concentration of approximately 1% by volume (a hydrogen mole fraction of 0.01). The hydrogen generation rate within the DSC/canister system will be (12 canisters times 7 cc/hr/canister or) 84 cc/hr of hydrogen. As an example, the NucFil-016 carbon composite filter has a hydrogen diffusivity of $9.34E-5$ mole/sec/mole fraction; the Pall DFV #1 stainless filter has a diffusivity of $5E-6$ mole/sec/mole fraction. For a DSC hydrogen concentration just inside the filter of 1% (a mole fraction of 0.01), these filters would release 75 cc/hr and 4 cc/hr,

respectively. (The difference in these two filters is that the NucFil-016 is a 2" diameter filter while the Pall filter is 3/4" diameter. Pall is able to manufacture larger filters.)

The NucFil-016 has a diffusivity of $9.34E-5$ mole/sec/mole fraction. The filter is 2" in diameter and approximately 1" long. An empty pipe that is 2" diameter and about 2-1/2" long has the same diffusivity. (This indicates that, so far as the molecular hydrogen is concerned, much of the filter is empty space.) Since the diffusion through the filters is additive, two filters has half the equivalent length of one filter, four filters gives 1/4 the equivalent length as one filter, etc. (That is, if one filter provides a diffusivity of $9.34E-5$ mole/sec/mole fraction, two filters will provide twice that diffusivity or $18.68 E-5$ mole/sec/mole fraction. etc.)

The DSC vent includes four NucFil-016 filters in parallel and has an equivalent length of less than 14" of 5" I.D. pipe as shown in the calculations below. [Note that four NucFil-016 filters could be installed or another filter with a hydrogen diffusivity of (4 times $9.34E-5$ mole/sec/mole fraction =) $3.74E-4$ mole/sec/mole fraction is also acceptable]. The steady state values of hydrogen using previous equations and equivalent length of filters is calculated as shown below:

The gas enters the DSC shield block through the two inch wide, six inch long openings. It then passes through the openings in the lid, shield plug, vent attachments, filter access areas and filter before it exits to the ambient. These vent paths are converted to equivalent lengths of 5" diameter tube as shown below:

$$\text{Area of a 5 inch pipe} = 2.5^2 * \pi = 19.63 \text{ in.}^2$$

The shield block is 1.75 inches in length.

$$L_{SB} = 19.63 * 1.75 / (2 * 2 * 6) = 1.43 \text{ in.}$$

Length up to the lid.

$$L_B = 19.63 * 1 / (7.54 * .5 * 6.83) = 0.76 \text{ in.}$$

Length through the shield plug with five inch diameter opening.

$$L_{SP} = 6.04 \text{ in.}$$

Length of vent attachment.

$$L_{VA} = 19.63 * 3 / (4.75^2 * \pi) = 0.83 \text{ in.}$$

Length of filter access.

$$L_{FA} = 19.63 * 1.4 / ((2.259/2)^2 * \pi * 4) = 1.17$$

The equivalent length of the five inch pipe for the NucFil filters is calculated below:

Diffusion equation :

$$N/A = D(\Delta C / L_F)$$

Where:

$$N = \text{moles/sec}$$

$$A = \text{cross-sectional area (cm}^2\text{)}$$

$$D = \text{Diffusion coefficient} = 0.611 \text{ cm}^2/\text{sec for hydrogen in air at } 0^\circ\text{C}$$

$$\Delta C = \text{concentration gradient (moles/cm}^3\text{)}$$

$$L_F = \text{equivalent length cm}$$

For the filter term $N/\Delta C$, cc per time is given as $9.34 \text{ E-}5 \text{ mole/sec/mole fraction}$

$$\text{Mole fraction} = 1.0 \text{ gram mole} / 22400 \text{ cc}$$

$$N/\Delta C = 9.34 \cdot 10^{-5} / 22400 = 2.094 \text{ cc/sec}$$

$$A \text{ for a 5 inch pipe is } 127 \text{ cm}^2 = (5 * 2.54) \pi / 4$$

Substituting in to the diffusion equation and solving for L_F :

$$2.094 \text{ cc/sec} = (0.611 \text{ cm}^2/\text{sec})(127 \text{ cm}^2) / L_F$$

$$L_F = 37 \text{ cm} = 14.58 \text{ inches of 5 in. Dia. Pipe.}$$

One filter has equivalent length of 14.58 inch of five inch diameter pipe. Four filters in parallel have an equivalent length of:

$$L_{FT} = 14.58/4 = 3.65 \text{ in.}$$

Equivalent total length for the DSC vent geometry is:

$$L = L_{SB} + L_B + L_{SP} + L_{VA} + L_{FA} + L_{FT} = 1.43 + 0.76 + 6.04 + 0.83 + 1.17 + 3.65 = 13.88 \text{ inches.}$$

This is less than the 16 inches used in the hydrogen concentration calculation that follows. Therefore, there is considerable margin in the DSC vent design.

Using the steady state formula for the DSC (Equation 4):

$$\text{Hydrogen Concentration in the DSC} = 12Q / (12Q + D(\text{DSC vent area} / \text{DSC vent length}))$$

where:

12 = the number of canisters in a DSC

Q = the hydrogen generation rate in cc/hr per canister = 7 cc/hr

D = the diffusion coeff for hydrogen in air @ 0°C = 0.611 sq. cm/sec = 2,199.6 sq. cm/hour

DSC vent area = 126.7 sq. cm

DSC vent length = 16" = 40.6 cm

$$C_{DSC} = (12*7) / [(12*7) + 2200(126.7 \text{ sq. cm} / 40.6 \text{ cm})] = 0.012 = 1.2 \%$$

$$C_{\text{canister}} = \frac{7 + (2200((1.27 / 361) + (1.27 / 15.7))(0.012))}{7 + 2200((1.27 / 361) + (1.27 / 15.7))} = 0.048 = 4.8\%$$

Equations 1 and 3 are solved with the following inputs to calculate canister and DSC hydrogen concentration as a function of time:

DSC vent diameter of 5"

DSC vent length of 16"

Canister generation rate of 7 cc/hr per canister

No Hansen couplers were used on the canisters

Other inputs are:

Individual Fuel Debris Canister free volume = 100,000 cc

Canister initial hydrogen concentration = 0%

Single canister hydrogen generation rate = 7 cc/ hr per canister = Q

Diffusion coefficient of hydrogen in air = 0.611 sq. cm/sec = 2,200 sq. cm/hr

Canister vent 1 cross-sectional area = 1.27 sq. cm. (1/2" I.D. Tube)

Canister vent 1 length = 360 cm (see preceding table)

Canister vent 2 cross-sectional area = 1.27 sq. cm. (1/2" I. D. Tube)

Canister vent 2 length = 60.2 cm (see preceding table)

Number of canisters per DSC = 12

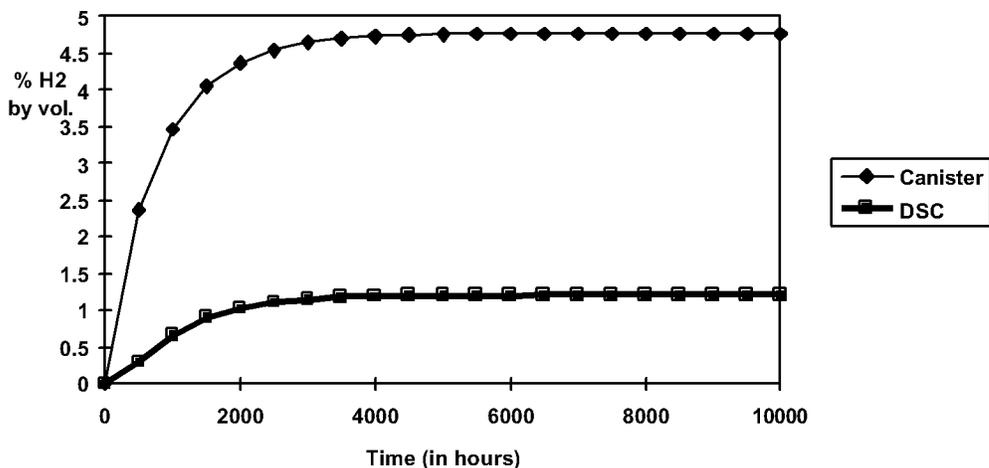
DSC free volume = 3,200,000 cc

DSC initial hydrogen concentration = 0%

DSC vent cross-sectional area = 127 sq. cm. (5" I.D. pipe)

DSC vent length = 16" = 40.6 cm

The following is a plot of the concentration versus time data calculated:



As calculated in the previous section, the steady-state DSC and canister hydrogen concentrations for this plot are 1.2% and 4.8%, respectively. The addition of the filters on the end of the DSC vent raised the steady-state concentrations slightly.

A carbon or stainless steel HEPA filter may be installed. The analysis above has used the diffusivity of the four NucFil-016 carbon filter with efficiencies of greater than 99.97% for 0.3 μ m DOP particles, but any filter with sufficient diffusivity and particulate capture efficiency may be used.

The radioactive drum vent filters manufactured by Nuclear Filter and Pall meet the essential specifications for the DSC vent filter.

C.8 Conservatism of these Methods

The analysis has neglected the normal diurnal atmospheric pressure variation for the INEL location. The analysis assumed that the canister/DSC dry storage system was isobaric (i.e., at constant pressure). (The average station barometric pressure is 25.06" Hg. Per Reference C.9, the annual mean daily pressure range is 0.10" Hg. in summer, which equates to a gas volume change of about 0.4% of the system volume per day.) It is conservative to neglect this breathing, since the daily pressure "breathing" will introduce approximately 400 cc (0.4 %) of DSC air into each canister free volume of approximately 100,000 cc, as well as introduce approximately 12,800 cc (0.4 %) of air into the atmosphere of the DSC. Note that while 0.4% of a canister volume (400 cc) is a relatively small amount of daily gas exchange, it is a large volume compared to the 7 cc/hr (=168 cc/day) of hydrogen generated in a canister over the

same period. This gas will dilute the hydrogen gas within the dry storage system and also will move hydrogen gas out of the dry storage system at a faster rate than that achieved by diffusion alone. In summary, there is substantial conservatism in neglecting the daily atmospheric pressure variation since, during a typical day, a greater volume of air will be introduced into the system than hydrogen.

The TMI-2 fuel debris has some decay heat that will cause thermal convection currents to be created. This convection will help aid the transport of the hydrogen. However, thermal convection currents were also neglected in the analyses.

The lowest diffusion coefficient for hydrogen in air is used. A higher diffusion coefficient would increase the rate of hydrogen transport from the system.

It was assumed that a stoichiometric mixture of oxygen and hydrogen was created as a result of the radiolysis. However, any bulk flow out of the canisters and DSC that would be provided by the appearance of oxygen in the canisters was neglected. Had the evolution of a stoichiometric amount of oxygen within the canisters been considered, the "bulk flow rate out" volume terms in Equations 1 through 4 would be increased from Q to $1.5Q$ for the canisters, and from $12Q$ to $18Q$ for the DSC. This would lower the steady-state concentrations for both the canisters and DSC.

It is assumed that the hydrogen recombiners present in all of the canisters were not functional.

It is assumed that entrance losses of the diffusion through the canister vents would amount to 10%, although this is a very slow process and there is little reason to suspect that entrance losses will be significant.

It is assumed that each of the 12 canisters in a single DSC will evolve hydrogen at the maximum calculated rate. It is unlikely that a single DSC will have a source term of 84 cc/hr hydrogen.

There will be a second (albeit smaller) filtered vent path provided from the DSC to the outside atmosphere. The drain line of the DSC will be used as a vent; however the contribution of that line to the hydrogen removal from the system was ignored.

C.9 Conclusions

The analysis shows that the DSC venting system will maintain the DSC and canisters below 5% hydrogen. Considering the above-mentioned conservatisms of the calculations, it is probable that both the DSC and the canisters will never even approach this 5% concentration.

C.10 References

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- C.3 D. Fletcher, et al, "Post-LOCA Hydrogen Generation in PWR Containments," Nuclear Technology, Volume 10, pp. 420-427, April 1971.
- C.4 NRC Letter NRC/TMI 85-083: William D. Travers to Frank Standerfer, "Defueling Canister TER," November 5, 1985.
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- C.6 Babcock and Wilcox Co. Drawings as follows:
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- C.11 L. Weber, et al, "Validation Testing of Radioactive Waste Drum Filter Vents," Pall Corporation, 1996.

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